
JMIR Perioperative Medicine

Technologies for pre- and post-operative education, preventative interventions, and clinical care for surgery and anaesthesiology patients, as well as informatics applications in anesthesia, surgery, critical care, and pain medicine

Volume 8 (2025) ISSN 2561-9128 Editor in Chief: Nidhi Rohatgi, MS, MD, SFHM

Contents

Corrigenda and Addenda

Correction: A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study ([e71874](#))

Daan Toben, Astrid de Wind, Eva van der Meij, Judith Huirne, Johannes Anema. 2

Original Papers

Implementation of Brief Submaximal Cardiopulmonary Testing in a High-Volume Presurgical Evaluation Clinic: Feasibility Cohort Study ([e65805](#))

Zyad Carr, Daniel Agarkov, Judy Li, Jean Charchafieh, Andres Brenes-Bastos, Jonah Freund, Jill Zafar, Robert Schonberger, Paul Heerdt. 4

Enhancing Quadruple Health Outcomes After Thoracic Surgery: Feasibility Pilot Randomized Controlled Trial Using Digital Home Monitoring ([e58998](#))

Mahesh Nagappa, Yamini Subramani, Homer Yang, Natasha Wood, Jill Querney, Lee-Anne Fochesato, Derek Nguyen, Nida Fatima, Janet Martin, Ava John-Baptiste, Rahul Nayak, Mehdi Qiabi, Richard Incelet, Dalilah Fortin, Richard Malthaner. 15

Reducing Greenhouse Gas Emissions and Modifying Nitrous Oxide Delivery at Stanford: Observational, Pilot Intervention Study ([e64921](#))

Eric Kraybill, David Chen, Saadat Khan, Praveen Kalra. 29

A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study ([e58878](#))

Daan Toben, Astrid de Wind, Eva van der Meij, Judith Huirne, Johannes Anema. 34

Development and Validation of a Routine Electronic Health Record-Based Delirium Prediction Model for Surgical Patients Without Dementia: Retrospective Case-Control Study ([e59422](#))

Emma Holler, Christina Ludema, Zina Ben Miled, Molly Rosenberg, Corey Kalbaugh, Malaz Boustani, Sanjay Mohanty. 47

Agreement Between Provider-Completed and Patient-Completed Preoperative Frailty Screening Using the Clinical Risk Analysis Index: Cross-Sectional Questionnaire Study ([e66440](#))

Mehraneh Khalighi, Amy Thomas, Karl Brown, Katherine Ritchey. 62

Corrigenda and Addenda

Correction: A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study

Daan Toben^{1,2}, MSc; Astrid de Wind^{2,3}, PhD; Eva van der Meij^{2,3}, PhD; Judith A F Huirne^{2,4}, PhD; Johannes R Anema^{1,2}, PhD

¹Department of Public and Occupational Health, Amsterdam UMC location Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

²Societal Participation & Health, Amsterdam Public Health research institute, Amsterdam, The Netherlands

³Department of Public and Occupational Health, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

⁴Department of Obstetrics and Gynaecology, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

Corresponding Author:

Daan Toben, MSc

Department of Public and Occupational Health

Amsterdam UMC location Vrije Universiteit Amsterdam

Van der Boechorststraat 7

Amsterdam, 1081 BT

The Netherlands

Phone: 31 647861694

Email: d.j.toben@amsterdamumc.nl

Related Article:

Correction of: <https://periop.jmir.org/2025/1/e58878>

(*JMIR Perioper Med* 2025;8:e71874) doi:[10.2196/71874](https://doi.org/10.2196/71874)

In “A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study” (*JMIR Perioper Med* 2025;8:e58878) the authors noted one error.

The affiliations were incorrectly published as:

Daan Toben^{1,2}, MSc; Astrid de Wind^{1,2}, PhD; Eva van der Meij^{2,3}, PhD; Judith A F Huirne^{2,3,4}, PhD; Johannes R Anema², PhD

¹Department of Public and Occupational Health, Amsterdam UMC location Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

²Societal Participation & Health, Amsterdam Public Health, Amsterdam, The Netherlands

³Department of Obstetrics and Gynaecology, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

⁴Department of Public Health, Amsterdam University Medical Center, University of Amsterdam, Amsterdam, The Netherlands

These have been revised as follows:

Daan Toben^{1,2}, MSc; Astrid de Wind^{2,3}, PhD; Eva van der Meij^{2,3}, PhD; Judith A F Huirne^{2,4}, PhD; Johannes R Anema^{1,2}, PhD

¹Department of Public and Occupational Health, Amsterdam UMC location Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

²Societal Participation & Health, Amsterdam Public Health research institute, Amsterdam, The Netherlands

³Department of Public and Occupational Health, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

⁴Department of Obstetrics and Gynaecology, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

The correction will appear in the online version of the paper on the JMIR Publications website on February 12, 2025 together with the publication of this correction notice. Because this was made after submission to PubMed, PubMed Central, and other full-text repositories, the corrected article has also been resubmitted to those repositories.

Submitted 28.01.25; this is a non-peer-reviewed article; accepted 28.01.25; published 12.02.25.

Please cite as:

Toben D, de Wind A, van der Meij E, Huirne JAF, Anema JR

Correction: A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study

JMIR Perioper Med 2025;8:e71874

URL: <https://periop.jmir.org/2025/1/e71874>

doi: [10.2196/71874](https://doi.org/10.2196/71874)

PMID:

©Daan Toben, Astrid de Wind, Eva van der Meij, Judith A F Huirne, Johannes R Anema. Originally published in JMIR Perioperative Medicine (<http://periop.jmir.org>), 12.02.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in JMIR Perioperative Medicine, is properly cited. The complete bibliographic information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Original Paper

Implementation of Brief Submaximal Cardiopulmonary Testing in a High-Volume Presurgical Evaluation Clinic: Feasibility Cohort Study

Zyad James Carr^{1,2}, MD; Daniel Agarkov^{1,2*}, MD; Judy Li², BSc; Jean Charchafli^{1,2*}, MD; Andres Brenes-Bastos^{1,2}, MD; Jonah Freund^{3*}, BSc; Jill Zafar^{1*}, MD; Robert B Schonberger^{1*}, MD, MHCDS; Paul Heerd^{1*}, MD, PhD

¹Department of Anesthesiology, Yale University, New Haven, CT, United States

²School of Medicine, Yale University, New Haven, CT, United States

³Syracuse University, Syracuse, NY, United States

*these authors contributed equally

Corresponding Author:

Zyad James Carr, MD

Department of Anesthesiology

Yale University

333 Cedar Street, TMP-3

New Haven, CT, 06510

United States

Phone: 1 2037852802

Email: zyad.carr@yale.edu

Abstract

Background: Precise functional capacity assessment is a critical component for preoperative risk stratification. Brief submaximal cardiopulmonary exercise testing (smCPET) has shown diagnostic utility in various cardiopulmonary conditions.

Objective: This study aims to determine if smCPET could be implemented in a high-volume presurgical evaluation clinic and, when compared to structured functional capacity surveys, if smCPET could better discriminate low functional capacity (≤ 4.6 metabolic equivalents [METs]).

Methods: After institutional approval, 43 participants presenting for noncardiac surgery who met the following inclusion criteria were enrolled: aged 60 years and older, a Revised Cardiac Risk Index of ≤ 2 , and self-reported METs of ≥ 4.6 (self-endorsed ability to climb 2 flights of stairs). Subjective METs assessments, Duke Activity Status Index (DASI) surveys, and a 6-minute smCPET trial were conducted. The primary end points were (1) operational efficiency, based on the time of the experimental session being ≤ 20 minutes; (2) modified Borg survey of perceived exertion, with a score of ≤ 7 indicating no more than moderate exertion; (3) high participant satisfaction with smCPET task execution, represented as a score of ≥ 8 (out of 10); and (4) high participant satisfaction with smCPET scheduling, represented as a score of ≥ 8 (out of 10). Student's *t* test was used to determine the significance of the secondary end points. Correlation between comparable structured surveys and smCPET measurements was assessed using the Pearson correlation coefficient. A Bland-Altman analysis was used to assess agreement between the methods.

Results: The mean session time was 16.9 (SD 6.8) minutes. The mean posttest modified Borg survey score was 5.35 (SD 1.8). The median patient satisfaction (on a scale of 1=worst to 10=best) was 10 (IQR 10-10) for scheduling and 10 (IQR 9-10) for task execution. Subjective METs were higher when compared to smCPET equivalents (extrapolated peak METs; mean 7.6, SD 2.0 vs mean 6.7, SD 1.8; $t_{42}=2.1$; $P<.001$). DASI-estimated peak METs were higher when compared to smCPET peak METs (mean 8.8, SD 1.2 vs mean 6.7, SD 1.8; $t_{42}=7.2$; $P<.001$). DASI-estimated peak oxygen uptake was higher than smCPET peak oxygen uptake (mean 30.9, SD 4.3 mL kg⁻¹ min⁻¹ vs mean 23.6, SD 6.5 mL kg⁻¹ min⁻¹; $t_{42}=7.2$; $P<.001$).

Conclusions: Implementation of smCPET in a presurgical evaluation clinic is both patient centered and clinically feasible. Brief smCPET measures, supportive of published reports regarding low sensitivity of provider-driven or structured survey measures for low functional capacity, were lower than those from structured surveys. Future studies will analyze the prediction of perioperative complications and cost-effectiveness.

Trial Registration: ClinicalTrials.gov NCT05743673; <https://clinicaltrials.gov/study/NCT05743673>

KEYWORDS

preoperative evaluation; submaximal cardiopulmonary exercise test; risk stratification; perioperative medicine; anesthesiology

Introduction

Background

Assessment of functional capacity or exercise tolerance, as measured by self-reported metabolic equivalents (METs), remains a cornerstone of preoperative risk stratification. METs are defined as multiples of the basal metabolic rate (1 MET=3.5 mL kg⁻¹ min⁻¹), and self-reported ability to climb 1 flight of stairs has a general consensus of 4 METs [1]. A threshold of ≤4.6 METs (self-reported inability to climb 2 flights of stairs) has been associated with major adverse cardiac events, all-cause mortality, and increased perioperative complications [2-4]. Despite its importance, published reports have cast doubt on the accuracy of provider-driven and self-reported assessment of functional capacity [5,6]. Thus, reliable and efficient methods to precisely characterize functional capacity continue to be of importance in preoperative risk stratification.

Cardiopulmonary exercise testing (CPET) precisely characterizes exercise tolerance by analyzing cellular respiration at rest and during exercise challenges. By measuring resting gas exchange followed by maximal exercise to expose pathophysiological impairments, CPET exploits a symptom-limited approach with a 3-minute resting stage, 3 minutes of unloaded cycling, and a 10- to 12-minute ramp stage with increasing resistance until terminated by the participant [7]. Abnormal CPET measures have been frequently associated with perioperative morbidity, with a peak oxygen uptake (VO₂) of <15 mL kg⁻¹ min⁻¹ reported as a threshold for elevated cardiopulmonary risk after thoracic and major noncardiac surgery [8-12]. In addition, peak VO₂ impairment predicts an increased risk of surgical site infection, postoperative respiratory failure, and critical care readmission [13]. However, CPET has not been widely adopted in preoperative testing, likely due to limited availability, required technical skills, necessity of maximal patient effort, complexity of task, and cost. Yet, conventional preoperative care, usually comprised of subjective or structured, survey-based, clinician estimation of preoperative functional capacity, has demonstrated poor sensitivity in the identification of patients with low functional capacity (≤4 METs), when compared to CPET [13,14].

In contrast to a conventional symptom-limited approach, submaximal cardiopulmonary exercise testing (smCPET) uses a time-limited approach and predictive analytics to provide estimates of peak cardiopulmonary performance [7]. A maximal exercise effort is not required since it analyzes the VO₂ efficiency slope to predict peak cardiopulmonary performance [15-17]. Of note, the VO₂ efficiency slope has a strong correlation with peak VO₂ ($r=0.941$), permitting effort-independent prediction of conventional CPET measures [16]. Brief smCPET has demonstrated diagnostic utility in predicting postoperative length of stay, complications, and

prognosis in heart failure, pulmonary hypertension, and other conditions [18-23].

Objectives

These advantages suggest that time-limited smCPET may be useful for rapid preoperative assessment of exercise tolerance. Therefore, the primary objective was to determine the logistic feasibility of smCPET integration within a high-volume presurgical evaluation clinic. Our measured feasibility end points were (1) operational efficiency, based on the experimental session length being <20 minutes; (2) modified Borg survey of perceived exertion, with a score of ≤7 indicating no more than moderate exertion; (3) high participant satisfaction with smCPET task execution, with a score of >8 (out of 10); and (4) high patient satisfaction with smCPET scheduling, with a score of >8 (of 10). Our secondary objective was to determine if comparable smCPET measures were significantly different from structured survey findings. The secondary end points were a comparison of (1) self-reported subjective METs from a survey versus smCPET equivalents (extrapolated peak METs), (2) Duke Activity Status Index (DASI) [24] estimates versus smCPET equivalents (extrapolated peak METs), and (3) estimated DASI maximal oxygen consumption (estimated peak VO₂) versus smCPET equivalents (extrapolated peak VO₂). This study hypothesized that brief smCPET would achieve two objectives: first, meet feasibility end points indicating successful implementation, and second, similar to prior published reports regarding provider-driven functional capacity assessments, identify lower peak METs and VO₂, when compared to structured surveys.

Methods

Trial Design

This is an ongoing prospective open-label clinical device study approved by the Yale University Institutional Review Board (IRB#2000033885; ClinicalTrials.gov: #NCT05743673 [25]; principal investigator: ZJC; date of registration: December 5, 2023). This clinical trial was registered prior to participant enrollment.

Study Population

Inclusion criteria for study enrollment included age of 60 years and older, a Revised Cardiac Risk Index (RCRI) [26] of ≤2, self-endorsed subjective METs of ≥4 (endorses reliably climbing 2 flights of stairs), and presenting for noncardiac surgery. The aim was to recruit 40 participants for the feasibility study. This number was estimated to be adequate to identify any study-related logistic process problems or patient-centered outcome deficiencies and to determine the operational efficiency of this novel system process. The RCRI≤2 criterion was selected given the novelty of smCPET in preoperative evaluation.

Given that participants were screened prior to surgical procedures, exclusion criteria were adapted to maintain current

standard-of-care practices in preoperative evaluation, which includes mandatory subspecialty evaluation of select cardiopulmonary conditions. Participants with recorded severe or critical heart valve disease, active exertional angina, nonambulation, gait abnormalities, end-stage renal disease, severe peripheral vascular disease, and neurological motor deficits were excluded. Additionally, non-English-speaking participants, those under legal guardianship, and participants documented to not have personal health care decision-making capacity were also excluded. After prescreening, a phone call was placed by a study team member, and eligible participants were invited for in-person written informed consent, preoperative evaluation, questionnaire assessment of METs, and a 6-minute smCPET experimental session.

Testing Environment

Testing was performed at the presurgical evaluation (PSE) clinic at Yale New Haven Hospital, which is responsible for more than 40,000 preoperative evaluations per year. On a daily basis, the PSE clinic is staffed by an anesthesiologist, 2 resident physicians, 3 certified nurse practitioners, and 6 nursing staff and contains 6 exam rooms.

Study Apparatus

The US Food and Drug Administration–approved Shape II is a compact, cardiopulmonary, breath-by-breath, exercise testing system that uses brief submaximal exercise effort (3 minutes) to generate multiple quantitative measures of actual and predicted peak cardiopulmonary performance measurements (Figure 1). Predicted peak exercise values are automatically calculated by the device using oxygen efficiency slope equations [16,17]. Furthermore, the device has been previously validated to conventional CPET measurements [27,28]. The compact design allows all the necessary equipment to be placed on a standard rolling cart and was deployed in a PSE clinic examination room (2.4 × 2.4 m). A stairstep (14-cm height) was used for the graded exercise portion. The graded exercise was performed with a device prompt (“begin exercise”), with auditory prompts at 1-minute intervals to increase step frequency if possible. A metronome is used to provide cadence. The device provides an option for either timed or symptom-limited assessment. The timed session was selected for all participants. The timed device session requires a total of 6 minutes: 2 minutes of seated baseline resting data, 3 minutes of escalating exercise using the stairstep, and 1 minute of seated recovery data to generate a variety of individual measures of cardiac and pulmonary physiological data (Multimedia Appendix 1).

Figure 1. Performance of submaximal cardiopulmonary exercise testing requires (A) 2 minutes of calibration data in the seated position with a disposal mouthpiece connected to the device, (B) 3 minutes of graded exercise using a stair step, and 1 minute of recovery data in the seated position. The submaximal cardiopulmonary device (white and blue box) is visible on the cart, attached to a laptop with calculation software. Coauthor JF gave express permission for the use of his likeness in this simulated participant session.



Data Collection

Participants received height, weight, and vital sign measurements (heart rate, blood pressure, and pulse oximetry). Informed written consent was performed, and participants were instructed on smCPET (approximately 5 minutes).

Session time was measured from the beginning of pretest METs questionnaires until the termination of the smCPET recovery phase. A session time of ≤ 20 minutes would indicate that 24

high-risk participants could be screened per day per machine, permitting high-volume assessment. Session components included (1) a 7-question subjective METs assessment, (2) a 12-question DASI survey, and (3) a timed smCPET (6 minutes).

The modified Borg survey of perceived exertion was performed at session termination. After study interventions, a standard preoperative evaluation was completed, and the participant was discharged. A 24-hour postexperiment survey of minor and major complications and patient satisfaction was performed by

telephone ([Multimedia Appendix 2](#)). With the exception of the patient satisfaction survey, all survey instruments were adapted from prior publications [29-31]. DASI-estimated peak METs and peak VO_2 were calculated from individual participants' DASI scores using the recommended formula.

Statistical Analysis

End points were reported as continuous variables, described as mean (SD); ordinal variables, as median (IQR and range); and categorical variables, as number (%). Secondary end points were first analyzed using the Student *t* test (2-tailed) to compare differences in comparable measurements. Agreement between structured survey findings and smCPET comparable measurements was assessed using 2 approaches. First, a Pearson correlation coefficient was calculated to evaluate the strength and direction of the linear relationship, followed by a Bland-Altman analysis to assess agreement between methods, where differences between paired measurements were plotted against their means. Mean difference (MD) and 95% limits of agreement (LOAs) were calculated. All analyses were carried out on R (version 4.1.1; R Foundation for Statistical Computing). To reduce the introduction of bias, a complete case analysis for missing data was performed, where participants with missing data were excluded from the analysis of the

respective end point. Similarly, dropouts were removed from the analysis. A *P* value of $<.05$ was accepted for significance.

Ethical Considerations

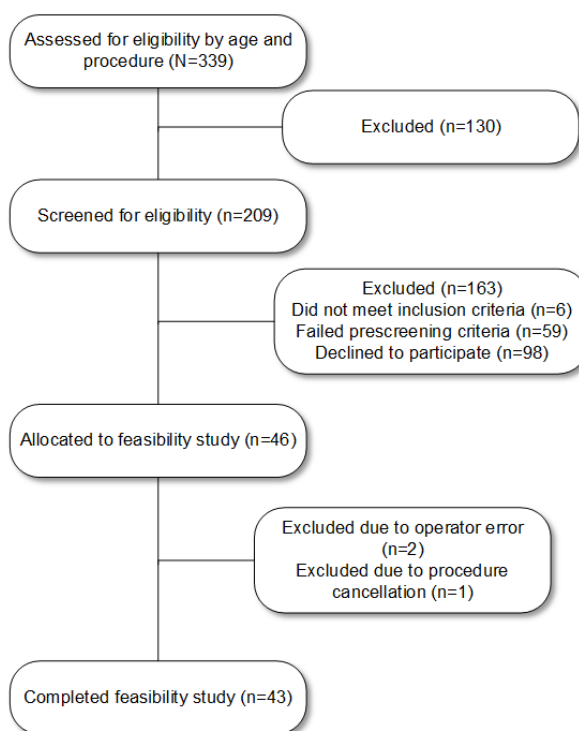
This study was performed in accordance with the principles of the Declaration of Helsinki. Approval was granted by the Yale University Institutional Review Board (IRB#2000033885). Informed consent was obtained from all participants included in the study. All provided data were deidentified prior to analysis to maintain participant privacy. No monetary compensation was provided to the participants. JF has given express written informed consent for the publication of his image in [Figure 1](#).

Results

Participant Recruitment

We identified 209 (61.6%) out of 339 potential participants that met eligibility criteria; 6 (1.8%) did not meet the inclusion criteria, 59 (17.4%) failed the prescreening criteria, and 98 (28.9%) declined study participation ([Figure 2](#)). Initially, 46 participants were enrolled but 3 (7%) were excluded (operator error: $n=2$; surgery cancellation: $n=1$), for a final cohort of 43 participants.

Figure 2. A flow diagram of participant enrollment.



Baseline Characteristics

Trial participants had a median age of 68 (IQR 66-73, range: 60-86 years), 20 (47%) of 43 were female, and the mean BMI was 27.5 (SD 6.0) kg/m^2 . Preoperative RCRI score was a median of 1 (IQR 1-1; range 1-2). Essential hypertension (22/43, 51%), hyperlipidemia (17/43, 39%), and solid tumor (25/43, 58%) were the most common premorbid conditions. A total of 22 (51%) out of 43 participants were former or active smokers.

Major abdominal surgeries comprised 27 (63%) out of the 43 surgical procedures ([Table 1](#)).

All participants completed the smCPET session components. The mean peak respiratory exchange ratio was 0.88 (SD 0.12), consistent with submaximal effort (respiratory exchange ratio <1.05). The ventilatory threshold was achieved in 22 (51%) of 43 participants (mean 227.9, SD 21.9 seconds in those that achieved ventilatory threshold).

Table 1. Baseline demographical data of the study cohort (n=43).

Variable	Values
Age (years), median (IQR; range)	68 (66-73; 60-86)
Sex, n (%)	
Male	23 (54)
Female	20 (47)
BMI (kg/m ²), mean (SD)	27.5 (6.0)
Revised Cardiac Risk Index score, median (IQR; range)	1 (1-1; 1-2)
Preoperative comorbidities, n (%)	
Essential hypertension	22 (51)
Hyperlipidemia	17 (40)
Ventricular dysrhythmia	1 (2)
Congestive heart failure	1 (2)
Myocardial infarction	3 (7)
Cerebrovascular disease	1 (2)
Chronic obstructive pulmonary disease	3 (7)
Asthma	4 (9)
Obstructive sleep apnea	3 (7)
History of prior lung resection	1 (2)
Diabetes mellitus	7 (16)
Thyroid disorders	7 (16)
Solid tumor	25 (58)
Anemia	1 (2)
Social history, n (%)	
Smoking	
Ever	22 (51)
Active	4 (9)
Former	18 (42)
Never	21 (49)
Marijuana use (active)	4 (9)
Alcohol use	
Active	24 (56)
Former	16 (37)
Never	3 (7)
Cardiovascular medication use, n (%)	
Beta-blocker	14 (33)
Calcium channel antagonist	9 (21)
ACE/ARB ^a antagonist	16 (37)
Diuretic	12 (28)
Surgical categories, n (%)	
Abdominal major	27 (63)
Musculoskeletal major	4 (9)
Neurosurgical major	2 (5)

Variable	Values
Thoracic major	5 (12)
Other major	5 (12)

^aACE/ARB; angiotensin converting enzyme inhibitor/angiotensin receptor blockers.

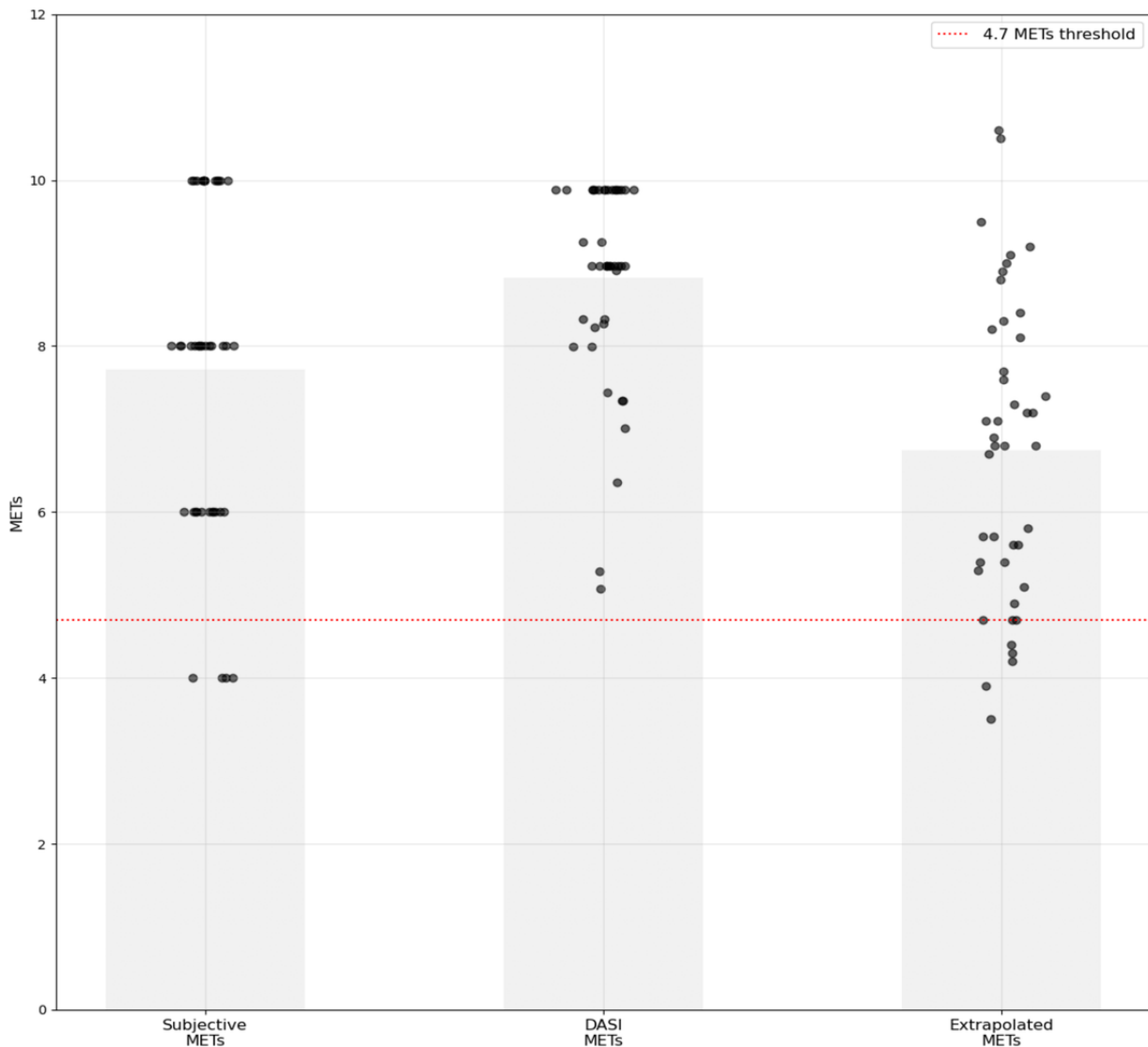
Primary End Points

The mean experimental session time was 16.9 (SD 6.8) minutes. The modified Borg survey score after experimental sessions was mean 5.35 (SD 1.8), corresponding to moderate perceived exertion. All 43 participants were reached for the 24-hour postexperiment survey. The median patient satisfaction (on a scale of 1=worst to 10=best) was 10 (IQR 10-10) for scheduling and 10 (IQR 9-10) for task execution. No major or minor complications associated with study testing were reported by participants. Operational efficiency was achieved within 15 experimental sessions among 4 study team members (3 physicians and 1 undergraduate researcher).

Secondary End Points

Average self-reported peak METs were higher when compared to smCPET equivalents (extrapolated peak METs; mean 7.6, SD 2.0 vs mean 6.7, SD 1.8; $t_{42}=2.1$; $P<.001$). DASI-estimated peak METs were higher when compared to the smCPET equivalents (extrapolated peak METs; mean 8.8, SD 1.2 vs mean 6.7, SD 1.8; $t_{42}=7.2$; $P<.001$). DASI-estimated peak VO_2 was higher than the smCPET equivalent (extrapolated peak VO_2 ; mean 30.9, SD 4.3 mL kg⁻¹ min⁻¹ vs mean 23.6, SD 6.5 mL kg⁻¹ min⁻¹; $t_{42}=2.1$; $P<.001$). Figure 3 provides a comparison of values obtained from smCPET compared to structured survey-estimated peak METs and DASI-estimated peak METs.

Figure 3. Comparison of elicited METs from 2 structured survey instruments (subjective METs and DASI) compared to predicted peak METs from submaximal cardiopulmonary exercise testing (dotted line represents 4.7 METs). DASI: Duke Activity Status Index; MET: metabolic equivalent.



To analyze the congruency between the 3 study instruments, correlation and Bland-Altman analyses were performed. DASI-estimated METs showed a moderate positive correlation versus subjective METs ($r=0.63$; $P<.001$). Weaker correlations were observed with smCPET-derived extrapolated peak METs versus DASI and subjective METs ($r=0.29$; $P=.06$ and $r=0.144$; $P=.36$, respectively). DASI versus subjective METs showed an MD of 1.1 (SD 1.49; 95% LOAs -1.82 to 4.02) METs, while DASI versus smCPET-derived extrapolated peak METs showed larger discrepancies with an MD of 2.07 (SD 1.86; 95% LOAs -1.58 to 5.73) METs. The comparison between subjective METs and smCPET-derived extrapolated peak METs showed intermediate systematic bias with the widest LOAs (MD 0.97, SD 2.43 METs; 95% LOAs -3.80 to 5.75). When comparing DASI and smCPET-derived extrapolated peak VO_2 values, a positive MD was observed, indicating that DASI estimates were consistently higher (MD 7.23, SD 6.54 mL $kg^{-1} min^{-1}$; 95% LOA -8.11 to 21.12) and showed poor agreement ($r=0.28$; [Multimedia Appendix 3](#)).

Discussion

Principal Findings

Integration of brief smCPET in a high-volume PSE clinic was feasible as measured by the primary end points of session time, patient satisfaction with smCPET task execution, perceived exertion, and session scheduling. The operational efficiency of study team members was acceptable within 15 experimental sessions. Finally, smCPET measures of peak METs and VO_2 were significantly lower, when compared to comparable structured survey results.

Mean session time, which included the subjective METs survey, DASI, and 6-minute smCPET session, was 16.9 (SD 6.8) minutes, with progressive improvement over the study time period as operators ($n=4$) became facile with the study instrument ([Multimedia Appendix 4](#)). It is important to note that smCPET comprised 6 minutes of the session time, shorter than reported times with conventional CPET (15-20 min/session) [32]. In high-volume PSE, this may be advantageous, as patients are often seen on short notice for preoperative evaluation. Participants were able to flexibly arrange smCPET around other clinic appointments, decreasing study participants' time constraints. This likely enhanced our high satisfaction score for scheduling. High patient satisfaction was observed with task execution and perceived exertion during smCPET. The tested device uses a stationary staircase for graded exercise, which was frequently familiar to participants. The short duration of graded exercise (3 minutes) was not perceived by any participant as maximum exertion by the Borg survey, likely contributing to the high level of patient satisfaction. Second, the Borg score of <7 after smCPET suggests a reasonable probability of success when transitioning its use to patients with more severe comorbidities, or preoperative deconditioning. It is important to note that the ventilatory threshold, or anaerobic threshold, was not measurable in 50% of our cohort, suggesting that the brief graded exercise contributed to the reported exertion level and high participant satisfaction.

One of the goals of smCPET is to make precise cardiopulmonary evaluation more widely available and patient centered, advantages that are acknowledged by its increasing adoption in the routine assessment of heart failure and pulmonary hypertension. Consistent with large-scale CPET application in cardiovascular clinical trials, smCPET did not result in findings of major or minor complications despite encouraging participants to safely provide their best effort within the timed and graded exercise component [33]. This is reassuring, as early termination of preoperative CPET trials, due to participant fatigue, safety, or other considerations, has been reported to be approximately 11% [13]. However, we purposefully selected functionally independent participants with self-reported ≥ 4.6 METs, and expansion to patients who are less functionally independent may result in higher smCPET session failure rates. Regardless, the safety of smCPET has been suggested by its routine application to high-risk and frail populations with severe cardiopulmonary disease, suggesting that a wide spectrum of preoperative populations can be safely tested using smCPET [20,22,34].

The structured survey estimated METs were, on average, significantly higher than their smCPET equivalents. Using the subjective METs structured survey, 8 (19%) of 43 participants reported peak METs within 10% of smCPET extrapolated peak METs, 12 (28%) were underestimated by $>10\%$, and 23 (53%) were overestimated by $>10\%$, when compared to smCPET values. Brief smCPET identified that 8 (19%) out of 43 study participants had ≤ 4.6 extrapolated peak METs (peak VO_2 equivalent: 14 mL $kg^{-1} min^{-1}$), corresponding to a METs threshold associated with higher perioperative cardiovascular risk [1,4]. Furthermore, smCPET identified 9 (21%) out of 43 participants with an age-adjusted peak VO_2 of less than 20 mL $kg^{-1} min^{-1}$, corresponding to poor aerobic capacity, and 2 (5%) with an extrapolated peak VO_2 less than 15 mL $kg^{-1} min^{-1}$, a measure frequently associated with higher perioperative risk [35]. These findings support prior descriptions of provider-driven and structured survey overestimation bias, highlighting the challenge of obtaining an accurate preoperative functional capacity assessment. Clinicians, when compared to CPET, had a 19.2% sensitivity in identifying low functional capacity (≤ 4 METs) [13,36]. Other investigations have also observed that preanesthesia evaluation calculation of self-reported METs overestimate functional capacity when compared to CPET assessment [6]. DASI was also found to poorly predict participants with lower peak VO_2 [13,24,36]. In a cohort of participants that would not necessarily receive extensive preoperative assessment, given that 100% reported the ability to reliably climb 2 flights of stairs, this may suggest opportunities to identify and preemptively optimize unexpected cardiopulmonary impairments prior to surgical intervention.

Worldwide, value-based health care has been a significant priority, and conventional preoperative evaluation may increase overall testing costs without improving perioperative outcomes [37-39]. Implementing brief smCPET for individualized preoperative cardiovascular evaluation may improve the precision of preoperative cardiovascular risk assessment and may potentially curb excess preoperative cardiovascular testing

commonly associated with older age and patients with higher comorbidities [40-42]. However widespread adoption of this technology in the perioperative space will require (1) further evidence of smCPET predictive validity for perioperative outcomes, (2) characterization of optimal system processes for patient selection, and (3) justification of cost-benefit.

Study Limitations

Several study limitations limit generalizability to other populations. Selection bias should be acknowledged given that participants who volunteered for the study are likely to be more health-conscious than usual patients who undergo PSE. A measurement bias may be introduced into the study given that researchers may unconsciously influence participant performance on smCPET or interpret results differently based on unconscious expectations. Similarly, a recall bias is often introduced when using structured, interview-style questionnaires such as those used in our study. Instrument bias may similarly impact smCPET findings; however, this is substantially reduced by routine device calibration.

Confounding factors are similar, where participants with higher fitness levels would find it easier to adapt to the stairstep exercise challenge. Our inclusion criteria purposely selected participants with lower comorbidities to ensure successful participation rates for this feasibility study. We acknowledge that certain premorbid conditions and chronic medication usage

may influence smCPET participants' performance, but we did not balance this factor in this exploratory study. Although CPET and smCPET predictive performance with cardiovascular perioperative morbidity and mortality has been previously published, our cohort is not yet powered for the assessment of perioperative outcomes with this device [19,23,43,44]. Finally, the finding of no device-related adverse events should be cautiously interpreted given the small sample size and the possibility of rare exercise-induced adverse events.

Conclusions

In summary, we observed that smCPET implementation was well accepted into the workflow of a high-volume PSE clinic. Operator efficiency with the smCPET instrument was rapid and achieved relative parity at 15 participant sessions. smCPET, when compared to usual session times for conventional CPET of 15-20 minutes, uses less than half the time (6 minutes), making it attractive for the purposes of precise but time-efficient preoperative evaluation of exercise tolerance. This feasibility analysis has (1) reinforced the operational integrity of our active study protocol assessing smCPET findings with perioperative outcomes and (2) affirmed satisfactory patient-centered outcomes with study procedures. Studies should further expand smCPET predictive validity to postoperative cardiopulmonary complications, assess cost-effectiveness, and develop optimal system processes for patient selection.

Acknowledgments

The authors would like to acknowledge the work of Rayna Lewoc, Elizabeth Womack, Elizabeth Cozza, Gwendolyn Burkett, and the staff of the Yale New Haven Hospital's presurgical evaluation clinic. This study was partially supported by Shape Medical Systems, Inc.

Data Availability

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Authors' Contributions

Study conception and design were performed by ZJC, PH, and RBS. The first draft of the manuscript was performed by ZJC, JC, JZ, and ABB. Data collection was performed by ZJC, JF, JL, and DA. Statistical analysis was performed by ZJC. Further manuscript editing was performed by all coauthors. All authors read and approved the final manuscript.

Conflicts of Interest

ZJC receives partial funding from Shape Medical Systems, Inc related to this work. RBS reports owning stock in Johnson and Johnson unrelated to this work. RBS reports that Yale University has received funding from Merck for a study in which he was involved, unrelated to this work. PH reported receiving research support grants from Edwards Lifesciences and consulting and/or royalty fees from Baudax Bio, Fire1Foundry, Cardiage LLC, and Edwards Lifesciences. All other authors have no competing interests.

Multimedia Appendix 1

A detailed description of the submaximal cardiopulmonary exercise testing device and its measures.

[[DOCX File, 18 KB - periop_v8i1e65805_app1.docx](#)]

Multimedia Appendix 2

Adapted subjective METs survey questions and 24 hour postsession minor and major adverse events survey. MET: metabolic equivalent.

[[PDF File \(Adobe PDF File\), 237 KB - periop_v8i1e65805_app2.pdf](#)]

Multimedia Appendix 3

Bland-Altman plots for the compared measures: (A) subjective METs versus smCPET-extrapolated peak METs showed a mean difference of 0.97 METs but the widest LOAs; (B) DASI-estimated peak METs versus smCPET-extrapolated peak METs showed a mean difference of 2.07 METs, the largest discrepancy; (C) DASI-estimated peak METs versus subjective METs showed a mean difference of 1.1 METs but narrower LOAs; and (D) DASI-estimated peak VO₂ versus smCPET-extrapolated peak VO₂ showed that DASI had consistently higher estimates, with a mean difference of 6.5 mL kg⁻¹ min⁻¹. DASI: Duke Activity Status Index; LOA: limit of agreement; mean diff: mean difference; MET: metabolic equivalent; smCPET: submaximal cardiopulmonary exercise testing; VO₂: peak oxygen uptake.

[PDF File (Adobe PDF File), 136 KB - [periop_v8i1e65805_app3.pdf](#)]

Multimedia Appendix 4

Operator efficiency as a function of session time (y-axis), defined as performance of two structured functional capacity survey instruments and submaximal cardiopulmonary exercise testing, versus session number (x-axis).

[PNG File, 98 KB - [periop_v8i1e65805_app4.png](#)]

References

1. Fleisher LA, Fleischmann KE, Auerbach AD, Barnason SA, Beckman JA, Bozkurt B, et al. 2014 ACC/AHA guideline on perioperative cardiovascular evaluation and management of patients undergoing noncardiac surgery: a report of the American College of Cardiology/American Heart Association Task Force on practice guidelines. *J Am Coll Cardiol* 2014;64(22):e77-137 [FREE Full text] [doi: [10.1016/j.jacc.2014.07.944](#)] [Medline: [25091544](#)]
2. Lurati Buse GAL, Puelacher C, Gualandro DM, Genini AS, Hidvegi R, Bolliger D, et al. Association between self-reported functional capacity and major adverse cardiac events in patients at elevated risk undergoing noncardiac surgery: a prospective diagnostic cohort study. *Br J Anaesth* 2021;126(1):102-110 [FREE Full text] [doi: [10.1016/j.bja.2020.08.041](#)] [Medline: [33081973](#)]
3. Reilly DF, McNeely MJ, Doerner D, Greenberg DL, Staiger TO, Geist MJ, et al. Self-reported exercise tolerance and the risk of serious perioperative complications. *Arch Intern Med* 1999;159(18):2185-2192. [doi: [10.1001/archinte.159.18.2185](#)] [Medline: [10527296](#)]
4. Biccard BM. Relationship between the inability to climb two flights of stairs and outcome after major non-cardiac surgery: implications for the pre-operative assessment of functional capacity. *Anaesthesia* 2005;60(6):588-593 [FREE Full text] [doi: [10.1111/j.1365-2044.2005.04181.x](#)] [Medline: [15918830](#)]
5. Weinstein AS, Sigurdsson MI, Bader AM. Comparison of preoperative assessment of patient's metabolic equivalents (METs) estimated from history versus measured by exercise cardiac stress testing. *Anesthesiol Res Pract* 2018;2018:5912726 [FREE Full text] [doi: [10.1155/2018/5912726](#)] [Medline: [30250484](#)]
6. Nieves-Alonso JM, Méndez Hernández RM, Ramasco Rueda F, Planas Roca A. Estimated metabolic equivalents of task do not correlate with the maximal oxygen consumption of patients undergoing lung resection surgery. *Rev Esp Anestesiol Reanim* 2022;69(7):437-441. [doi: [10.1016/j.redare.2021.01.006](#)] [Medline: [35869005](#)]
7. Glaab T, Taube C. Practical guide to cardiopulmonary exercise testing in adults. *Respir Res* 2022;23(1):9 [FREE Full text] [doi: [10.1186/s12931-021-01895-6](#)] [Medline: [35022059](#)]
8. Loewen GM, Watson D, Kohman L, Herndon JE, Shennib H, Kernstine K, et al. Preoperative exercise Vo₂ measurement for lung resection candidates: results of Cancer and Leukemia Group B Protocol 9238. *J Thorac Oncol* 2007;2(7):619-625 [FREE Full text] [doi: [10.1097/JTO.0b013e318074bba7](#)] [Medline: [17607117](#)]
9. Benzo R, Kelley GA, Recchi L, Hofman A, Sciarba F. Complications of lung resection and exercise capacity: a meta-analysis. *Respir Med* 2007;101(8):1790-1797 [FREE Full text] [doi: [10.1016/j.rmed.2007.02.012](#)] [Medline: [17408941](#)]
10. Hartley RA, Pichel AC, Grant SW, Hickey GL, Lancaster PS, Wisely NA, et al. Preoperative cardiopulmonary exercise testing and risk of early mortality following abdominal aortic aneurysm repair. *Br J Surg* 2012;99(11):1539-1546. [doi: [10.1002/bjs.8896](#)] [Medline: [23001820](#)]
11. Older P, Hall A, Hader R. Cardiopulmonary exercise testing as a screening test for perioperative management of major surgery in the elderly. *Chest* 1999;116(2):355-362. [doi: [10.1378/chest.116.2.355](#)] [Medline: [10453862](#)]
12. Argillander TE, Heil TC, Melis RJF, van Duijvendijk P, Klaase JM, van Munster BC. Preoperative physical performance as predictor of postoperative outcomes in patients aged 65 and older scheduled for major abdominal cancer surgery: a systematic review. *Eur J Surg Oncol* 2022;48(3):570-581 [FREE Full text] [doi: [10.1016/j.ejso.2021.09.019](#)] [Medline: [34629224](#)]
13. Wijeyesundera DN, Pearse RM, Shulman MA, Abbott TEF, Torres E, Ambosta A, et al. Assessment of functional capacity before major non-cardiac surgery: an international, prospective cohort study. *Lancet* 2018;391(10140):2631-2640. [doi: [10.1016/S0140-6736\(18\)31131-0](#)] [Medline: [30070222](#)]
14. Struthers R, Erasmus P, Holmes K, Warman P, Collingwood A, Sneyd JR. Assessing fitness for surgery: a comparison of questionnaire, incremental shuttle walk, and cardiopulmonary exercise testing in general surgical patients. *Br J Anaesth* 2008;101(6):774-780 [FREE Full text] [doi: [10.1093/bja/aen310](#)] [Medline: [18953057](#)]

15. Ferguson M, Shulman M. Cardiopulmonary exercise testing and other tests of functional capacity. *Curr Anesthesiol Rep* 2022;12(1):26-33 [FREE Full text] [doi: [10.1007/s40140-021-00499-6](https://doi.org/10.1007/s40140-021-00499-6)] [Medline: [34840532](https://pubmed.ncbi.nlm.nih.gov/34840532/)]
16. Baba R, Nagashima M, Goto M, Nagano Y, Yokota M, Tauchi N, et al. Oxygen uptake efficiency slope: a new index of cardiorespiratory functional reserve derived from the relation between oxygen uptake and minute ventilation during incremental exercise. *J Am Coll Cardiol* 1996;28(6):1567-1572 [FREE Full text] [doi: [10.1016/s0735-1097\(96\)00412-3](https://doi.org/10.1016/s0735-1097(96)00412-3)] [Medline: [8917273](https://pubmed.ncbi.nlm.nih.gov/8917273/)]
17. Hollenberg M, Tager IB. Oxygen uptake efficiency slope: an index of exercise performance and cardiopulmonary reserve requiring only submaximal exercise. *J Am Coll Cardiol* 2000;36(1):194-201 [FREE Full text] [doi: [10.1016/s0735-1097\(00\)00691-4](https://doi.org/10.1016/s0735-1097(00)00691-4)] [Medline: [10898434](https://pubmed.ncbi.nlm.nih.gov/10898434/)]
18. Snowden CP, Prentis JM, Anderson HL, Roberts DR, Randles D, Renton M, et al. Submaximal cardiopulmonary exercise testing predicts complications and hospital length of stay in patients undergoing major elective surgery. *Ann Surg* 2010;251(3):535-541. [doi: [10.1097/SLA.0b013e3181cf811d](https://doi.org/10.1097/SLA.0b013e3181cf811d)] [Medline: [20134313](https://pubmed.ncbi.nlm.nih.gov/20134313/)]
19. Prentis JM, Manas DMD, Trenell MI, Hudson M, Jones DJ, Snowden CP. Submaximal cardiopulmonary exercise testing predicts 90-day survival after liver transplantation. *Liver Transpl* 2012;18(2):152-159 [FREE Full text] [doi: [10.1002/lt.22426](https://doi.org/10.1002/lt.22426)] [Medline: [21898768](https://pubmed.ncbi.nlm.nih.gov/21898768/)]
20. Oakland HT, Joseph P, Elassal A, Cullinan M, Heerdt PM, Singh I. Diagnostic utility of sub-maximum cardiopulmonary exercise testing in the ambulatory setting for heart failure with preserved ejection fraction. *Pulm Circ* 2020;10(4):2045894020972273 [FREE Full text] [doi: [10.1177/2045894020972273](https://doi.org/10.1177/2045894020972273)] [Medline: [33282205](https://pubmed.ncbi.nlm.nih.gov/33282205/)]
21. Joseph P, Savarimuthu S, Zhao J, Yan X, Oakland HT, Cullinan M, et al. Noninvasive determinants of pulmonary hypertension in interstitial lung disease. *Pulm Circ* 2023;13(1):e12197 [FREE Full text] [doi: [10.1002/pul2.12197](https://doi.org/10.1002/pul2.12197)] [Medline: [36814586](https://pubmed.ncbi.nlm.nih.gov/36814586/)]
22. Bernstein EJ, Mandl LA, Gordon JK, Spiera RF, Horn EM. Submaximal heart and pulmonary evaluation: a novel noninvasive test to identify pulmonary hypertension in patients with systemic sclerosis. *Arthritis Care Res* 2013;65(10):1713-1718 [FREE Full text] [doi: [10.1002/acr.22051](https://doi.org/10.1002/acr.22051)] [Medline: [23740875](https://pubmed.ncbi.nlm.nih.gov/23740875/)]
23. Woods PR, Bailey KR, Wood CM, Johnson BD. Submaximal exercise gas exchange is an important prognostic tool to predict adverse outcomes in heart failure. *Eur J Heart Fail* 2011;13(3):303-310 [FREE Full text] [doi: [10.1093/eurjhf/hfq187](https://doi.org/10.1093/eurjhf/hfq187)] [Medline: [21036777](https://pubmed.ncbi.nlm.nih.gov/21036777/)]
24. Hlatky MA, Boineau RE, Higginbotham MB, Lee KL, Mark DB, Califf RM, et al. A brief self-administered questionnaire to determine functional capacity (the Duke Activity Status Index). *Am J Cardiol* 1989;64(10):651-654. [doi: [10.1016/0002-9149\(89\)90496-7](https://doi.org/10.1016/0002-9149(89)90496-7)] [Medline: [2782256](https://pubmed.ncbi.nlm.nih.gov/2782256/)]
25. A feasibility study of the SHAPE™ test of aerobic fitness in older adults presenting for moderate to high-risk surgery. *ClinicalTrials.gov*. 2023. URL: <https://clinicaltrials.gov/study/NCT05743673> [accessed 2025-01-21]
26. Ford MK, Beattie WS, Wijesundera DN. Systematic review: prediction of perioperative cardiac complications and mortality by the revised cardiac risk index. *Ann Intern Med* 2010;152(1):26-35. [doi: [10.7326/0003-4819-152-1-201001050-00007](https://doi.org/10.7326/0003-4819-152-1-201001050-00007)] [Medline: [20048269](https://pubmed.ncbi.nlm.nih.gov/20048269/)]
27. Miller AD, Woods PR, Olson TP, Hulsebus ML, O'Malley KA, MacCarter D, et al. Validation of a simplified, portable cardiopulmonary gas exchange system for submaximal exercise testing. *Open Sport Med J* 2010;4(1):34-40. [doi: [10.2174/1874387001004010034](https://doi.org/10.2174/1874387001004010034)]
28. Kim CH, Hansen JE, MacCarter DJ, Johnson BD. Algorithm for predicting disease likelihood from a submaximal exercise test. *Clin Med Insights Circ Respir Pulm Med* 2017;11:1179548417719248 [FREE Full text] [doi: [10.1177/1179548417719248](https://doi.org/10.1177/1179548417719248)] [Medline: [28757799](https://pubmed.ncbi.nlm.nih.gov/28757799/)]
29. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982;14(5):377-381. [Medline: [7154893](https://pubmed.ncbi.nlm.nih.gov/7154893/)]
30. McAuley P, Myers J, Abella J, Froelicher V. Evaluation of a specific activity questionnaire to predict mortality in men referred for exercise testing. *Am Heart J* 2006;151(4):890.e1-890897. [doi: [10.1016/j.ahj.2005.09.017](https://doi.org/10.1016/j.ahj.2005.09.017)] [Medline: [16569555](https://pubmed.ncbi.nlm.nih.gov/16569555/)]
31. Bell EC, Cox NS, Goh N, Glaspole I, Westall GP, Watson A, et al. Oxygen therapy for interstitial lung disease: a systematic review. *Eur Respir Rev* 2017;26(143):160080 [FREE Full text] [doi: [10.1183/16000617.0080-2016](https://doi.org/10.1183/16000617.0080-2016)] [Medline: [28223395](https://pubmed.ncbi.nlm.nih.gov/28223395/)]
32. Albouaini K, Egred M, Alahmar A, Wright DJ. Cardiopulmonary exercise testing and its application. *Heart* 2007;93(10):1285-1292 [FREE Full text] [doi: [10.1136/hrt.2007.121558](https://doi.org/10.1136/hrt.2007.121558)] [Medline: [17890705](https://pubmed.ncbi.nlm.nih.gov/17890705/)]
33. O'Connor CM, Whellan DJ, Lee KL, Keteyian SJ, Cooper LS, Ellis SJ, et al. Efficacy and safety of exercise training in patients with chronic heart failure: HF-ACTION randomized controlled trial. *JAMA* 2009;301(14):1439-1450 [FREE Full text] [doi: [10.1001/jama.2009.454](https://doi.org/10.1001/jama.2009.454)] [Medline: [19351941](https://pubmed.ncbi.nlm.nih.gov/19351941/)]
34. Woods PR, Frantz RP, Taylor BJ, Olson TP, Johnson BD. The usefulness of submaximal exercise gas exchange to define pulmonary arterial hypertension. *J Heart Lung Transplant* 2011;30(10):1133-1142 [FREE Full text] [doi: [10.1016/j.healun.2011.03.021](https://doi.org/10.1016/j.healun.2011.03.021)] [Medline: [21622009](https://pubmed.ncbi.nlm.nih.gov/21622009/)]
35. Kaminsky LA, Arena R, Myers J, Peterman JE, Bonikowske AR, Harber MP, et al. Updated reference standards for cardiorespiratory fitness measured with cardiopulmonary exercise testing: data from the Fitness Registry and the Importance of Exercise National Database (FRIEND). *Mayo Clin Proc* 2022;97(2):285-293 [FREE Full text] [doi: [10.1016/j.mayocp.2021.08.020](https://doi.org/10.1016/j.mayocp.2021.08.020)] [Medline: [34809986](https://pubmed.ncbi.nlm.nih.gov/34809986/)]

36. Wijeyesundera DN, Beattie WS, Hillis GS, Abbott TEF, Shulman MA, Ackland GL, Measurement of Exercise Tolerance before Surgery Study Investigators, et al. Integration of the Duke Activity Status Index into preoperative risk evaluation: a multicentre prospective cohort study. *Br J Anaesth* 2020;124(3):261-270 [FREE Full text] [doi: [10.1016/j.bja.2019.11.025](https://doi.org/10.1016/j.bja.2019.11.025)] [Medline: [31864719](https://pubmed.ncbi.nlm.nih.gov/31864719/)]
37. World Economic Forum. Value in Healthcare: Laying the Foundation for Health System Transformation. Geneva, Switzerland: World Economic Forum; 2017.
38. Mahajan A, Esper SA, Cole DJ, Fleisher LA. Anesthesiologists' role in value-based perioperative care and healthcare transformation. *Anesthesiology* 2021;134(4):526-540. [doi: [10.1097/ALN.0000000000003717](https://doi.org/10.1097/ALN.0000000000003717)] [Medline: [33630039](https://pubmed.ncbi.nlm.nih.gov/33630039/)]
39. Beckerleg W, Kobewka D, Wijeyesundera DN, Sood MM, McIsaac DI. Association of preoperative medical consultation with reduction in adverse postoperative outcomes and use of processes of care among residents of Ontario, Canada. *JAMA Intern Med* 2023;183(5):470-478 [FREE Full text] [doi: [10.1001/jamainternmed.2023.0325](https://doi.org/10.1001/jamainternmed.2023.0325)] [Medline: [36972037](https://pubmed.ncbi.nlm.nih.gov/36972037/)]
40. Ellenbogen MI, Drmanovic A, Segal JB, Kapoor S, Wagner PC. Patient, provider, and system-level factors associated with preoperative cardiac testing: a systematic review. *J Hosp Med* 2023;18(11):1021-1033. [doi: [10.1002/jhm.13206](https://doi.org/10.1002/jhm.13206)] [Medline: [37728150](https://pubmed.ncbi.nlm.nih.gov/37728150/)]
41. Kumar M, Wilkinson K, Li YH, Masih R, Gandhi M, Saadat H, et al. Association of a novel electronic form for preoperative cardiac risk assessment with reduction in cardiac consultations and testing: retrospective cohort study. *JMIR Perioper Med* 2024;7:e63076 [FREE Full text] [doi: [10.2196/63076](https://doi.org/10.2196/63076)] [Medline: [39269754](https://pubmed.ncbi.nlm.nih.gov/39269754/)]
42. Ferré F, Laurent R, Furelau P, Doumard E, Ferrier A, Bosch L, et al. Perioperative risk assessment of patients using the MyRISK digital score completed before the preanesthetic consultation: prospective observational study. *JMIR Perioper Med* 2023;6:e39044 [FREE Full text] [doi: [10.2196/39044](https://doi.org/10.2196/39044)] [Medline: [36645704](https://pubmed.ncbi.nlm.nih.gov/36645704/)]
43. Bédard B, Koliakos E, Demarchi MS, Perentes J, Licker MJ, Triponez F, et al. Ventilatory efficiency slope is associated with cardiopulmonary complications after thoracoscopic anatomical lung resection. *Interact Cardiovasc Thorac Surg* 2022;35(1):ivac039 [FREE Full text] [doi: [10.1093/icvts/ivac039](https://doi.org/10.1093/icvts/ivac039)] [Medline: [35157073](https://pubmed.ncbi.nlm.nih.gov/35157073/)]
44. Kallianos A, Rapti A, Tsimpoukis S, Charpidou A, Dannos I, Kainis E, et al. Cardiopulmonary exercise testing (CPET) as preoperative test before lung resection. *In Vivo* 2014;28(6):1013-1020 [FREE Full text] [Medline: [25398794](https://pubmed.ncbi.nlm.nih.gov/25398794/)]

Abbreviations

- CPET:** cardiopulmonary exercise testing
- DASI:** Duke Activity Status Index
- LOA:** limit of agreement
- MD:** mean difference
- MET:** metabolic equivalent
- PSE:** presurgical evaluation
- RCRI:** Revised Cardiac Risk Index
- smCPET:** submaximal cardiopulmonary exercise testing
- VO₂:** oxygen uptake

Edited by T Aslanidis; submitted 26.08.24; peer-reviewed by DJ Elmer, N Agnew; comments to author 18.12.24; revised version received 21.12.24; accepted 08.01.25; published 17.02.25.

Please cite as:

*Carr ZJ, Agarkov D, Li J, Charchaflieh J, Brenes-Bastos A, Freund J, Zafar J, Schonberger RB, Heerd P
Implementation of Brief Submaximal Cardiopulmonary Testing in a High-Volume Presurgical Evaluation Clinic: Feasibility Cohort Study*

JMIR Perioper Med 2025;8:e65805

URL: <https://periop.jmir.org/2025/1/e65805>

doi: [10.2196/65805](https://doi.org/10.2196/65805)

PMID:

©Zyad James Carr, Daniel Agarkov, Judy Li, Jean Charchaflieh, Andres Brenes-Bastos, Jonah Freund, Jill Zafar, Robert B Schonberger, Paul Heerd. Originally published in *JMIR Perioperative Medicine* (<http://periop.jmir.org>), 17.02.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in *JMIR Perioperative Medicine*, is properly cited. The complete bibliographic information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Original Paper

Enhancing Quadruple Health Outcomes After Thoracic Surgery: Feasibility Pilot Randomized Controlled Trial Using Digital Home Monitoring

Mahesh Nagappa^{1*}, MD; Yamini Subramani^{1*}, MD; Homer Yang^{1*}, MD; Natasha Wood^{2*}, MSc; Jill Querney^{1*}, MD; Lee-Anne Fochesato^{1*}, MSc; Derek Nguyen^{1*}, BMSc; Nida Fatima^{1*}, MBBS; Janet Martin^{1*}, MSc; Ava John-Baptiste^{1*}, MSc; Rahul Nayak^{3*}, MD; Mehdi Qiabi^{3*}, MD; Richard Incelet^{3*}, MD; Dalilah Fortin^{3*}, MD; Richard Malthaner^{3*}, MD

¹Department of Anesthesia and Perioperative Medicine, London Health Sciences Centre and St. Joseph Health Care, Lawson Health Research Institute, Schulich School of Medicine and Dentistry, Western University, London, ON, Canada

²Department of Nursing, Thoracic Surgery, London Health Sciences Centre, Lawson Health Research Institute, Schulich School of Medicine and Dentistry, Western University, London, ON, Canada

³Department of Surgery, Division of Thoracic Surgery, London Health Sciences Centre and St. Joseph Health Care, Lawson Health Research Institute, Schulich School of Medicine and Dentistry, Western University, London, ON, Canada

* all authors contributed equally

Corresponding Author:

Mahesh Nagappa, MD

Department of Anesthesia and Perioperative Medicine

London Health Sciences Centre and St. Joseph Health Care, Lawson Health Research Institute, Schulich School of Medicine and Dentistry

Western University

339 Windermere Road

London, ON, N6A 5A5

Canada

Phone: 1 5196858500 ext 34436

Email: Mahesh.Nagappa@lhsc.on.ca

Abstract

Background: Surgical recovery after hospital discharge often presents challenges for patients and caregivers. Postoperative complications and poorly managed pain at home can lead to unexpected visits to the emergency department (ED) and readmission to the hospital. Digital home monitoring (DHM) may improve postoperative care compared to standard methods.

Objective: We conducted a feasibility study for a randomized controlled trial (RCT) to assess DHM's effectiveness following thoracic surgical procedures compared to standard care.

Methods: We conducted a 2-arm parallel-group pilot RCT at a single tertiary care center. Adult patients undergoing thoracic surgical procedures were randomized 1:1 into 2 groups: the DHM group and the standard of care (control group). We adhered to the intention-to-treat analysis principle. The primary outcome was predetermined RCT feasibility criteria. The trial would be feasible if more than 75% of trial recruitment, protocol adherence, and data collection were achieved. Secondary outcomes included 30-day ED visit rates, 30-day readmission rates, postoperative complications, length of stay, postdischarge 30-day opioid consumption, 30-day quality of recovery, patient-program satisfaction, caregiver satisfaction, health care provider satisfaction, and cost per case.

Results: All RCT feasibility criteria were met. The trial recruitment rate was 87.9% (95% CI 79.4%-93.8%). Protocol adherence and outcome data collection rates were 96.3% (95% CI 89.4%-99.2%) and 98.7% (95% CI 92.9%-99.9%), respectively. In total, 80 patients were randomized, with 40 (50%) in the DHM group and 40 (50%) in the control group. Baseline patient and clinical characteristics were comparable between the 2 groups. The DHM group had fewer unplanned ED visits (2.7% vs 20.5%; $P=.02$), fewer unplanned admission rates (0% vs 7.6%; $P=.24$), lower rates of postoperative complications (20% vs 47.5%, $P=.01$) shorter hospital stays (4.0 vs 6.9 days; $P=.05$), but more opioid consumption (111.6, SD 110.9) vs 74.3, SD 71.9 mg morphine equivalents; $P=.08$) compared to the control group. DHM also resulted in shorter ED visit times (130, SD 0 vs 1048, SD 1093 minutes; $P=.48$) and lower cost per case (CAD \$12,145 [US \$ 8436.34], SD CAD \$8779 [US \$ 6098.20] vs CAD \$17,247 [US \$11,980.37], SD

CAD \$15,313 [US \$10,636.95]; $P=.07$). The quality of recovery scores was clinically significantly better than the controls (185.4, SD 2.6 vs 178.3, SD 3.3; $P<.001$). All 37 patients who completed the intervention answered the program satisfaction survey questionnaires (100%; 95% CI 90.5%-100%). Only 36 out of 80 caregivers responded to the caregiver satisfaction questionnaires at the end of the fourth week post hospital discharge (47.7%; 95% CI 35.7%-59.1%). Health care providers reported a 100% satisfaction rate.

Conclusions: This pilot RCT demonstrates the feasibility of conducting a full-scale trial to assess DHM's efficacy in improving postoperative care following thoracic surgery. DHM shows promise for enhancing continuity of care and warrants further investigation.

Trial Registration: ClinicalTrials.gov NCT04340960; <https://clinicaltrials.gov/study/NCT04340960>

(*JMIR Perioper Med* 2025;8:e58998) doi:[10.2196/58998](https://doi.org/10.2196/58998)

KEYWORDS

remote monitor; digital home monitoring; continuity of care; quadruple health outcomes; patient satisfaction; caregivers satisfaction; healthcare provider satisfaction; feasibility; RCT; thoracic surgery; postoperative monitoring; surgical recovery; perioperative medicine; patient care; questionnaire

Introduction

Recovery following surgical discharge poses significant challenges for patients and their caregivers. This challenge is compounded by the growing practice of discharging patients earlier after surgical procedures, intensifying the postoperative care demands. Moreover, the health care system often operates within a framework of fragmented and poorly integrated services, exacerbating the difficulties faced by patients transitioning from hospital to home after surgery, which can lead to complications and inadequately managed pain, resulting in returns to the hospital or visits to the emergency department (ED) [1-5].

Numerous studies underscore the critical role of postdischarge continuity of care in reducing ED visits and readmission rates (RRs) [6-11]. For instance, Shargall et al [12] successfully implemented an "Integrated Comprehensive Care" program involving allied health care professionals, significantly reducing 30-day RRs among thoracic surgery patients. Similar reductions in RRs have been attributed to patient education, well-coordinated discharge planning, physician follow-up, and in-home visits [13]. Data from Canada highlight that within the first 7 days following surgical discharge, 28.3% of ED diagnoses fell under the Canadian Emergency Department Triage and Acuity Scale (CTAS) IV or V, indicating less urgent or nonurgent cases [14]. It is reasonable to assume that many of these patients could have avoided ED visits by providing appropriate transitional care [15].

To address the needs of patients at a higher risk of postdischarge complications, the concept of continuity of care through digital home monitoring (DHM) emerges as a promising avenue to enhance education, modify behavior, and ultimately achieve improved patient outcomes [9]. With this approach, care teams gain insights into each patient's condition daily or weekly, eliminating the reliance on sporadic office visits, typically occurring only once or twice a year [16]. This continuous and comprehensive view of patient health empowers care teams to make timely adjustments to care plans and proactively engage patients in self-managing care [17]. A virtual care option that

extends postdischarge continuity of care offers a viable solution [18-21].

Given the intricacies of providing continuity of care through DHM and the challenges associated with conducting a well-designed randomized controlled trial (RCT) in this context, a pilot study emerges as an essential preliminary step. The primary aim of this pilot study is to assess acceptability, identify logistical requirements, optimize the study design and data collection process, and evaluate readiness for a full-scale trial [22]. Undertaking an RCT that involves continuity of care with a DHM solution is resource-intensive. It raises practical concerns for all stakeholders, including hospital administrators, nurses, clinicians, and patients. Although the primary objective of this pilot study is to examine the feasibility of conducting a comprehensive RCT, this research specifically aims to investigate the feasibility of continuity of care using DHM on postoperative outcomes in patients following thoracic surgery. We hypothesize that continuity of care facilitated by DHM will reduce 30-day ED visits compared to standard care practices.

Methods

Overview

A parallel-group, 2-arm pragmatic pilot feasibility RCT was conducted from September 2022 to January 2023 at the London Health Sciences Centre. Participants were allocated 1:1 to receive continuity of care with DHM or standard of care (control) following the discharge after their thoracic surgical procedures. All participants provided written or electronic informed consent using the REDCap (Research Electronic Data Capture) tool hosted at the London Health Sciences Centre (REDCap e-consent). The analyses and reporting adhered to the CONSORT (Consolidated Guidelines of Reporting Trials) guidelines for pilot trials and the CONSORT-EHEALTH (Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth) checklist [23,24].

To execute the components of the DHM interventions, the health care team was trained from May 2021 to August 2022 using the Plan-Do-Study-Act cycle. Inclusion criteria were patients aged 18 years or older, undergoing a thoracic surgical procedure

(eg, elective anatomic lung resection or any major foregut procedure, such as an esophagectomy), and the surgeon in agreement with patient enrollment. Accredited thoracic surgeons performed all surgeries. Exclusion criteria were patients with unstable disease processes in the postoperative period (eg, postoperative intensive care unit stay) or those with factors that could impact outcome assessment (eg, cognitive impairment, inability to understand English, and limited access to a telephone, computer, or internet services). Patients were also excluded postoperatively if they had intraoperative or immediate postoperative complications requiring an intensive care unit stay.

Upon enrollment, eligible participants were randomized using the simple randomization feature of REDCap. No stratification factors or blocking were applied. The assignment of groups was concealed until the moment of randomization, at which point REDCap automatically allocated participants to the study arms [25]. All consecutive postoperative patients were approached to participate in the study. The randomization occurred on the day of discharge so that in-hospital care was not biased. Due to the pragmatic nature of the trial, patients, surgeons, clinical navigators (CNs), and other health care providers were not masked in the group allocation.

Preoperative, intraoperative, and postoperative patient management followed standard practices and were similar in both groups. A standardized care pathway for postthoracic surgical procedures was implemented for postoperative pain control involving acetaminophen, nonsteroidal anti-inflammatory drugs, hydromorphone, and adjunct medications, such as pregabalin. These were also prescribed on discharge unless otherwise contraindicated. Patients were monitored continuously after surgery while still in the postanesthesia care unit. While on the surgical ward, routine nursing assessments were conducted per the thoracic unit's standard of care. Patients in the control group were discharged home without any monitoring, per the current standard of care. Patients who experienced postdischarge complications were instructed to contact their surgeon's office or visit the hospital ED.

Patients in the DHM group received the same in-hospital care as the control group. In addition, DHM patients signed up for the cloud-based technology platform Vivify Health (Plano, Texas) digital portal with a unique username and password. Through the digital portal, the patient would connect with the CN, who guided the patient through every recovery step. The CN connected, engaged, and educated the patients regarding the recovery pathway. The CN also established clear expectations for patients. Before patients were ready for discharge, patients in the DHM group were given a DHM kit and shown how to use it to maintain continuity of care through the digital care platform. The DHM kit contained a noninvasive blood pressure (NIBP), hemoglobin oxygen saturation (SpO₂), and heart rate (HR) monitor. The data was transferred to a secured digital care platform through the app. DHM patients had access to speak to one of the health care providers at any time of day (CN or virtual care physician). The CN monitored the dashboard from 8 AM to 4 PM. After 4 PM, the CN handed

over the monitoring dashboard to one of the preassigned physicians (ie, virtual care physicians). Both the CN and physicians were trained in the platform. The health care provider used the digital platform to communicate, engage, and manage patients remotely and efficiently.

Patients measured their vital signs for 2 weeks. The patient also had daily scheduled video calls on days 1-15 after hospital discharge and on an as-needed basis from days 16-30. During the video calls, patients interacted with the CN and responded to symptom questionnaires. The CN organized unscheduled video visits on days without planned virtual visits if they detected changes in patient vital signs or recovery symptom questionnaires requiring follow-up. During virtual visits, the CN discussed any symptoms the patient was experiencing, evaluated their wounds, and obtained a picture if needed. The CN monitored the digital care platform dashboard from the provider side, with an alert for NIBP, HR, SpO₂, wound concerns, home medications, and pain. Alerts were displayed in a color-coded fashion on the dashboard. The CN also monitored the patient's symptoms and identified any changes from the patient's baseline. The CN called a preassigned clinician (ie, the patient's surgeon, a study physician, or a nurse practitioner) if any of the patient's symptoms required medical attention. Physicians could add or modify treatments as needed, and if required, they could have the patient come to an outpatient or ED facility for evaluation or management. Instructions were provided for the patient to call an emergency number (ie, 911) in collaboration and consultation with a physician if appropriate if any symptom indicated immediate distress. The CN and patients were just one button or "mouse click" away from each other, with multiple options to communicate by phone, SMS text message, email, or the virtual care platform (video chat). All these modes of communication were through a secured platform. The CN monitored and intervened by providing patients with advice and next steps if they had health concerns. Self-help educational videos were also available for patients.

This RCT was conducted as a pilot study, with a primary emphasis on assessing feasibility outcomes, which include trial recruitment, protocol adherence, and data collection. We followed the traffic light approach criteria for reporting feasibility outcomes [25-27]. This approach defined (1) feasible (green, 75%-100%) where all feasibility outcomes were met and no protocol modifications were needed; (2) feasible with modification (amber, 50%-75%) where all feasibility outcomes were met or could be met with protocol modifications; and (3) not feasible (red, <50%) where even with protocol modifications, feasibility outcomes could not be met. The clinical outcomes were assessed secondarily to inform the measurement strategy and sample size requirements for a future RCT (ie, by estimating variability, SDs, and prevalence of critical clinical outcomes). Our quadruple health outcome measurement strategy included (1) postoperative outcomes like 30-day ED visits, 30-day RRs, postoperative complications, in-hospital length of stay, 30-day quality of recovery (QoR-40) [28], and postdischarge 30-day opioid consumption; (2) patient-program satisfaction and caregiver satisfaction [29]; (3) health care provider satisfaction; and (4) financial sustainability like cost per case analysis.

Patient-reported outcomes were collected up to 30 days post hospital discharge. Daily data was collected using automatic electronic questionnaires completed digitally and transmitted directly to the REDCap database. Patients also had the option to complete daily questionnaires by video or telephone with a CN. The questionnaires were completed on a smartphone, tablet, or personal computer. Masked assessors verified the data in the REDCap database. Information regarding the 30-day ED visits, 30-day RRs, postoperative complications, postdischarge 30-day opioid consumption, and in-hospital length of stay was obtained from electronic medical records. The patient-program satisfaction survey consisted of 9 questions collected by the research assistant at the end of the 30 days in the DHM group. Patient agreement or satisfaction with statements was recorded on a 5-point scale (from 1=strongly disagree to 5=strongly agree) using a checkmark (✓), with a higher score indicating a higher level of patient agreement or satisfaction. The caregiver survey consists of 17 “Yes” or “No” questions collected by the research assistant at the end of the 30 days in the RPM program in both the DHM and control groups. The satisfaction survey for health care providers comprised 9 questionnaires, addressed at the project's conclusion through the Microsoft Teams survey link and disseminated via electronic mail. Case costing data consisting of the average direct surgical and nonsurgical inpatient costs was obtained for the DHM group and control groups according to the Ontario case costing initiative methodology for 2019-2020 data [30].

The following factors were considered in creating the 5 grades of interventions during the postoperative follow-up using RPM programs: phone calls, video calls, asynchronous messages, self-help educational materials, the amount of time the CN spent addressing the patient's concerns, and escalation to the virtual care physician. The definition of levels of digital health intervention: (1) no intervention and no assessment; (2) no intervention, but the automatic collection of signs, symptoms, and vital signs questionnaires; (3) mild intervention, wherein the CN spends less than 15 minutes with the patient; (4) moderate intervention, characterized by the CN spending 15-30 minutes with the patient; and (5) severe intervention, involving either the CN spending more than 30 minutes with the patient

or the situation being escalated to a virtual care physician for further management.

Based on previous data, at least 70 measured participants were required to estimate SD with enough precision for future sample size calculations [31]. We aimed to recruit and obtain outcome data from 80 patients (40 per group), allowing for an attrition rate of approximately 15%. This sample size was also consistent with recommendations regarding the minimum number of participants required to identify feasibility issues [32]. We used “intention-to-treat” analysis. No formal comparison between the study arms was undertaken for outcomes, given that this is a feasibility study. Quantitative secondary outcome measures were summarized descriptively using appropriate summary statistics in the result section and by the trial arm in the tabular column. Continuous variables were reported as mean, standard deviation, and median (range), as appropriate. Categorical variables were reported as counts and percentages. Statistical analyses were performed using GraphPad Prism (GraphPad) software.

Ethical Considerations

This study was formally registered with ClinicalTrials.gov (NCT04340960) and received full board review and approval from the institutional research ethics board at Western University (HSREB 114886). All individual participants involved in the study provided informed consent. Furthermore, appropriate measures were implemented to maintain the confidentiality and anonymity of patient data throughout the research. The study posed no significant risks to the participants, who kept the right to withdraw without facing repercussions regarding their standard of care. Ultimately, no financial compensation was offered to the participants involved in the study.

Results

A total of 91 consecutive patients were considered for inclusion in our study. In total, 80 patients met the inclusion criteria, consented to participate, and were randomized to either the control (n=40) group or the DHM (n=40) group (Figure 1). The 2 groups' patient demographics and clinical characteristics were similar (Table 1).

Figure 1. CONSORT (Consolidated Standards of Reporting Trials) flow diagram. DHM: digital home monitoring.

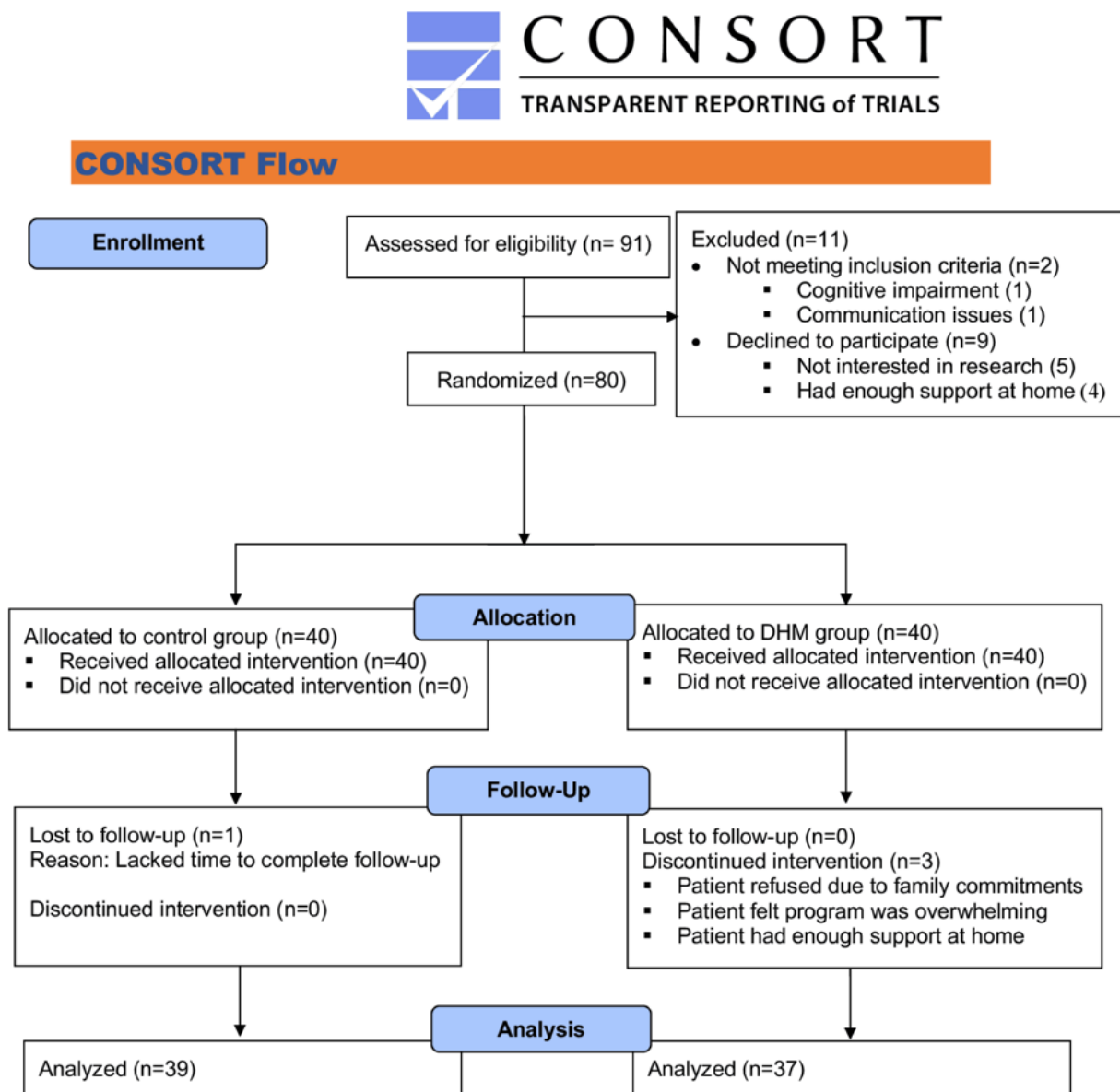


Table 1. Patient demographic and clinical characteristics.

	Control group	DHM ^a group	Total	<i>P</i> value
Age (years), mean (SD)	65.5 (14.7)	63.3 (15.0)	64.4 (14.8)	.51
Gender, n (%)				.36
Female	25 (62.5)	20 (50)	45 (56.2)	
Male	15 (37.5)	20 (50)	35 (43.7)	
BMI (kg/m²), mean (SD)	30.1 (12.3)	27.8 (5.0)	28.9 (9.40)	.28
Outside the London area, n (%)				.48
Yes	23 (57.5)	27 (67.5)	50 (62.5)	
No	17 (42.5)	13 (32.5)	30 (37.5)	
Disease type, n (%)				.99
Primary lung cancer	17 (42.5)	17 (42.5)	34 (42.5)	
Secondary lung cancer	7 (17.5)	7 (17.5)	14 (17.5)	
Others	16 (40)	16 (40)	32 (40)	
PFT, mean (SD) (n)				
FEV ₁ ^b	85.8 (18.2) (16)	88.5 (21.1) (19)	87.3 (19.6) (35)	.69
DLCO ^c	74.6 (19.6) (16)	77.6 (17.1) (18)	76.2 (18.1) (34)	.64
Cancer type, n (%)				.40
Malignant	24 (60)	23 (57.5)	47 (58.7)	
Benign	2 (5)	0 (0)	2 (2.5)	
Others	14 (35)	17 (42.5)	31 (38.7)	
Side of surgery, n (%)				.06
Right	17 (42.5)	8 (20)	25 (31.2)	
Left	10 (25)	18 (45)	28 (35)	
N/A ^d	13 (32.5)	14 (35)	27 (33.7)	
Type of resection, n (%)				.30
Wedge	13 (32.5)	11 (27.5)	24 (30)	
Segmentectomy	4 (10)	1 (2.5)	5 (6.2)	
Lobectomy	8 (20)	12 (30)	20 (25)	
Pneumonectomy	0 (0)	0 (0)	0	
Pleural	3 (7.5)	0 (0)	3 (3.7)	
Mediastinal	1 (2.5)	2 (5)	3 (3.7)	
Foregut procedure	11 (27.5)	14 (35)	25 (31.2)	
Surgical approach, n (%)				.17
Thoracotomy	12 (30)	7 (17.5)	19 (23.7)	
Laparotomy	8 (20)	5 (12.5)	13 (16.2)	
VATS ^e	18 (45)	21 (52.5)	39 (48.7)	
Laparoscopic	2 (5)	7 (17.5)	9 (11.2)	
Staging (pTNM^f), n (%)				.66
IA/IB	14 (35)	9 (22.5)	23 (28.7)	
IIA/IIB	4 (10)	8 (20)	12 (15)	
IIIA/IIIB	3 (7.5)	2 (5)	5 (6.2)	
IV	2 (5)	1 (2.5)	3 (3.7)	

	Control group	DHM ^a group	Total	<i>P</i> value
Metastatic disease	1 (2.5)	2 (5)	3 (3.7)	
N/A	16 (40)	18 (45)	34 (42.5)	
Histology, n (%)				.95
Adenocarcinoma	13 (32.5)	12 (30)	25 (31.2)	
Small cell carcinoma	2 (5)	1 (2.5)	3 (3.7)	
Metastasis	2 (5)	2 (5)	4 (5)	
Others	1 (2.5)	0 (0)	1 (1.2)	
Carcinoid	0 (0)	1 (2.5)	1 (1.2)	
N/A	22 (55)	24 (60)	46 (57.5)	
Smoking history, n (%)				.76
Quit smoking	21 (52.5)	21 (52.5)	42 (52.5)	
Active smokers	5 (12.5)	3 (7.5)	8 (10)	
Nonsmokers	14 (35)	16 (40)	30 (37.5)	

^aDHM: digital home monitoring.

^bFEV1: forced expiratory volume at the end of 1 second.

^cDLCO: diffusing capacity of lung for carbon monoxide.

^dN/A: not applicable.

^eVATS: video-assisted thoracoscopy.

^fpTNM: tumor (T), lymph nodes (N), metastasis (M).

Among the eligible patients who declined enrollment, the most common reason was not being interested in participating in research while receiving care (5.4%), followed by patients having enough support at home for recovery after hospital discharge (4.3%). In total, 3 patients from the DHM group withdrew in the second week after hospital discharge. The first patient withdrew due to family commitments, the second patient felt the program was overwhelming, and the last patient had enough support at home during recovery and decided to withdraw from the program. Only one patient from the control group was lost at the end of the 30-day follow-up period. In total, 76 patients—39 in the control group and 37 in the DHM

group—completed the study. Out of 80 caregivers who provided consent for enrollment, only 36 caregivers (16 in the control group and 20 in the DHM group) responded to the caregiver satisfaction questionnaires at the end of the fourth week (47.7%; 95% CI 35.7%-59.1%).

Our study met all green feasibility criteria (Table 2). All 5 thoracic surgeons agreed to have their patients consecutively recruited and adhere to the study protocol. The recruitment rate was 87.9% (95% CI 79.4%-93.8%), and protocol adherence was 96.3% (95% CI 89.4%-99.2%). Data were collected for outcomes in 98.7% (95% CI 92.9%-99.9%) of participants.

Table 2. Feasibility outcomes.

	Not feasible (red) ^a	Feasible with modification (amber) ^b	Feasible (green) ^c	Study results
Trial recruitment	<50%	50%-74%	75%-100%	87.91%
Protocol adherence	<50%	50%-74%	75%-100%	96.25%
Outcome data collection	<50%	50%-74%	75%-100%	98.70%

^aNot feasible (red) <50%: even with protocol modifications, some feasibility outcomes cannot be met.

^bFeasible with modification (amber) 50%-75%: all feasibility outcomes are met or can be met with protocol modifications.

^cFeasible (green) 75%-100%: all feasibility outcomes are met; no protocol modifications are needed.

The mean age of the sample was 64.4 (SD 14.8) years, with 56.2% being female, and the mean BMI was 28.9 (SD 9.4) kg/m². Most patients had malignant cancer (58.7%) and primary lung cancer (42.5%). Patients most commonly underwent wedge resection (30%), lobectomy (25%), or foregut procedures (31.2%). The most common surgical approach was video-assisted thoracoscopy (48.7%), followed by thoracotomy (23.7%), and then laparotomy (16.2%).

The mean total length of stay in the hospital was 5.4 (SD 6.6) days (control vs DHM: 6.9, SD 8.8 vs 4.0, SD 2.7), and the incidence of postoperative complications was 33.7% (control vs DHM: 47.5% vs 20%). The total number of ED visits in this sample was 11.2% (control vs DHM: 20.5% vs 2.7%). All these ED visits were unplanned, and the mean time spent in the ED was 894 (SD 1047) minutes (control vs DHM: 1048, SD 1093 vs 130, SD 0). One patient from the DHM group presented to

the ED with testicular pain. Patients from the control group presented with abdominal bloating or distension, wound concerns, dysphagia, or pain crises. The total hospital RR for the sample was 6.5% (control vs DHM: 7.6% vs 5.4%). The unplanned hospital RR was 3.9% (control vs DHM: 7.6% vs 0%), and the planned hospital RR was 2.6% (control vs DHM: 0% vs 5.4%), respectively. The mean 30-day morphine

equivalent dose opioid consumption was 92 (SD 94.2) mg (control vs DHM: 74.3, SD 71.9 vs 111.6, SD 110.9), and the mean in-hospital cost per case was CAD \$14,729 (US \$10,227.96; SD CAD \$12,702 [US \$8820.40]; control vs DHM: CAD \$17,247 [US \$11,976.49], SD CAD \$15,313 [US \$10,633.50] vs CAD \$12,145 [US \$8433.61], SD CAD \$8779 [US \$6096.23]; [Table 3](#)).

Table 3. Postoperative outcomes.

	Control group	DHM ^a group	Total	<i>P</i> value
LOS ^b (days), mean (SD)	6.9 (8.8)	4.0 (2.7)	5.4 (6.6)	.05
Postoperative complications, n (%)	19 (47.5)	8 (20)	27 (33.75)	.01
Unplanned ED ^c visits, n (%)	8 (20.5)	1 (2.7)	9 (11.25)	.02
Planned ED visits, n (%)	0	0	0	— ^d
Time spent in ED (min), mean (SD)	1048 (1093)	130 (0)	894 (1047)	.48
Unplanned RR ^e , n (%)	3 (7.6)	0	3 (3.9)	.24
Planned RR, n (%)	0	2 (5.4)	2 (2.6)	.23
Total RR, n (%)	3 (7.6)	2 (5.4)	5 (6.5)	.99
30-Day morphine equivalent dose consumption (mg), mean (SD)	74.3 (71.9)	111.6 (110.9)	92.4 (94.2)	.08
Cost per case (CAD \$; CAD \$1=US \$0.69), mean (SD)	17,247 (15,313)	12,145 (8779)	14,729 (12,702)	.07

^aDHM: digital home monitoring.

^bLOS: length of hospital stay.

^cED: emergency department.

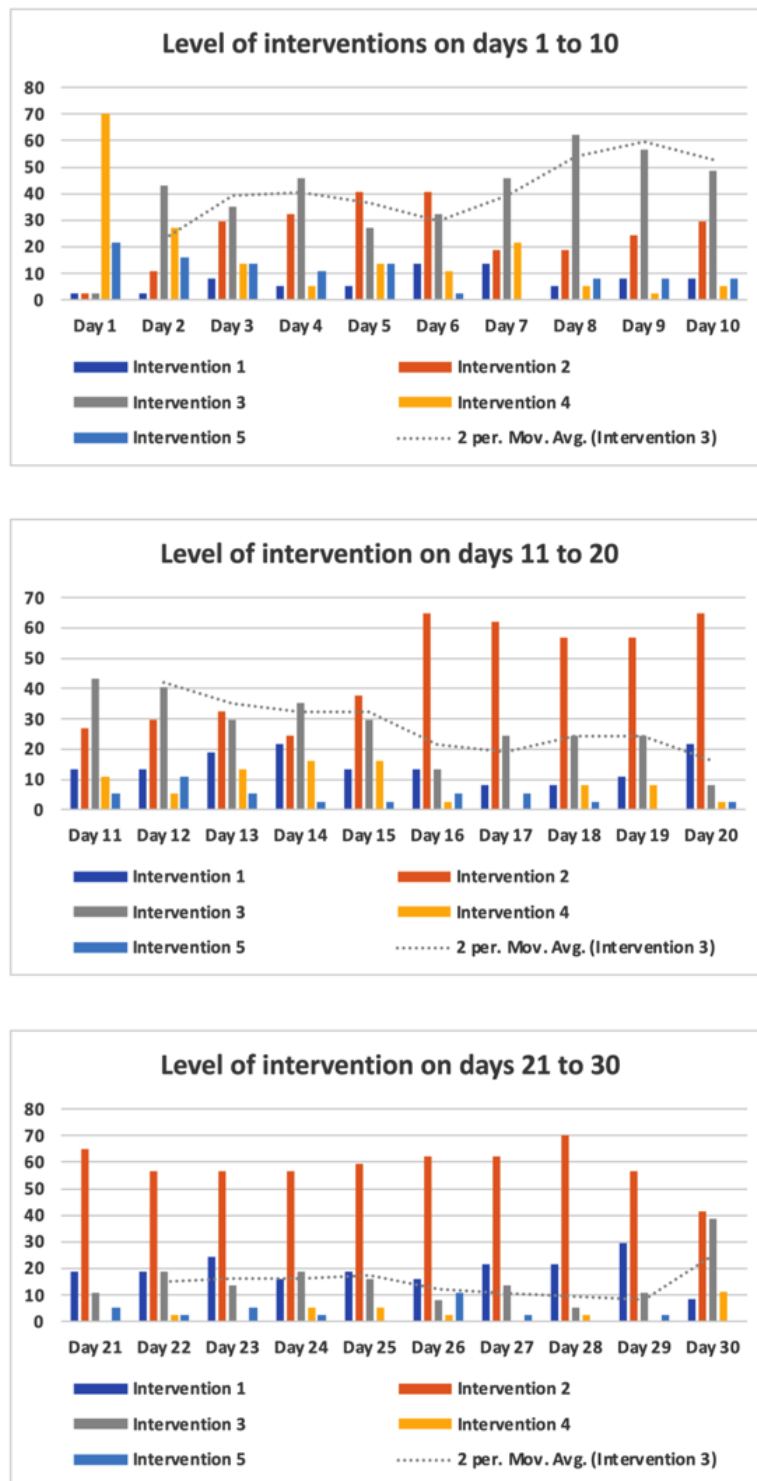
^dNot applicable.

^eRR: readmission rate.

The remote monitoring team most often used level 2 or 3 interventions, except for postdischarge day 1, where intervention level 4 was the most common ([Figure 2](#)). Comparing interventions over 0-15 days and 16-30 days revealed that level 2 interventions rose significantly from 26.6% to 59.5% ($P<.001$). In contrast, level 3, 4, and 5 interventions dropped substantially

from 38.5% to 16.6%, 15.8% to 3.4%, and 8.6% to 3.2%, respectively ($P<.001$). The most common issues addressed through the digital platform included pain (23%), surgical wound concerns (11%), shortness of breath (10%), diarrhea (7%), medication management (7%), nausea or vomiting (5%), and dizziness (5%; [Multimedia Appendix 1](#)).

Figure 2. Levels of digital health intervention.



At 30 days postoperatively, the mean global QoR-40 score for the sample was 181.9 (SD 5.0). The scores for individual domains included emotional status (39.3, SD 1.4), physical

comfort (53.5, SD 0.6), psychological support (33.1, SD 1.7), physical independence (22.7, SD 0.6), and pain (33.1, SD 0.4; Table 4).

Table 4. Quality of recovery.

	Control group (n=39)	DHM ^a group (n=37)	Total (N=76)	P value
Global QoR-40 ^b , mean (SD)	178.3 (3.3)	185.4 (2.6)	181.9 (5.0)	<.001
Emotional status, mean (SD)	38.3 (0.8)	40.4 (0.6)	39.3 (1.4)	<.001
Physical comfort, mean (SD)	53.0 (0.7)	53.9 (0.7)	53.5 (0.6)	<.001
Psychological support, mean (SD)	31.9 (0.5)	34.3 (0.2)	33.1 (1.7)	<.001
Physical independence, mean (SD)	22.2 (0.5)	23.2 (0.4)	22.7 (0.6)	<.001
Pain, mean (SD)	32.7 (0.6)	33.4 (0.5)	33.1 (0.4)	<.001

^aDHM: digital home monitoring.

^bQoR-40: 30-day quality of recovery.

Responses from the patient and caregiver satisfaction surveys administered at the end of the fourth week postoperatively were recorded ([Multimedia Appendices 2 and 3](#), respectively). All 37 patients who completed the intervention answered the program satisfaction survey questionnaires (100%; 95% CI 90.5%-100%). More than 95% of patients agreed or strongly agreed that the instructions for setting up the remote monitoring system were easy to understand. All 37 patients in the DHM group agreed or strongly agreed that they felt safe at home and that the CN and physicians responded promptly and efficiently. All patients in the DHM group either agreed or strongly agreed that they would recommend the remote monitoring system program to future patients. Out of 80 caregivers who provided consent for enrollment, only 36 caregivers responded to the caregiver satisfaction questionnaires at the end of the fourth week post hospital discharge (47.7%; 95% CI 35.7%-59.1%). While taking care of the family members at home after the hospital discharge, our sample caregivers reported less burden on family members (8.5%), less interference with personal activities (28.5%), feeling less confined to staying at home (37.1%), and less physical strain (14.2%). However, caregivers reported taking more time off work than initially anticipated (14.2%), employment activities being affected (14.2%), educational activities being affected (8.5%), increased demand on time (31.4%), changes in personal plans (51.4%), and family adjustments (62.8%). Health care providers reported a 100% satisfaction rate ([Multimedia Appendix 4](#)).

Discussion

The findings from this trial support the feasibility of conducting a full-scale RCT to compare DHM with the current standard of care after thoracic surgery. The study showed excellent feasibility, achieving a recruitment rate of 87.9%, protocol adherence of 96.3%, and collecting outcome data for 98.7% of participants. These results indicate significant engagement and compliance, reinforcing the study's viability for broader implementation.

The most common barrier to participation among eligible patients in this study was a lack of willingness to participate in research while receiving care (n=5, 5.4%). Other reasons included patients who felt they had enough support at home to

recover after hospital discharge (n=4, 4.3%). However, all patients consented to randomization due to the preconception that the care team would connect with them after hospital discharge to aid their recovery. This finding suggests that recruitment for a full-scale trial may be facilitated by addressing implicit biases and emphasizing the importance of continuous connection with the care team to improve postoperative outcomes. Most patients preferred being assigned to the continuity of care with a DHM group rather than the standard care group (70%). In comparison, 25% of the patients did not express any preference.

Using smartphone technology for postoperative follow-up and patient communication has significantly minimized the chances of ED visits and RRs [33,34]. In the United Kingdom, a remote monitoring initiative for 900 colorectal patients reduced costs by 63% while achieving high patient satisfaction [35]. Likewise, a quality improvement study involving 48 thoracic patients with robotic lobectomies found that home monitoring effectively enabled safe early discharges and demonstrated possible economic benefits [36]. Conversely, in an RCT that included 292 postsurgical patients, there was no notable difference between the home monitoring and control groups in ED visits post surgery. Patients in the remote patient monitoring group had an average adherence rate of 86% for daily vital sign logging and 78% for daily question logging [37]. Still, home monitoring was well-received by both patients and physicians, although technological challenges diminished its benefits. Many of these studies relied on automatic data collection methods. Our research yields similar findings but is a prospective RCT focused on thoracic surgical patients. We incorporated more pragmatic inclusion criteria with the caregivers' surveys and used Vivify technology. Our intervention is labor-intensive, differing from other studies, including educational resources, automated questionnaires, vital sign data collection, 2-way communication, and daily CN calls.

This pilot RCT examined the feasibility and clinical impact of continuous DHM on postoperative outcomes in patients undergoing major thoracic surgery. The DHM group had fewer postoperative complications, unplanned ED visits, and unplanned RRs. A potential explanation may be the increased continuity of care and the clinician's ability to monitor a patient's

clinical status to implement necessary interventions before the progression of postoperative complications or ED visits [38-41]. Moreover, the global QoR-40 score and all individual domains were rated higher in the DHM group. This may have resulted from increased patient surveillance and clinician intervention to ensure patients remain on an acceptable path to recovery [42]. However, this trial was not powered or designed with the QoR-40 scores as a primary outcome; thus, these findings must be interpreted cautiously. The satisfaction survey results indicate that patients and health care providers highly value the remote monitoring program. However, caregivers have shown mixed responses. Our findings imply that while patients and providers regard the program positively, further support for caregivers could improve their experience and address the reported increased time demands and schedule adjustments. This can be explored further in the full-scale RCT.

A potential barrier to implementing a DHM system is the difficulty of setting it up and using it by the patient. However, in our study, most patients reported that setup instructions were easy to understand and did not find the system difficult to use. Overall, satisfaction with the program was excellent, and all participants would recommend the remote monitoring system to future patients. Of note, caregivers of patients in the DHM group reported that caregiving affected their personal, educational, and work activities more than the control group. This may be explained by the need to assist the patient in recording vitals and concerns and uploading this information to the digital care platform.

One strength of our study was the diverse patient population regarding gender, age, and BMI. Pathologies such as primary malignancies, secondary malignancies, and nonmalignant diseases were also included. Surgical procedures were diverse, with various types of resections and surgical approaches. The

heterogeneity of the study patients indicates that this can be universally implemented in other surgical populations. Patients and their caregivers were adequately trained to record vital signs and upload concerns online, reducing the workload of the home care team. Furthermore, extensive remote patient monitoring was implemented, including HR, NIBP, SpO₂, and daily assessment measurements.

The limitations of this study include the fact that it was not statistically powered to detect postoperative outcome differences. As such, any between-group comparison should be interpreted with caution. Additionally, patients were only followed for 4 weeks postoperatively, so data on the efficacy of continuous DHM on postoperative outcomes beyond this time point remain unknown. Since January 2023, Vivify technology has not been available in Ontario, Canada, and we will be using different technology in our next project to explore these promising results. The potential threats to this feasibility may be reproducibility and scalability associated with the entirely new platform and the maintenance of labor-intensive resource intervention. Further, the cost of the intervention should have been evaluated in this study. Finally, this study was performed at a single center in patients undergoing major thoracic surgery and may need exploration to implement in other surgical populations at different institutions.

In conclusion, the VivifyHealth digital health platform provides a user-friendly interface to extend continuity of care. DHM effectively improved the quality of patients' recovery while decreasing postoperative complications, unplanned ED visits, and hospital RRs. Effective implementation of these platforms may reduce the utilization of scarce health care resources while maintaining excellent patient outcomes and satisfaction. Findings from this pilot trial support the feasibility of conducting a robust full-scale trial to explore these promising results.

Acknowledgments

This study was supported by the Innovation Fund of the Academic Health Sciences Centre—Alternative Funding Plan (AFP) of the Academic Medical Organization of Southwestern Ontario (AMOSO-AFP budget INN20-003), the Department of Anesthesia Internal Research Fund (IRF), and the London Health Sciences Centre Foundation award.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Health problems addressed via a digital home monitoring program.

[PNG File, 130 KB - [periop_v8i1e58998_app1.png](#)]

Multimedia Appendix 2

Patient/Program Satisfaction Questionnaires.

[DOCX File, 34 KB - [periop_v8i1e58998_app2.docx](#)]

Multimedia Appendix 3

Caregivers Satisfaction.

[DOCX File, 34 KB - [periop_v8i1e58998_app3.docx](#)]

Multimedia Appendix 4

Healthcare Provider satisfaction.

[\[DOCX File, 33 KB - periop_v8i1e58998_app4.docx\]](#)

Multimedia Appendix 5

CONSORT eHEALTH checklist (V 1.6.1).

[\[PDF File \(Adobe PDF File\), 431 KB - periop_v8i1e58998_app5.pdf\]](#)

References

1. Dickinson KJ, Taswell JB, Allen MS, Blackmon SH, Nichols FC, Shen R, et al. Unplanned readmission after lung resection: complete follow-up in a 1-year cohort with identification of associated risk factors. *Ann Thorac Surg* 2017;103(4):1084-1091. [doi: [10.1016/j.athoracsur.2016.09.065](https://doi.org/10.1016/j.athoracsur.2016.09.065)] [Medline: [27993376](https://pubmed.ncbi.nlm.nih.gov/27993376/)]
2. Konstantinidis K, Woodcock-Shaw J, Dinesh P, Brunelli A. Incidence and risk factors for 90-day hospital readmission following video-assisted thoracoscopic anatomical lung resection†. *Eur J Cardiothorac Surg* 2019;55(4):666-672. [doi: [10.1093/ejcts/ezy345](https://doi.org/10.1093/ejcts/ezy345)] [Medline: [30364954](https://pubmed.ncbi.nlm.nih.gov/30364954/)]
3. Lee AJ, Liu X, Borza T, Qin Y, Li BY, Urish KL, et al. Role of post-acute care on hospital readmission after high-risk surgery. *J Surg Res* 2019;234:116-122 [FREE Full text] [doi: [10.1016/j.jss.2018.08.053](https://doi.org/10.1016/j.jss.2018.08.053)] [Medline: [30527462](https://pubmed.ncbi.nlm.nih.gov/30527462/)]
4. Kidane B, Higgins S, Hirpara DH, Kaaki S, Shen YC, Allison F, et al. From emergency department visit to readmission after esophagectomy: analysis of burden and risk factors. *Ann Thorac Surg* 2021;112(2):379-386. [doi: [10.1016/j.athoracsur.2020.11.020](https://doi.org/10.1016/j.athoracsur.2020.11.020)] [Medline: [33310147](https://pubmed.ncbi.nlm.nih.gov/33310147/)]
5. Nelson DB, Lapid DJ, Mitchell KG, Correa AM, Hofstetter WL, Mehran RJ, et al. Perioperative outcomes for stage I non-small cell lung cancer: differences between men and women. *Ann Thorac Surg* 2018;106(5):1499-1503. [doi: [10.1016/j.athoracsur.2018.06.070](https://doi.org/10.1016/j.athoracsur.2018.06.070)] [Medline: [30118712](https://pubmed.ncbi.nlm.nih.gov/30118712/)]
6. Yang H, Dervin G, Madden S, Beaulé PE, Gagné S, Crossan ML, et al. Postoperative home monitoring after joint replacement: feasibility study. *JMIR Perioper Med* 2018;1(2):e10168 [FREE Full text] [doi: [10.2196/10168](https://doi.org/10.2196/10168)] [Medline: [33401364](https://pubmed.ncbi.nlm.nih.gov/33401364/)]
7. Yang H, Dervin G, Madden S, Fayad A, Beaulé P, Gagné S, et al. Postoperative home monitoring after joint replacement: retrospective outcome study comparing cases with matched historical controls. *JMIR Perioper Med* 2018;1(2):e10169 [FREE Full text] [doi: [10.2196/10169](https://doi.org/10.2196/10169)] [Medline: [33401365](https://pubmed.ncbi.nlm.nih.gov/33401365/)]
8. van Walraven C, Mamdani M, Fang J, Austin PC. Continuity of care and patient outcomes after hospital discharge. *J Gen Intern Med* 2004;19(6):624-631 [FREE Full text] [doi: [10.1111/j.1525-1497.2004.30082.x](https://doi.org/10.1111/j.1525-1497.2004.30082.x)] [Medline: [15209600](https://pubmed.ncbi.nlm.nih.gov/15209600/)]
9. Minervini F, Taylor J, Hanna WC, Agzarian J, Hughes K, Pinkney P, et al. Can a mobile app technology reduce emergency department visits and readmissions after lung resection? A prospective cohort study. *Can J Surg* 2022;65(6):E798-E804 [FREE Full text] [doi: [10.1503/cjs.000122](https://doi.org/10.1503/cjs.000122)] [Medline: [36418065](https://pubmed.ncbi.nlm.nih.gov/36418065/)]
10. Leppin AL, Gionfriddo MR, Kessler M, Brito JP, Mair FS, Gallacher K, et al. Preventing 30-day hospital readmissions: a systematic review and meta-analysis of randomized trials. *JAMA Intern Med* 2014;174(7):1095-1107 [FREE Full text] [doi: [10.1001/jamainternmed.2014.1608](https://doi.org/10.1001/jamainternmed.2014.1608)] [Medline: [24820131](https://pubmed.ncbi.nlm.nih.gov/24820131/)]
11. Young JM, Butow PN, Walsh J, Durcinoska I, Dobbins TA, Rodwell L, et al. Multicenter randomized trial of centralized nurse-led telephone-based care coordination to improve outcomes after surgical resection for colorectal cancer: the CONNECT intervention. *J Clin Oncol* 2013;31(28):3585-3591. [doi: [10.1200/jco.2012.48.1036](https://doi.org/10.1200/jco.2012.48.1036)]
12. Shargall Y, Hanna WC, Schneider L, Schieman C, Finley CJ, Tran A, et al. The integrated comprehensive care program: a novel home care initiative after major thoracic surgery. *Semin Thorac Cardiovasc Surg* 2016;28(2):574-582. [doi: [10.1053/j.semtcvs.2015.12.003](https://doi.org/10.1053/j.semtcvs.2015.12.003)] [Medline: [28043480](https://pubmed.ncbi.nlm.nih.gov/28043480/)]
13. Fox JP, Suter LG, Wang K, Wang Y, Krumholz HM, Ross JS. Hospital-based, acute care use among patients within 30 days of discharge after coronary artery bypass surgery. *Ann Thorac Surg* 2013;96(1):96-104 [FREE Full text] [doi: [10.1016/j.athoracsur.2013.03.091](https://doi.org/10.1016/j.athoracsur.2013.03.091)] [Medline: [23702228](https://pubmed.ncbi.nlm.nih.gov/23702228/)]
14. Book. All-Cause Readmission to Acute Care/Return to the Emergency Department. Ottawa, ON: Canadian Institute for Health Information; 2012.
15. Cleeland CS, Wang XS, Shi Q, Mendoza TR, Wright SL, Berry MD, et al. Automated symptom alerts reduce postoperative symptom severity after cancer surgery: a randomized controlled clinical trial. *J Clin Oncol* 2011;29(8):994-1000. [doi: [10.1200/jco.2010.29.8315](https://doi.org/10.1200/jco.2010.29.8315)] [Medline: [21282546](https://pubmed.ncbi.nlm.nih.gov/21282546/)]
16. Sun V, Dumitra S, Ruel N, Lee B, Melstrom L, Melstrom K, et al. Wireless monitoring program of patient-centered outcomes and recovery before and after major abdominal cancer surgery. *JAMA Surg* 2017;152(9):852-859 [FREE Full text] [doi: [10.1001/jamasurg.2017.1519](https://doi.org/10.1001/jamasurg.2017.1519)] [Medline: [28593266](https://pubmed.ncbi.nlm.nih.gov/28593266/)]
17. Cheng X, Yang Y, Shentu Y, Ding Z, Zhou Q, Tan Q, et al. Remote monitoring of patient recovery following lung cancer surgery: a messenger application approach. *J Thorac Dis* 2021;13(2):1162-1171 [FREE Full text] [doi: [10.21037/jtd-21-27](https://doi.org/10.21037/jtd-21-27)] [Medline: [33717589](https://pubmed.ncbi.nlm.nih.gov/33717589/)]

18. Avery KNL, Richards HS, Portal A, Reed T, Harding R, Carter R, et al. Developing a real-time electronic symptom monitoring system for patients after discharge following cancer-related surgery. *BMC Cancer* 2019;19(1):463 [FREE Full text] [doi: [10.1186/s12885-019-5657-6](https://doi.org/10.1186/s12885-019-5657-6)] [Medline: [31101017](https://pubmed.ncbi.nlm.nih.gov/31101017/)]
19. Keng CJS, Goriawala A, Rashid S, Goldstein R, Schmocker S, Easson A, et al. Home to stay: an integrated monitoring system using a mobile app to support patients at home following colorectal surgery. *J Patient Exp* 2020;7(6):1241-1246 [FREE Full text] [doi: [10.1177/2374373520904194](https://doi.org/10.1177/2374373520904194)] [Medline: [33457571](https://pubmed.ncbi.nlm.nih.gov/33457571/)]
20. Hong TH, Kim MK, Ryu DJ, Park JS, Bae GC, Jeon YS. The reliability of remote patient-reported outcome measures via mobile apps to replace outpatient visits after rotator cuff repair surgery: repetitive test-retest comparison study for 1-year follow-up. *J Med Internet Res* 2021;23(3):e20989 [FREE Full text] [doi: [10.2196/20989](https://doi.org/10.2196/20989)] [Medline: [33646133](https://pubmed.ncbi.nlm.nih.gov/33646133/)]
21. Subramani Y, Querney J, Singh P, Zhang Y, Fochesato L, Fatima N, et al. Preoperative anesthesia virtual video consultations in a preadmission clinic: quality improvement study. *JMIR Perioper Med* 2024;7:e57541 [FREE Full text] [doi: [10.2196/57541](https://doi.org/10.2196/57541)] [Medline: [39052992](https://pubmed.ncbi.nlm.nih.gov/39052992/)]
22. Kistin C, Silverstein M. Pilot studies: a critical but potentially misused component of interventional research. *J Am Med Assoc* 2015;314(15):1561-1562 [FREE Full text] [doi: [10.1001/jama.2015.10962](https://doi.org/10.1001/jama.2015.10962)] [Medline: [26501530](https://pubmed.ncbi.nlm.nih.gov/26501530/)]
23. Eldridge SM, Chan CL, Campbell MJ, Bond CM, Hopewell S, Thabane L, PAFS Consensus Group. CONSORT 2010 statement: extension to randomised pilot and feasibility trials. *Pilot Feasibility Stud* 2016;2(1):64 [FREE Full text] [doi: [10.1186/s40814-016-0105-8](https://doi.org/10.1186/s40814-016-0105-8)] [Medline: [27965879](https://pubmed.ncbi.nlm.nih.gov/27965879/)]
24. Eysenbach G, CONSORT-EHEALTH Group. CONSORT-EHEALTH: improving and standardizing evaluation reports of Web-based and mobile health interventions. *J Med Internet Res* 2011;13(4):e126 [FREE Full text] [doi: [10.2196/jmir.1923](https://doi.org/10.2196/jmir.1923)] [Medline: [22209829](https://pubmed.ncbi.nlm.nih.gov/22209829/)]
25. Singh J. Randomization and online databases for clinical trials. *J Pharmacol Pharmacother* 2014;5(2):173-174. [doi: [10.4103/0976-500x.130155](https://doi.org/10.4103/0976-500x.130155)]
26. Thabane L, Lancaster G. A guide to the reporting of protocols of pilot and feasibility trials. *Pilot Feasibility Stud* 2019;5(1):37 [FREE Full text] [doi: [10.1186/s40814-019-0423-8](https://doi.org/10.1186/s40814-019-0423-8)] [Medline: [30858987](https://pubmed.ncbi.nlm.nih.gov/30858987/)]
27. Avery KNL, Williamson PR, Gamble C, O'Connell Francischetto E, Metcalfe C, Davidson P, et al. Informing efficient randomised controlled trials: exploration of challenges in developing progression criteria for internal pilot studies. *BMJ Open* 2017;7(2):e013537. [doi: [10.1136/bmjopen-2016-013537](https://doi.org/10.1136/bmjopen-2016-013537)] [Medline: [28213598](https://pubmed.ncbi.nlm.nih.gov/28213598/)]
28. Gornall B, Myles P, Smith C, Burke J, Leslie K, Pereira M, et al. Measurement of quality of recovery using the QoR-40: a quantitative systematic review. *Br J Anaesth* 2013;111(2):161-169 [FREE Full text] [doi: [10.1093/bja/aet014](https://doi.org/10.1093/bja/aet014)] [Medline: [23471753](https://pubmed.ncbi.nlm.nih.gov/23471753/)]
29. Nagappa M, Querney J, Martin J, John-Baptiste A, Subramani Y, Lanting B, et al. Perioperative satisfaction and health economic questionnaires in patients undergoing an elective hip and knee arthroplasty: a prospective observational cohort study. *Anesth Essays Res* 2021;15(4):413-438 [FREE Full text] [doi: [10.4103/aer.aer_5_22](https://doi.org/10.4103/aer.aer_5_22)] [Medline: [35422546](https://pubmed.ncbi.nlm.nih.gov/35422546/)]
30. OCC. Ontario Case Costing Initiative. URL: <http://www.occp.com/mainPage.htm?> [accessed 2015-07-18]
31. Teare MD, Dimairo M, Shephard N, Hayman A, Whitehead A, Walters SJ. Sample size requirements to estimate key design parameters from external pilot randomised controlled trials: a simulation study. *Trials* 2014;15(1):264 [FREE Full text] [doi: [10.1186/1745-6215-15-264](https://doi.org/10.1186/1745-6215-15-264)] [Medline: [24993581](https://pubmed.ncbi.nlm.nih.gov/24993581/)]
32. Viechtbauer W, Smits L, Kotz D, Budé L, Spigt M, Serroyen J, et al. A simple formula for the calculation of sample size in pilot studies. *J Clin Epidemiol* 2015;68(11):1375-1379. [doi: [10.1016/j.jclinepi.2015.04.014](https://doi.org/10.1016/j.jclinepi.2015.04.014)] [Medline: [26146089](https://pubmed.ncbi.nlm.nih.gov/26146089/)]
33. Lu K, Marino NE, Russell D, Singareddy A, Zhang D, Hardi A, et al. Use of short message service and smartphone applications in the management of surgical patients: a systematic review. *Telemed J E Health* 2018;24(6):406-414. [doi: [10.1089/tmj.2017.0123](https://doi.org/10.1089/tmj.2017.0123)] [Medline: [29111887](https://pubmed.ncbi.nlm.nih.gov/29111887/)]
34. Dawes AJ, Lin AY, Varghese C, Russell MM, Lin AY. Mobile health technology for remote home monitoring after surgery: a meta-analysis. *Br J Surg* 2021;108(11):1304-1314. [doi: [10.1093/bjs/znab323](https://doi.org/10.1093/bjs/znab323)] [Medline: [34661649](https://pubmed.ncbi.nlm.nih.gov/34661649/)]
35. Siddika A, Tolia-Shah D, Pearson TE, Richardson NGB, Ross AHM. Remote surveillance after colorectal cancer surgery: an effective alternative to standard clinic-based follow-up. *Colorectal Dis* 2015;17(10):870-875. [doi: [10.1111/codi.12970](https://doi.org/10.1111/codi.12970)] [Medline: [25851058](https://pubmed.ncbi.nlm.nih.gov/25851058/)]
36. Mangiameli G, Bottoni E, Tagliabue A, Giudici VM, Crepaldi A, Testori A, et al. Early hospital discharge on day two post-robotic lobectomy with telehealth home monitoring. *J Clin Med* 2024;13(20):13 [FREE Full text] [doi: [10.3390/jcm13206268](https://doi.org/10.3390/jcm13206268)] [Medline: [39458218](https://pubmed.ncbi.nlm.nih.gov/39458218/)]
37. Spaulding A, Loomis E, Brennan E, Klein D, Pierson K, Willford R, et al. Postsurgical remote patient monitoring outcomes and perceptions: a mixed-methods assessment. *Mayo Clin Proc Innov Qual Outcomes* 2022;6(6):574-583. [doi: [10.1016/j.mayocpiqo.2022.09.005](https://doi.org/10.1016/j.mayocpiqo.2022.09.005)] [Medline: [36304524](https://pubmed.ncbi.nlm.nih.gov/36304524/)]
38. Costantino ME, Frey B, Hall B, Painter P. The influence of a postdischarge intervention on reducing hospital readmissions in a Medicare population. *Popul Health Manag* 2013;16(5):310-316 [FREE Full text] [doi: [10.1089/pop.2012.0084](https://doi.org/10.1089/pop.2012.0084)] [Medline: [23537154](https://pubmed.ncbi.nlm.nih.gov/23537154/)]
39. Hu Y, McMurry TL, Isbell JM, Stukenborg GJ, Kozower BD. Readmission after lung cancer resection is associated with a 6-fold increase in 90-day postoperative mortality. *J Thorac Cardiovasc Surg* 2014;148(5):2261-2267.e1 [FREE Full text] [doi: [10.1016/j.jtcvs.2014.04.026](https://doi.org/10.1016/j.jtcvs.2014.04.026)] [Medline: [24823283](https://pubmed.ncbi.nlm.nih.gov/24823283/)]

40. Van Haren RM, Correa AM, Sepesi B, Rice DC, Hofstetter WL, Roth JA, et al. Hospital readmissions after pulmonary resection: post-discharge nursing telephone assessment identifies high risk patients. *J Thorac Dis* 2020;12(3):184-190 [FREE Full text] [doi: [10.21037/jtd.2020.02.08](https://doi.org/10.21037/jtd.2020.02.08)] [Medline: [32274083](https://pubmed.ncbi.nlm.nih.gov/32274083/)]
41. Varela G, Aranda JL, Jiménez MF, Novoa N. Emergency hospital readmission after major lung resection: prevalence and related variables. *Eur J Cardiothorac Surg* 2004;26(3):494-497. [doi: [10.1016/j.ejcts.2004.05.035](https://doi.org/10.1016/j.ejcts.2004.05.035)] [Medline: [15302041](https://pubmed.ncbi.nlm.nih.gov/15302041/)]
42. Gordon WJ, Henderson D, DeSharone A, Fisher HN, Judge J, Levine DM, et al. Remote patient monitoring program for hospital discharged COVID-19 patients. *Appl Clin Inform* 2020;11(5):792-801 [FREE Full text] [doi: [10.1055/s-0040-1721039](https://doi.org/10.1055/s-0040-1721039)] [Medline: [33241547](https://pubmed.ncbi.nlm.nih.gov/33241547/)]

Abbreviations

CN: clinical navigator

CONSORT: Consolidated Standards of Reporting Trials

CONSORT-EHEALTH: Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth

CTAS: Canadian Emergency Department Triage and Acuity Scale

DHM: digital home monitoring

ED: emergency department

HR: heart rate

NIBP: noninvasive blood pressure

QoR-40: 30-day quality of recovery

RCT: randomized controlled trial

REDCap: Research Electronic Data Capture

RR: readmission rate

SpO2: hemoglobin oxygen saturation

Edited by R Saffary; submitted 05.04.24; peer-reviewed by J Shiffermiller; comments to author 30.10.24; revised version received 11.11.24; accepted 05.01.25; published 12.02.25.

Please cite as:

Nagappa M, Subramani Y, Yang H, Wood N, Querney J, Fochesato LA, Nguyen D, Fatima N, Martin J, John-Baptiste A, Nayak R, Qiabi M, Inculet R, Fortin D, Malthaner R

Enhancing Quadruple Health Outcomes After Thoracic Surgery: Feasibility Pilot Randomized Controlled Trial Using Digital Home Monitoring

JMIR Perioper Med 2025;8:e58998

URL: <https://periop.jmir.org/2025/1/e58998>

doi: [10.2196/58998](https://doi.org/10.2196/58998)

PMID:

©Mahesh Nagappa, Yamini Subramani, Homer Yang, Natasha Wood, Jill Querney, Lee-Anne Fochesato, Derek Nguyen, Nida Fatima, Janet Martin, Ava John-Baptiste, Rahul Nayak, Mehdi Qiabi, Richard Inculet, Dalilah Fortin, Richard Malthaner. Originally published in *JMIR Perioperative Medicine* (<http://periop.jmir.org>), 12.02.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in *JMIR Perioperative Medicine*, is properly cited. The complete bibliographic information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Original Paper

Reducing Greenhouse Gas Emissions and Modifying Nitrous Oxide Delivery at Stanford: Observational, Pilot Intervention Study

Eric P Kraybill¹, BS; David Chen¹, MD; Saadat Khan¹, MEng; Praveen Kalra¹, MBBS, MD

Stanford Hospital, Stanford, CA, United States

Corresponding Author:

Praveen Kalra, MBBS, MD

Stanford Hospital

300 Pasteur Drive

Suite H3580

Stanford, CA, 94305

United States

Phone: 1 650 725 6412

Email: pkalra@stanford.edu

Abstract

Background: Inhalational anesthetic agents are a major source of potent greenhouse gases in the medical sector, and reducing their emissions is a readily addressable goal. Nitrous oxide (N₂O) has a long environmental half-life relative to carbon dioxide combined with a low clinical potency, leading to relatively large amounts of N₂O being stored in cryogenic tanks and H cylinders for use, increasing the chance of pollution through leaks. Building on previous findings, Stanford Health Care's (SHC's) N₂O emissions were analyzed at 2 campuses and targeted for waste reduction as a precursor to system-wide reductions.

Objective: We aimed to determine the extent of N₂O pollution at SHC and subsequently whether using E-cylinders for N₂O storage and delivery at the point of care in SHC's ambulatory surgery centers could reduce system-wide emissions.

Methods: In phase 1, total SHC (Palo Alto, California) N₂O purchase data for calendar year 2022 were collected and compared (volume and cost) to total Palo Alto clinical delivery data using Epic electronic health records. In phase 2, a pilot study was conducted in the 8 operating rooms of SHC campus A (Redwood City). The central N₂O pipelines were disconnected, and E-cylinders were used in each operating room. E-cylinders were weighed before and after use on a weekly basis for comparison to Epic N₂O delivery data over a 5-week period. In phase 3, after successful implementation, the same methodology was applied to campus B, one of 3 facilities in Palo Alto.

Results: In phase 1, total N₂O purchased in 2022 was 8,217,449 L (33,201.8 lbs) at a total cost of US \$63,298. Of this, only 780,882.2 L (9.5%) of N₂O was delivered to patients, with 7,436,566.8 L (90.5%) or US \$57,285 worth lost or wasted. In phase 2, the total mass of N₂O use from E-cylinders was 7.4 lbs (1 lb N₂O=247.5 L) or 1831.5 L at campus A. Epic data showed that the total N₂O volume delivered was 1839.3 L (7.4 lbs). In phase 3, the total mass of N₂O use from E-cylinders was 10.4 lbs or 2574 L at campus B (confirming reliability within error propagation margins). Epic data showed that the total N₂O volume delivered was 2840.3 L (11.5 lbs). Over phases 2 and 3, total use for campuses A and B was less than the volume of 3 E-cylinders (1 E-cylinder=1590 L).

Conclusions: Converting N₂O delivery from centralized storage to point-of-care E-cylinders dramatically reduced waste and expense with no detriment to patient care. Our results provide strong evidence for analyzing N₂O storage in health care systems that rely on centralized storage, and consideration of E-cylinder implementation to reduce emissions. The reduction in N₂O waste will help meet SHC's goal of reducing scope 1 and 2 emissions by 50% before 2030.

(*JMIR Perioper Med* 2025;8:e64921) doi:[10.2196/64921](https://doi.org/10.2196/64921)

KEYWORDS

anesthetic gases; emissions; green house gas; sustainability; pilot study; electronic health record; implementation; nitrous oxide; global warming

Introduction

Reducing greenhouse gas (GHG) emissions is a priority that must be addressed to reduce climate change and its negative impacts on earth and its inhabitants. The US Environmental Protection Agency (EPA) classifies GHG emissions into different categories, with scope 1 emissions defined as direct GHG emissions from sources that are controlled by organizations, including health care systems, and scope 2 emissions being indirect GHG emissions associated with the purchase of electricity, heat, steam, or cooling [1]. Stanford Health Care (SHC) has signed on to the US Department of Health and Human Services' pledge to reduce its scope 1 and 2 emissions by 50% by 2030 [2]. Within the medical sector, inhalational anesthetic gases that are directly released into the atmosphere are a major source of potent GHGs. Thus, there is a fertile opportunity to reduce GHGs by reducing the emission of anesthetic gases [3]. By collecting annual emissions data within the SHC system, improvements to sustainability and infrastructure could be explored.

Global warming potential (GWP) represents the energy a gas is able to absorb relative to carbon dioxide (CO₂), with a larger GWP representing increased planetary warming [4]. The environmental impacts of 2 inhaled anesthetic gases over a 100-year period (ie, global warming potential of GHGs over a 100-year period [GWP100]) are particularly relevant: desflurane, a volatile halogenated agent with particularly high GWP100 of 2540, and nitrous oxide (N₂O) with a lower GWP100 of 298 but used in much higher volumes than other anesthetic gases, and with longer half-life compared to CO₂, leading to lasting environmental consequences [5]. Further, because of its low clinical potency, large amounts of N₂O must be stored for use, increasing the chance of pollution through leaks. Centrally piped cryogenic liquid, centrally piped gas, and portable E-cylinders are the standard options for delivering N₂O [6]. Miles of pipes and innumerable valves in centrally piped systems lead to an abundance of leaks, contributing to excessive loss and waste [6]. While desflurane has already been discontinued from routine clinical use at SHC, we aimed to determine the degree to which N₂O emissions could be reduced and waste prevented, building on prior studies highlighting the waste of N₂O in other institutions [7].

Methods

Phase 1

To begin investigating N₂O emissions, purchase data (volume and cost) were collected and compared to total use data (clinical delivery) using the Epic SlicerDicer tool, part of the Epic electronic health record (EHR) [8]. Epic yearly clinical use data for N₂O are available per clinical service in the SHC's operating rooms. Gas losses in the system can be estimated by comparing documented gas delivery at the point of care with the volume of N₂O purchased. Initial data analysis revealed a drastic amount of lost N₂O, leading us to perform a pilot study (phase 2,

E-cylinder implementation) to enable remediation aimed at reducing N₂O emissions.

Phase 2

Using the Institute for Healthcare Improvement framework of "Plan, Do, Study, Act" for performance improvement [9], a pilot study was conducted in the 8 operating rooms of the SHC campus in Redwood City, California (campus A). E-cylinder canisters were deployed in each operating room and all central N₂O pipelines were disconnected. EHR documentation of gas delivered in liters (volume) was compared to measured E-cylinder mass. To verify use and track N₂O leaving each tank, the E-cylinders were weighed before and after use on a weekly basis with the difference in mass converted to volume (liters). Since the measured pressure remains the same as long as liquid remains in the cylinders, pressure differences cannot be used for measuring N₂O flow until only gas is left (at which point the pressure drop correlates with the amount of gas being removed) [10]. By using the conversion of 1 lb (0.45 kg) of N₂O being equal to 247.5 L [6], the volume of N₂O dispensed could be calculated. Total calculated volume leaving the E-cylinders based on measured mass was compared to total volume delivered according to Epic data.

Phase 3

Following the results of phase 2, a secondary study was conducted in 16 operating rooms at Blake Wilbur Drive Palo Alto, California (campus B). Phase 3 used the same methodology as phase 2 over a 3-week period.

Ethical Considerations

Due to the nature of the research and institutional approval, no IRB approval was necessary. No identifying patient data was used as we only measured nitrous oxide gas delivery and utilization.

Results

Phase 1

According to the Stanford Medicine Sustainability Program Office [2], the annual Palo Alto SHC 2022 Scope 1 emissions were 19,374 MTCO₂e (metric ton of CO₂ equivalent, the standard unit for comparing different GHGs to quantify their environmental impact and GWP) of which medical gases (including N₂O, CO₂, sevoflurane, and isoflurane) represented 4862 MTCO₂e. N₂O contributed 4590 MTCO₂e of the medical gases. Thus, medical gases account for 25.1% of all SHC scope 1 emissions, and N₂O alone accounts for 94.4% of those emissions (or 23.7% of the total).

Annual clinical usage of N₂O in 2022 per Epic data (Table 1) was 780,882.2 L (3155.1 lbs or 1431.1 kg), with the greatest use being for orthopedic surgery, general surgery, and neurosurgery cases. However, the total amount of N₂O purchased was 8,217,449 L (33,201.8 lbs or 15,060.1 kg), at a total cost of US \$63,298. Thus, only 9.5% of the total purchased N₂O was actually delivered to patients, and 90.5% (or US \$57,285 worth) was wasted.

Table 1. Annualized data comparing centralized N₂O system to hypothetical E-cylinders for Stanford Health Care (SHC; all campuses).

	Amount purchased (L)	Cost (US \$)	Amount used (L)	Amount lost as waste (L)
Centralized system	8,217,449	63,298	780,882.2	7,436,566.8
E-cylinders	780,882.2 ^a	6015	780,882.2	0 ^b

^aAmount needed to purchase with zero surplus based on use data under experimental conditions.

^bAnnualized E-cylinder data are extrapolated from experimental conditions; real-world conditions may vary.

With these data indicating a loss of greater than 90% between storage tanks and clinical use, a highly inefficient storage and pipeline system was recognized. The proposed solution (for phase 2 of the study) was to decommission the storage tanks and pipelines and switch to portable E-cylinders that stored and delivered N₂O at the point of care.

Phase 2

The change in mass of the E-cylinders indicated that N₂O use at campus A totaled 7.4 lbs (3.4 kg), or a volume of 1831.5 L, over the 5-week study period. Epic data showed total N₂O volume delivered to be 1839.3 L calculated to 7.4 lbs (3.4 kg; consistent with the measured 7.4 lbs). Using the standard of 1 E-cylinder=1590 L or 6.4 lbs (2.9 kg) [11], total use equaled 1.16 E-cylinders.

Phase 3

The E-cylinder change in mass indicated that N₂O use at campus B totaled 10.4 lbs (4.7 kg), or 2574 L, over the 3-week data collection period. Epic data showed total N₂O volume delivered to be 2840.3 L calculated to 11.5 lbs (5.2 kg; compared to the measured 10.4 lbs, which would be equivalent to 1.63 E-cylinders) [11].

Discussion

Principal Findings

Results from phase 1 corroborate findings from previous studies in the United Kingdom and Portland, Oregon [12,13], which reveal excessive waste from centralized storage of N₂O and pipe systems for delivery. Phases 2 and 3 of this study, from 2 different SHC campuses, demonstrate the efficient, cost-effective elimination of waste through substitution of E-cylinders with storage and delivery at the point of care. In phases 2 and 3, avoidable N₂O emissions were almost completely eliminated (Multimedia Appendix 1). The discrepancy between actual weighed N₂O and Epic-reported use for campus A was 7.8 L, or <0.1 lb (<0.1 kg). Campus B had a greater discrepancy with the difference in actual weighed N₂O and Epic-reported use being 266.3 L, or 1.1 lbs (0.45 kg). The amount of gas delivered according to the EHR was greater than the amount actually measured at the source, potentially accounted for by limited precision of the scales used to weigh

the E-cylinders (only to 0.1-lb increments), or accidental reconnection of N₂O pipelines in one operating room during phase 3. This issue was detected after 1 week and immediately rectified.

E-cylinders provide an efficient and effective solution, but they hold limitations. E-cylinders must be stored properly to ensure that they do not present a catalyst in the event of a fire [14]. However, no policy implementation is required as E-cylinders are already in use in operating rooms and costs associated with storage can be offset by the N₂O saved. Ready accessibility, lower cost, reduced supply chain issues, and efficiency of E-cylinders far outweigh the abovementioned disadvantages.

Limitations

The limitations of this study include the fact that real-world use and waste may vary from our experimental conditions, likely incurring greater losses. If e-cylinder valves are accidentally left open, losses may simulate those from centralized pipelines until the valve is closed [6] or the E-cylinder is emptied. The amount of N₂O to be purchased would need to be greater than the amount used in our example (Table 1), to provide surplus in the E-cylinders as well as spare E-cylinders. Prospective estimates of volume when making a purchase order would likely exceed actual use. Both recording and documentation of N₂O readings and the scale measurements are susceptible to error.

Conclusions

Converting the delivery of N₂O from centralized storage to point-of-care E-cylinders has dramatically reduced waste and expense with no detriment to patient care. Stanford's pledge to reduce scope 1 and 2 emissions by 50% can be achieved and even surpassed if this practice is changed in all SHC locations. The introduction of E-cylinders will provide a nondisruptive means for immediately decreasing emissions while continuing to provide optimal anesthetic care. Pilot studies throughout Stanford's campuses continue, with the goal of removing the centralized N₂O system and switching to E-cylinders at other sites, thereby significantly reducing anesthetic GHG emissions. Efforts to reduce GHG emissions may begin locally but have applications globally. Reducing the anesthetic carbon footprint of health care organizations is necessary for our planet and can begin with the reduction of wasteful emissions.

Acknowledgments

We would like to acknowledge the Stanford Sustainability Planning Office for their support throughout the project.

Authors' Contributions

EPK conducted the data analysis and drafted and edited the manuscript. DC conducted the data analysis and edited the manuscript. SK collected and analyzed the data. PK conceptualized the study, conducted and analyzed the data, and edited the manuscript. PK and SK (SaadatKhan@stanfordhealthcare.org) are co-corresponding authors.

Conflicts of Interest

PK is an associate editor for *JMIR Perioperative Medicine*.

Multimedia Appendix 1

Reduction in N₂O emissions per metric ton of CO₂ equivalents by switching from the original central supply to portable supply E-cylinder storage.

[PNG File, 58 KB - [periop_v8i1e64921_app1.png](#)]

References

1. Scope 1 and Scope 2 Inventory Guidance. United States Environmental Protection Agency. 2020. URL: <https://www.epa.gov/climateleadership/scope-1-and-scope-2-inventory-guidance> [accessed 2024-12-16]
2. Stanford Medicine. Our Sustainability Commitment. Stanford Health Care. URL: <https://stanfordhealthcare.org/sustainability-program-office/sustainability-program-office/what-we-do/our-sustainability-commitment.html> [accessed 2024-12-16]
3. Chesebro BB, Gandhi S. Mitigating the systemic loss of nitrous oxide: a narrative review and data-driven practice analysis. *Br J Anaesth* 2024 Dec;133(6):1413-1418. [doi: [10.1016/j.bja.2024.08.028](https://doi.org/10.1016/j.bja.2024.08.028)] [Medline: [39322471](https://pubmed.ncbi.nlm.nih.gov/39322471/)]
4. Understanding Global Warming Potentials. United States Environmental Protection Agency. 2016. URL: <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials> [accessed 2024-12-16]
5. Sulbaek Andersen MP, Nielsen OJ, Wallington TJ, Karpichev B, Sander SP. Medical intelligence article: assessing the impact on global climate from general anesthetic gases. *Anesth Analg* 2012 May;114(5):1081-1085. [doi: [10.1213/ANE.0b013e31824d6150](https://doi.org/10.1213/ANE.0b013e31824d6150)] [Medline: [22492189](https://pubmed.ncbi.nlm.nih.gov/22492189/)]
6. Collaborating to prevent nitrous oxide waste in medical gas systems. Practice Greenhealth. URL: <https://practicegreenhealth.org/tools-and-resources/collaborating-prevent-nitrous-oxide-waste-medical-gas-systems> [accessed 2024-12-16]
7. Seglenieks R, Wong A, Pearson F, McGain F. Discrepancy between procurement and clinical use of nitrous oxide: waste not, want not. *Br J Anaesth* 2022 Jan;128(1):e32-e34 [FREE Full text] [doi: [10.1016/j.bja.2021.10.021](https://doi.org/10.1016/j.bja.2021.10.021)] [Medline: [34802695](https://pubmed.ncbi.nlm.nih.gov/34802695/)]
8. Our Software. Epic Systems Corporation. URL: <https://www.epic.com/software/> [accessed 2024-12-16]
9. How to Improve: Model for Improvement. Institute for Healthcare Improvement. URL: <https://www.ihc.org/resources/how-to-improve> [accessed 2024-12-16]
10. Medical Gases: Storage and Supply. Anesthesia Key. 2019. URL: <https://aneskey.com/medical-gases-storage-and-supply-2/> [accessed 2024-12-16]
11. Rose G, McLarney J. Pneumatic Systems. In: *Anesthesia Equipment Simplified*. New York, NY: McGraw-Hill Education; 2014.
12. Devlin-Hegedus JA, McGain F, Harris RD, Sherman JD. Action guidance for addressing pollution from inhalational anaesthetics. *Anaesthesia* 2022 Sep 21;77(9):1023-1029 [FREE Full text] [doi: [10.1111/anae.15785](https://doi.org/10.1111/anae.15785)] [Medline: [35729804](https://pubmed.ncbi.nlm.nih.gov/35729804/)]
13. Sherman J. It's time hospitals abandon nitrous oxide pipes. *ASA Monitor* 2024;88:33 [FREE Full text] [doi: [10.1097/01.ASM.0001006828.24359.cd](https://doi.org/10.1097/01.ASM.0001006828.24359.cd)]
14. Nitrous oxide. CAMEO Chemicals. URL: <https://cameochemicals.noaa.gov/chemical/8909#:~:text=It%20is%20noncombustible%20but%20it,to%20rupture%20violently%20and%20rocket> [accessed 2024-12-11]

Abbreviations

EHR: electronic health record
EPA: Environmental Protection Agency
GHG: greenhouse gas
GWP: global warming potential
GWP100: global warming potential of GHGs over a 100-year period
MTCO₂e: metric ton of carbon dioxide equivalent
N₂O: nitrous oxide
SHC: Stanford Health Care

Edited by T Aslanidis; submitted 09.08.24; peer-reviewed by A Maleki, LM Western; comments to author 07.10.24; revised version received 27.11.24; accepted 02.12.24; published 09.01.25.

Please cite as:

Kraybill EP, Chen D, Khan S, Kalra P

Reducing Greenhouse Gas Emissions and Modifying Nitrous Oxide Delivery at Stanford: Observational, Pilot Intervention Study

JMIR Perioper Med 2025;8:e64921

URL: <https://periop.jmir.org/2025/1/e64921>

doi: [10.2196/64921](https://doi.org/10.2196/64921)

PMID:

©Eric P Kraybill, David Chen, Saadat Khan, Praveen Kalra. Originally published in JMIR Perioperative Medicine (<http://periop.jmir.org>), 09.01.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in JMIR Perioperative Medicine, is properly cited. The complete bibliographic information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Original Paper

A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study

Daan Toben^{1,2}, MSc; Astrid de Wind^{2,3}, PhD; Eva van der Meij^{2,3}, PhD; Judith A F Huirne^{2,4}, PhD; Johannes R Anema^{1,2}, PhD

¹Department of Public and Occupational Health, Amsterdam UMC location Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

²Societal Participation & Health, Amsterdam Public Health research institute, Amsterdam, The Netherlands

³Department of Public and Occupational Health, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

⁴Department of Obstetrics and Gynaecology, Amsterdam UMC location University of Amsterdam, Amsterdam, The Netherlands

Corresponding Author:

Daan Toben, MSc

Department of Public and Occupational Health

Amsterdam UMC location Vrije Universiteit Amsterdam

Van der Boechorststraat 7

Amsterdam, 1081 BT

The Netherlands

Phone: 31 647861694

Email: d.j.toben@amsterdamumc.nl

Abstract

Background: Day surgery is being increasingly implemented across Europe, driven in part by capacity problems. Patients recovering at home could benefit from tools tailored to their new care setting to effectively manage their convalescence. The mHealth application ikHerstel is one such tool, but although it administers its functions in the home, its implementation hinges on health care professionals within the hospital.

Objective: We conducted a feasibility study of an additional patient-oriented implementation strategy for ikHerstel. This strategy aimed to empower patients to access and use ikHerstel independently, in contrast to implementation as usual, which hinges on the health care professional acting as gatekeeper. Our research question was “How well are patients able to use ikHerstel independently of their health care professional?”

Methods: We investigated the implementation strategy in terms of its recruitment, reach, dose delivered, dose received, and fidelity. Patients with a recent or prospective elective surgery were recruited using a wide array of materials to simulate patient-oriented dissemination of ikHerstel. Data were collected through web-based surveys. Descriptive analysis and open coding were used to analyze the data.

Results: Recruitment yielded 213 registrations, with 55 patients ultimately included in the study. The sample was characterized by patients undergoing abdominal surgery, with high literacy and above average digital health literacy, and included an overrepresentation of women (48/55, 87%). The implementation strategy had a reach of 81% (63/78), with 87% (55/67) of patients creating a recovery plan. Patients were satisfied with their independent use of ikHerstel, rating it an average 7.0 (SD 1.9) of 10, and 54% (29/54) of patients explicitly reported no difficulties in using it. A major concern of the implementation strategy was conflicts in recommendations between ikHerstel and the health care professionals, as well as the resulting feelings of insecurity experienced by patients.

Conclusions: In this small feasibility study, most patients were satisfied with the patient-oriented implementation strategy. However, the lack of involvement of health care professionals due to the strategy contributed to patient concerns regarding conflicting recommendations between ikHerstel and health care professionals.

(*JMIR Perioper Med* 2025;8:e58878) doi:[10.2196/58878](https://doi.org/10.2196/58878)

KEYWORDS

perioperative care; recovery; feasibility; convalescence; patient-oriented; surgery; perioperative; eHealth; mHealth; tailor; customize; patient care; digital intervention; health intervention; patient education; surgical care; hospital care; digital health; perioperative medicine; elective surgery; technology; caregiver; mobile app; digital care

Introduction

Day surgery—defined as admittance to and discharge from a hospital within 24 hours following surgery—has seen a marked increase in Organisation for Economic Co-operation and Development member countries over the past decades [1]. The appeal of day surgery derives from multiple factors, including its reduced cost, decreased morbidity and mortality, and high levels of patient satisfaction [2-6]. When it comes to postsurgical recovery, however, the reports are more nuanced. Tran et al [7] showed how 1 in 3 patients exhibit suboptimal recovery trajectories following day surgery. Patients recovering at home describe feelings of insecurity, an experience moderated by the timely provision of information, professional support, and expectation management [4,8-12]. mHealth interventions have been shown to be effective when it comes to targeting these domains and their use in the perioperative setting is well appreciated by patients [13,14]. In the Netherlands specifically, the Patient Journey app has been shown to improve postoperative outcomes for patients with musculoskeletal disorders [15].

Similarly, the mHealth intervention ikHerstel (meaning “I recover” in Dutch) is a tool designed to support patients undergoing abdominal surgery during their perioperative period. The intervention’s ability to speed up postoperative recovery, reduce pain, and improve patients’ quality of life has been established in previous studies [12,16-18]. However, its implementation occurs on the level of the hospital ward, and it hinges on the involvement of health care professionals within the ward, who act as both distributors of the intervention and instructors of patients. This strategy features benefits as well as challenges: health care professionals are well situated to select eligible patients and can improve adherence to treatment when they use effective communication strategies [19,20]. However, at the time of publishing, the intervention has been implemented in only 10% of hospitals in the Netherlands. Wider implementation is hampered by, among other factors, financial barriers present in the Dutch health care system that make upscaling of telemonitoring interventions in general a difficult enterprise [21]. This limits ikHerstel’s reach, leaving patients bereft of its aforementioned benefits.

In this feasibility study, we explored a patient-oriented implementation strategy for ikHerstel that aimed to circumvent this hospital-level barrier by targeting patients directly. If successful, this strategy could operate in addition to implementation as usual, with reimbursement flowing from health insurers to patients. We therefore aimed to evaluate whether it would be successful in increasing the intervention’s reach and whether patients, once reached, were able to use ikHerstel independently from their health care professional.

Methods

Ethical Considerations

Approval for the study was granted by the medical ethics committee of Amsterdam University Medical Center on May 31, 2022 (2022.0224). Informed consent was obtained through postal mail and patients were informed of their ability to opt

out of participation in the study at any time. Patients were provided with access to ikHerstel free of charge but were not offered any remuneration for their participation in the study. Data were deidentified by the coordinating researcher, and patients were labeled using random strings. The patient identification keys were kept in a separate location from the data.

Study Setting

We conducted a prospective study assessing the feasibility of a patient-oriented implementation strategy for the ikHerstel mHealth intervention. Our assessment was performed based on the model of Steckler and Linnan [22]; its outcomes were reach, dose delivered, dose received, fidelity, and recruitment. In consultation with health insurers and a patient interest group, we aimed to include 100 perioperative patients representing the theoretical user base of the ikHerstel app, that is, any patients who were theoretically able to access the app and use it in such a way as to manage their own recovery, regardless of age, gender, nationality, literacy, digital literacy, or health literacy. Recruitment started in September 2022 and lasted through September 2023.

Inclusion and Exclusion Criteria

Patients were eligible for inclusion if they were older than 18 years, proficient in the Dutch language, and prospective recipients of one of the following elective surgical procedures: laparoscopic or abdominal hysterectomy, laparoscopic cholecystectomy, open or laparoscopic inguinal hernia surgery, or laparoscopic adnexal surgery. Patients were excluded if the date of their surgery was ≥ 14 days prior to inclusion, they were undergoing a combination of surgeries, they had comorbidities that invalidated the convalescence recommendations provided by ikHerstel, they were undergoing oncological surgery, or they were receiving care from a hospital that had already implemented ikHerstel.

Intervention and Procedure

ikHerstel was developed in collaboration with health care professionals of a diverse background. Its development process has been described previously [23]. An overview of the current functions and layout of ikHerstel is provided in [Multimedia Appendix 1](#). Its aim is to prepare patients and manage their expectations preoperatively and to support them in recovery of the daily functions of life postoperatively [23]. Each patient received the ikHerstel intervention in addition to usual care. Patients were able to interact with the intervention in the form of a mobile app, which they used up to the point of their total recovery. They were provided with personal accounts in which they constructed their recovery plan through goal attainment by selecting 8 personal activities from a list of 31 to constitute their most important recovery goals. In this way, one patient might create a plan focused on performing tasks around the house while another might create one centered on regaining the ability to run long distances. Patients monitored their recovery plan through the mobile app: they were asked to indicate when they were able to perform each of the activities in their plan. The total postoperative recovery was visible as a percentage within the app. Additionally, educational material about recovery

was provided to patients in the form of text and video animations through the app's library screen.

Implementation Strategy as Usual

In its current form, ikHerstel's implementation strategy hinges on health care professionals, who recruit eligible patients, introduce them to the app and its potential benefits, and provide them with access by creating a personal account. This final step is particularly crucial, as patients cannot access ikHerstel without an account, and health care professionals preload each account with recovery-related data specific to the patient's surgical procedure. Implementation occurs at the level of the hospital ward. A medical liaison associated with ikHerstel trains the ward's staff in the app's use and goals and in carrying out support tasks like creating patient accounts. The hospital ward is also provided with a web portal that mediates these administrative functions, allows for monitoring of each patient's recovery, and provides health care professionals with organizational support.

Patient-Oriented Implementation Strategy

The patient-oriented implementation strategy piloted in this study circumvented health care professionals, relying instead on patients to sign up and use ikHerstel independently. Health care professionals did not have access to the app or the web portal. Instead, these responsibilities were assigned to the coordinating researcher as a placeholder for the support staff of the ikHerstel spinoff company. During the course of the study, the coordinating researcher created patients' accounts and loaded

them with surgery-related data based on information provided by the patients. Patient monitoring through the web portal was not performed. In case of questions concerning ikHerstel, patients were directed to the coordinating researcher, whose contact details were provided. Patients with medical questions were directed by the researcher to consult their health care professional. This highlights the key role still reserved for health care professionals in this patient-oriented implementation, as they retained responsibility for care of their patients, including monitoring for adverse outcomes. Accordingly, patients were informed that their health care professional held final authority over the content and provision of care. Figure 1 illustrates the differences between the implementation strategies. Table 1 presents an overview of the recruitment tools that were used, distinguishing between hospital-independent and -dependent tools.

With the exception of the magazine advertisements, all advertisements followed the same basic design, created with low-literacy patients in mind. An example is provided in Multimedia Appendix 2. These materials were distributed to patients in hospitals, on patient fora, on webpages of patient interest groups, in patient magazines, through internet search engine advertisements, and within patient groups on social media. Each advertisement linked to a web portal where patients were informed of the study and asked to leave their contact details. Patients were subsequently contacted via telephone by the coordinating researcher, who provided further information and performed screening on the basis of the inclusion and exclusion criteria.

Figure 1. Schematic representation of the differences between implementation as usual and the patient-oriented implementation.

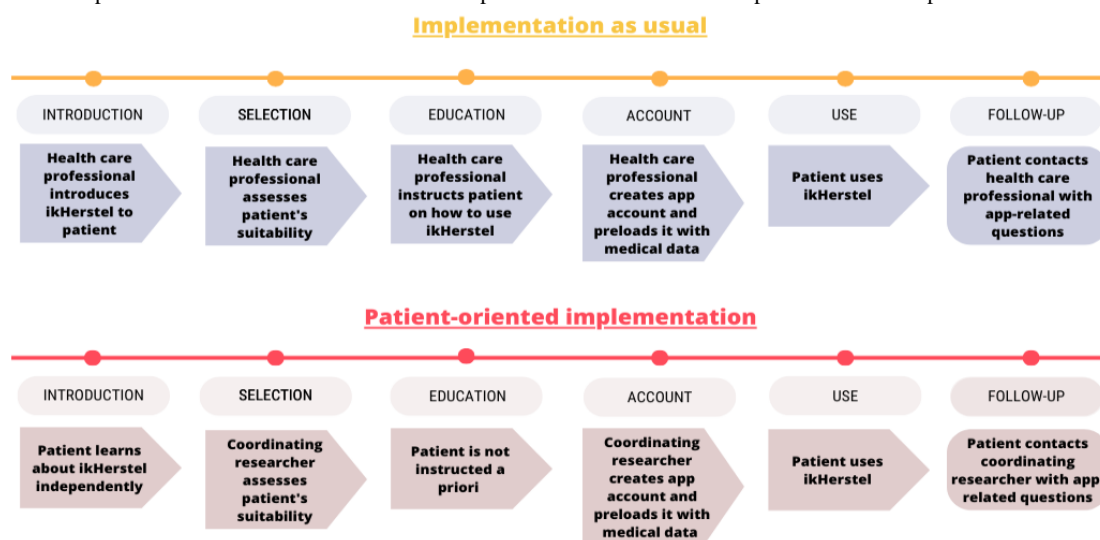


Table 1. Materials used for study recruitment and the frequency of their use, split into hospital-dependent and -independent tools.

Materials	Frequency of use, n
Hospital-independent	
Forum advertisements	15
Webpage advertisements	2
Internet search engine advertisements	1
Social media advertisements	4
Magazine advertisements	2
Hospital-dependent	
Flyers	11
Posters	10
Business cards	6
Electronic displays	5
Hospital staff	2

Data Collection

Data were collected through a set of 4 digital surveys constructed, distributed, and maintained through Survalyzer (Survalyzer AG). A baseline survey (T_0) was used to collect demographic data. Follow-up surveys were distributed to patients at T_1 (3 weeks), T_2 (6 weeks), and T_3 (12 weeks) after surgery to collect data on the user experience.

Background Factors and Implementation Outcomes

Demographic data included socioeconomic factors like age, sex, and education level, which is aligned with a previous study by van der Meij et al [24]. Demographics also included a measure of patients' traditional literacy, operationalized on the basis of the Diagnostic Illiteracy Scale, where a score of 14 points or higher constitutes a risk of the individual being illiterate [25]. Digital literacy was operationalized using patient self-assessment and a scanning tool (Quickscan) developed for physicians by the Dutch patient advocate organization Pharos, which characterizes patients as digitally unskilled with a score of 10 points or higher [26].

The model by Steckler and Linnan [22], commonly used in public health, describes the evaluation of implementation outcomes as a concatenated appraisal of an intervention's context, reach, dose delivered, dose received, fidelity, and recruitment. Operationalization of these outcomes was performed similarly to previous process evaluations of ikHerstel to facilitate comparison [24,27]. We omitted the aspect of fidelity, as the app does not deviate from protocol in its delivery

of the intervention. We also omitted context, as this is described in earlier publications, as well as the aspect of implementation, as we judged its transformation of the other aspects into a summative score to be a bad fit for our study. We also evaluated the recruitment tools and their channels (hospital dependent vs independent) in terms of their effectiveness in recruiting eligible patients to use the app. To compute this count, we asked patients to state how they were informed about the study.

We measured patient attitudes in alignment with the patient-oriented character of the implementation strategy and for comparison with previous research [24,27]. We operationalized patient attitudes as patients' self-reported satisfaction rating and their experienced barriers to use. We additionally measured patient attitudes using the unified theory of acceptance and use of technology 2 (UTAUT2), developed by Venkatesh et al [28]. Briefly, this framework describes an individual's intention to use a technology as being determined by 7 constructs: performance expectancy, effort expectancy, social influence, facilitating conditions, hedonic motivation, price value, and habit. Social influence and hedonic motivation were deemed less relevant to ikHerstel's context and thus were not included. Relevant UTAUT2 survey items were selected by the researchers, adapted to the research context, and translated into Dutch. Response categories followed a 4-point Likert scale centered on agreement. The resultant survey is provided in [Multimedia Appendix 3](#). A full overview of the study's outcomes and their operationalization is presented in [Table 2](#).

Table 2. Operationalization of implementation outcomes and patient attitudes.

	Description	Operationalization
Implementation outcomes^a		
Reach	The proportion of the intended target audience that participated in the study	Numerator: number of patients who met the inclusion criteria and signed an informed consent form; denominator: number of patients who met the inclusion criteria, regardless of their eventual participation in the study
Dose delivered	The number or amount of intended units of the intervention provided to the study population	Numerator: number of patients who were provided with an account for the ikHerstel app; denominator: number of patients who met the inclusion criteria and signed an informed consent form
Dose received	The extent to which participants actively engaged with, interacted with, were receptive to, or used the intervention	Numerator: number of patients who activated their ikHerstel account, created a recovery plan, and used the app on a weekly basis; denominator: number of patients who were provided with an account for the ikHerstel app
Recruitment	The effectiveness of the procedures used to attract participants	An appraisal of the effectiveness of each recruitment medium (hospital dependent vs independent) and tool in terms of the number of inclusions versus registrations they produced
Patient attitudes		
Patient satisfaction	__ ^b	Patient satisfaction, assessed through a self-reported score between 0 and 10
Barriers to use	—	Five open questions: <ul style="list-style-type: none"> • What did you like about using ikHerstel? • What makes using ikHerstel easy? • What did you dislike about using ikHerstel? • What makes using ikHerstel difficult? • Do you have any other comments about the ikHerstel app?
Performance expectancy ^c	The degree to which using the technology will provide benefits to consumers	The degree to which patients view ikHerstel as being able to beneficially affect their postsurgical recovery; operationalized as 3 self-reported items, scored using a 1-4 Likert scale
Effort expectancy ^c	The degree of ease associated with consumers' use of the technology	The degree to which patients feel using ikHerstel is simple and straightforward; operationalized as 3 self-reported items, scored using a 1-4 Likert scale
Facilitating conditions ^c	Consumers' perceptions of the resources and support available to perform a behavior	The degree to which patients feel they are supported in their use of ikHerstel; operationalized as 2 self-reported items, scored using a 1-4 Likert scale
Price value ^c	Consumers' cognitive tradeoff between the perceived benefits of the technology and the monetary cost for using it	The degree to which patients are willing to pay for their use of ikHerstel; operationalized as 1 self-reported item, scored using a 1-4 Likert scale
Habit ^c	The extent to which consumers tend to perform behaviors automatically because of learning	The degree to which patients feel their use of ikHerstel has become habitual; operationalized as 1 self-reported item, scored using a 1-4 Likert scale

^aBased on the model by Steckler and Linnan [22].

^bNot applicable.

^cBased on the unified theory of acceptance and use of technology 2 by Venkatesh et al [28].

Data Analysis

Descriptive statistics were used to summarize the study's findings according to each process outcome as well as the UTAUT2 dimensions. Open-ended patient attitude items were assessed and categorized by the coordinating researcher, and the resultant categories were subsequently reviewed by another researcher from the research team.

Results

Reach

In the period between September 2022 and September 2023, 216 patients registered for the study. A schematic representation of the inclusion process is presented in [Figure 2](#). Initial screening via telephone resulted in 148 exclusions. A major reason for exclusion was timing, as many patients only signed up for ikHerstel once their surgery had already taken place. The exclusion criteria were revised to account for this unexpected result, allowing patients to participate up to 14 days following their surgery. This nevertheless still led to 42 exclusions due to

timing. A total of 68 patients were identified as eligible for participation and were subsequently sent informed consent forms. Among these 42 patients, 5 were excluded due to incompatible types of surgery that had not been identified as such prior to telephone screening. This resulted in a total of 63 included patients, which constitutes a reach of 81% ($63 / (216 - (109 + 5 + 24))$).

Baseline characteristics of these respondents are presented in [Table 3](#). A majority of respondents were female, corresponding

to one half of the included surgery types being gender specific for women. All the respondents had Dutch nationality and close to two-thirds (35/55) had a high level of education. All patients scored full points on the Quickscan test, and only one respondent gave a categorical self-description as being not very digitally skilled. The same held true for traditional literacy, with none of the respondents scoring in a range that would put them at risk of having low literacy skills [29].

Figure 2. Flow chart for inclusion in the study.

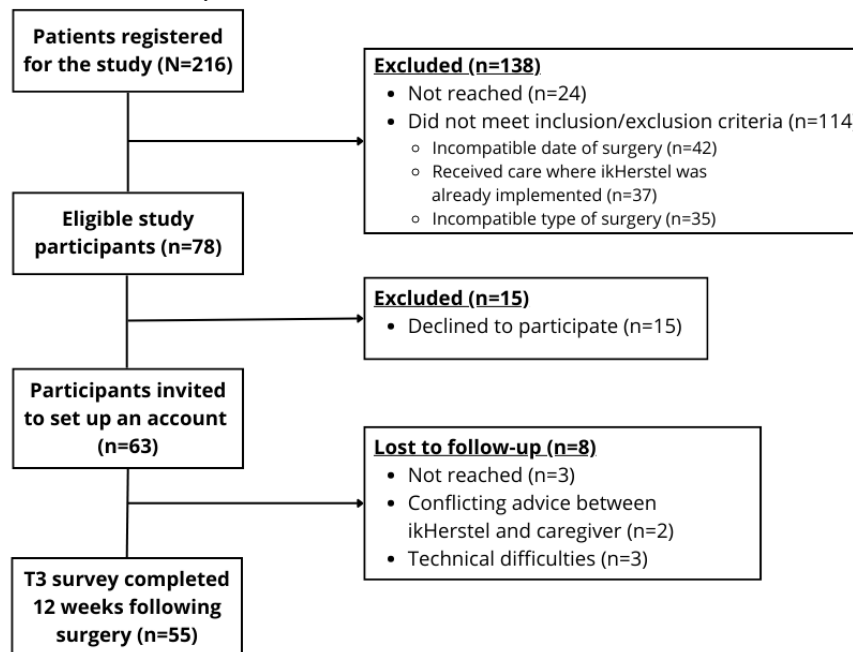


Table 3. Sample characteristics (n=55).

Variables	Values
Age (years), mean (SD)	48.6 (12.4)
Sex, n (%)	
Male	7 (13)
Female	48 (87)
Nationality, n (%)	
Dutch	55 (100)
Education, n (%)	
Low	7 (13)
Intermediate	13 (24)
High	35 (64)
Type of surgery, n (%)	
Laparoscopic uterus extirpation	21 (38)
Abdominal uterus extirpation	8 (15)
Vaginal uterus extirpation	6 (11)
Laparoscopic adnexal surgery	5 (9)
Laparoscopic cholecystectomy	10 (18)
Laparoscopic inguinal hernia surgery	4 (7)
Open inguinal hernia surgery	1 (2)
Digital skills—Quickscan, mean (SD)	6 (0)
Digital skills—self-scan (categorical), n (%)	
Very digitally skilled	29 (53)
Of average skill	25 (46)
Not or not very digitally skilled	1 (2)
Digital skills—self-scan (numeric), mean (SD)	7.9 (1.5)
Literacy score, mean (SD)	8.5 (2.6)

Dose Delivered

Of the 63 patients who signed the informed consent form and met the inclusion and exclusion criteria, 63 were provided with an account in the ikHerstel app. The dose-delivered fraction therefore computes to a percentage of 100%.

Dose Received

Of the 63 patients who were provided with an account, 55 activated their account and created a personalized recovery plan. Of these 55 patients, 34 reported using the app on a weekly or

more frequent basis. The dose received fraction (34/63) therefore computes to a percentage of 54%.

Recruitment

An overview of the number of registrations and inclusions per recruitment tool is provided in [Table 4](#). Most of the registrations (87/216, 40%) originated from tools that were dependent on hospitals, like posters, waiting room electronic displays, and hospital staff. Tools outside of the hospital yielded 36% (77/216) of registrations. However, they yielded more eligible patients (32 vs 31), as well as a higher proportion of eligible patients (32/77) compared to hospital-dependent tools (31/87).

Table 4. Overview of the number of registrations and eligible patients per recruitment tool.

Tools	Registrations, n (N=216)	Eligible patients, n (n=63)
Hospital-independent		
Forum advertisements	14	8
Webpage advertisements	1	0
Internet search	17	7
Social media	18	13
Magazine advertisements	21	2
Other ^a	6	2
Subtotal	77	32
Hospital-dependent		
Flyers	11	6
Posters	10	6
Business cards	2	2
Electronic displays	11	7
Hospital staff	24	8
Unspecified ^b	27	0
Other ^c	2	2
Subtotal	87	31
Unknown ^d	52	0

^aThis category included person-to-person contacts (n=5) and receiving an email of unknown origin (n=1).

^bThese respondents stated that the hospital was the source of their contact with ikHerstel.

^cThis category included patient-to-patient contacts in the convalescence room (n=1) and the webpage of the hospital (n=1).

^dThese respondents did not state how they came into contact with ikHerstel, mostly due to a lack of communication or stated interest on their part.

Patient Attitudes

Patients rated their overall satisfaction with ikHerstel an average 7.0 (SD 1.9) of 10. One patient did not answer the open-ended questions. A substantial proportion of patients (14/54) explicitly stated not having any dislikes about using ikHerstel, and an even greater proportion (29/54) explicitly reported no difficulties in using it. Most patients (49/54) reported positive experiences with ikHerstel. The most frequently stated (17/49) positive experience with ikHerstel related to its provision of perspective when it came to recovery. Patients furthermore found the app was clear in its presentation of information (10/49) and easy to use (8/46). Other stated likes related to the app's motivating power (6/49), its function as a source of information (3/49), its comforting effect (2/49), the patients' ability to benchmark their recovery (2/49), and a general statement of satisfaction (1/49). A majority of patients (50/54) reported on aspects that made using ikHerstel easy. The most frequently stated aspect was its clarity in presenting information (23/50). Patients also found it easy to navigate through the app (20/50) and praised its round-the-clock availability as a mobile phone app (6/50). One patient simply affirmed its ease of use, and others (4/50) found nothing about it easy. One patient stated, "Easy to use and provides motivation to start exercising and pick up activities again."

The most striking dislikes reported by patients were those concerning its recommendations. In some cases, what the app prescribed was misaligned with what patients felt they could handle. This mismatch ran both ways, as some patients felt the app was too ambitious, while others reported it was holding them back: "...that you [ikHerstel] go much faster than my recovery. That feels like failure because it repeatedly says you are behind on your recovery. It became more and more frustrating."

Another frequently stated mismatch was between ikHerstel and health care professionals. Of the 45 patients who reported receiving recovery recommendations from their health care professional, 33 stated that the recommendations provided by ikHerstel conflicted "sometimes" or more frequently. The majority of these (n=17) described the health care professional as conservative when it came to performing activities compared to the app. Others (n=8) reported that the app's recommendations were more elaborate and covered a wider slice of their daily life. Some patients (n=6) explicitly stated a dislike of the mismatch. In these cases as well, health care professionals' prescriptions were more conservative, and as a result, these patients reported feelings of frustration and insecurity: "[T]he recommendations from both the hospital and the GP [general practitioner]'s assistant were so much more conservative regarding when you should try and pick up activities that it made me feel insecure."

Other dislikes related to difficulties with inputting data (n=14), a lack of personalization (n=7), a lack of functionalities (n=5), the demotivating effect of the app (n=3), accessibility (n=1), technical failures (n=1), and miscellaneous difficulties (n=3); 14 patients found nothing to dislike. One patient stated, "After altering one of the activities, I had to redo all the input I had previously provided."

UTAUT2 Dimensions

Among UTAUT2 survey dimensions, respondents rated their performance expectancy an average of 2.7 (SD 0.8) of 4 points. Effort expectancy was rated at 3.3 (SD 0.8) of 4 points and facilitating conditions at 3.4 (SD 0.7) of 4 points. The dimension of price value was scored an average 1.7 (SD 0.7) of 4 points, corresponding to 6 of 55 patients confirming that they would be agreeable to paying for the services provided by ikHerstel. A substantial proportion of patients (20/52) stated their use of ikHerstel had become habitual, resulting in an average score of 2.3 (SD 0.9) of 4 points for the dimension of habit.

Discussion

Principal Findings

In this feasibility study, we aimed to evaluate a patient-oriented implementation strategy for the mHealth intervention ikHerstel. We included 55 patients undergoing abdominal surgery among 216 registrations, and we investigated whether direct distribution of ikHerstel was a feasible addition to its implementation through hospitals. Hospital-dependent recruitment yielded slightly more registrations, while hospital-independent recruitment produced more eligible patients. The patient-oriented strategy constituted a reach of 81% (63/78), and 100% of reached patients were sent the intervention, after which 54% (34/63) engaged with it. Patients reported general satisfaction with ikHerstel, scoring it an average 7.0 (SD 1.9) of 10 points.

Other studies have examined user experiences with mHealth apps in the perioperative setting. To illustrate, a cross-sectional study on the Patient Journey app yielded higher levels of satisfaction compared to this study [15]. Patients were likewise positive about the app's ease of use and its clear provision of useful information. A systematic review of patient experiences with mHealth confirms that this is a main benefit of these interventions [13]. The finding that patients regretted losing the possibility of communicating with their health care professional through the app was not replicated in our study. A previous process evaluation concerning a version of ikHerstel that did feature this function found that patients appreciated it, but that it should not replace a telephone appointment with their health care professional [24].

We hypothesized that the patient-oriented implementation strategy would increase ikHerstel's reach. However, in terms of absolute scale, this expectation proved incorrect. Over the span of a year, only 216 registrations were generated, compared to the 1031 and 673 reported in previous studies, where hospitals played a central role in recruitment through their waiting lists [24,27]. Despite lower registration numbers, the reach of the patient-oriented implementation strategy was better, or at least comparable to, previous studies, at 81%, compared to 40% and

60%, respectively [24,27]. In addition to scale, an advantage of recruitment through hospitals was apparent when comparing the rate of and reasons for exclusion. Only 5% of patients were excluded due to ineligibility in the study by van der Meij et al [24], compared to our study's exclusion rate of 53%. Poor timing (n=42, 37%), double registration (n=37, 32%), and ineligible types of surgery (n=35, 31%) make up the reasons for exclusion. In fact, poor timing proved such a barrier to participation that we were forced to revise our exclusion criteria halfway through the study to include patients up to 14 days after their surgery. Our assumption that patients would start looking for tools to support them through their perioperative journey prior to surgery proved false. In practice, this means that a substantial proportion of patients missed out on ikHerstel's preoperative functions designed to enhance preparation and manage expectations.

The mismatch between ikHerstel's recommendations and those of health care professionals also points to the strategic position of these professionals in perioperative care. Patients listed this mismatch not only as a source of dislike but also as one of feelings of insecurity. Other studies have reported similar findings [13,15]. The conflict itself may arise due to the conservative character of many health care professionals, as some studies indicate [30,31]. Complications that arose may likewise have caused mismatches by altering patients' needs and invalidating the care provision of ikHerstel. Both cases advocate for the integral role of health care professionals in mHealth implementation strategies, as they are ideally situated to select patients and to adjust care provision when complications arise. By replacing these agents with a researcher, we effectively placed a part of our intervention outside of the broader system of care. Despite this, most patients had no trouble using ikHerstel independently. More than half of patients reported no difficulties and a quarter of patients explicitly found nothing to dislike.

Patients find value in mHealth apps in their provision of information that would otherwise not be readily available, and find even more value if that information is tailored to the patients' individual situation [32]. In light of our own findings, it seems vital that health care professionals are involved in how mHealth is implemented to provide this function: as gatekeepers, selecting the right patients; as anchors, integrating an intervention into the broader system of care; but not as tech support, as patients seem able to navigate mHealth independently. Health care professionals could be involved through professional training, introducing them to the mHealth evidence base, or it may take the form of colleagues operating as implementation champions [33].

Limitations

A number of limitations need to be addressed, the first being the absence of health care professionals' perspectives in our evaluation of the implementation strategy's feasibility. The patient-oriented character of the study was chosen in dialogue with patient interest groups and health insurers, and aligns with the study's aim of empowering patients to access ikHerstel even if their hospital has not implemented it. Health care professionals' assessments of our strategy may nevertheless have yielded important insights, as they may have shed light

on conflicting recovery recommendations that were received by the participants.

Another limitation is the study's lack of a diverse sample of patients. We disproportionately included highly educated women of Dutch nationality. While an overrepresentation of women was expected due to the overrepresentation of gynecological types of surgery in our study, this does not explain the sample's high level of education or the lack of international patients. In the case of the latter, the use of the Dutch language in our recruitment material may well have discouraged any international patients from engaging with the study. For the former, the multimedia recruitment strategy we used, emphasizing access to a medical innovation, may have selected for highly educated patients, as some studies have reported on the association between educational level and the use of health services [34-37]. Here too, we may see a reflection of the absence of a health care professional, whose prompting influence might have worked to transcend such barriers. A study on sex differences regarding intention to use mHealth apps in the Netherlands found that women had a more negative attitude of mHealth, perceiving it as being less useful than did men [38]. This may have driven the difference in overall satisfaction scores between this study and the previous study by van der Meij et

al [24], who included a more equal distribution of male versus female patients. Stratification by sex provides some weight to this argument, producing an average satisfaction score of 8.3 for men versus 6.8 for women, although these figures lack reliability precisely due to our sample's low representation of men.

Conclusions

The patient-oriented implementation strategy evaluated in this study was an equivocal success. One of its main hypothesized advantages of more easily reaching a wide audience of patients was not demonstrated. However, its method of recruitment has low costs, and most patients were satisfied and engaged with the mHealth app. Lack of involvement of health care professionals, rather than usability issues on the patients' side, contributed to patients' concerns regarding conflicting recommendations between ikHerstel and health care professionals. Given patient engagement, satisfaction, and improvement in outcomes [12,16-18] with use of such apps, hospitals should consider strategies where health care professionals are involved in selecting patients that may benefit from mHealth apps for postoperative recovery after day surgery and guiding patients' care.

Acknowledgments

We would like to thank Jeroen de Wilde, Tim Thurlings, Patiëntenfederatie Nederland, and Coöperatie VGZ for helping collect patient data.

Conflicts of Interest

EvdM, JAFH, and JRA are the developers of the mHealth care program under study. JAFH and JRA are consultants and certificate holders of a spinoff company for implementation of the mobile app component of the IkHerstel intervention in the Netherlands (ie, the intervention under study). This spinoff company had no impact on the submitted work. JAFH received grants from Nederlandse Organisatie voor Wetenschappelijk Onderzoek, ZonMw, and Samsung during the conduct of the study and received a fee from Olympus outside the submitted work. JRA holds a chair in insurance medicine paid by the Dutch Social Security Agency and has received grants from ZonMw, Nederlandse Organisatie voor Wetenschappelijk Onderzoek, Instituut Gak, Uitvoeringsinstituut Werknemersverzekeringen, Sociale Zaken en Werkgelegenheid, VWS (Volksgezondheid, Welzijn en Sport), Pfizer, Achmea, CVZ (College Voor Zorgverzekeringen), and Zorginstituut; all outside the submitted work. EvdM declares no competing interests.

Multimedia Appendix 1

Screening structure and content of ikHerstel.

[[DOCX File , 316 KB - periop_v8i1e58878_app1.docx](#)]

Multimedia Appendix 2

Advertisement design.

[[DOCX File , 796 KB - periop_v8i1e58878_app2.docx](#)]

Multimedia Appendix 3

Unified theory of acceptance and use of technology survey items.

[[DOCX File , 22 KB - periop_v8i1e58878_app3.docx](#)]

References

1. Health at a glance: Europe. Organisation for Economic Co-operation and Development/European Union. 2018. URL: https://www.oecd.org/en/publications/health-at-a-glance-europe-2018_health_glance_eur-2018-en/full-report.html [accessed 2025-01-07]

2. Madsen H, Henderson W, Dyas A, Bronsert M, Colborn K, Lambert-Kerzner A, et al. Inpatient versus outpatient surgery: a comparison of postoperative mortality and morbidity in elective operations. *World J Surg* 2023 Mar;47(3):627-639. [doi: [10.1007/s00268-022-06819-z](https://doi.org/10.1007/s00268-022-06819-z)] [Medline: [36380104](#)]
3. Friedlander DF, Krimphove MJ, Cole AP, Marchese M, Lipsitz SR, Weissman JS, et al. Where is the value in ambulatory versus inpatient surgery? *Ann Surg* 2021 May 01;273(5):909-916. [doi: [10.1097/SLA.0000000000003578](https://doi.org/10.1097/SLA.0000000000003578)] [Medline: [31460878](#)]
4. Lemos P, Pinto A, Morais G, Pereira J, Loureiro R, Teixeira S, et al. Patient satisfaction following day surgery. *J Clin Anesth* 2009 May;21(3):200-205. [doi: [10.1016/j.jclinane.2008.08.016](https://doi.org/10.1016/j.jclinane.2008.08.016)] [Medline: [19464614](#)]
5. Martin AD, Nunez RN, Andrews JR, Martin GL, Andrews PE, Castle EP. Outpatient prostatectomy: too much too soon or just what the patient ordered. *Urology* 2010 Feb;75(2):421-424. [doi: [10.1016/j.urology.2009.08.085](https://doi.org/10.1016/j.urology.2009.08.085)] [Medline: [19969327](#)]
6. Mathis MR, Naughton NN, Shanks AM, Freundlich RE, Pannucci CJ, Chu Y, et al. Patient selection for day case-eligible surgery: identifying those at high risk for major complications. *Anesthesiology* 2013 Dec;119(6):1310-1321 [FREE Full text] [doi: [10.1097/ALN.0000000000000005](https://doi.org/10.1097/ALN.0000000000000005)] [Medline: [24108100](#)]
7. Tran TT, Kaneva P, Mayo NE, Fried GM, Feldman LS. Short-stay surgery: what really happens after discharge? *Surgery* 2014 Jul;156(1):20-27. [doi: [10.1016/j.surg.2014.03.024](https://doi.org/10.1016/j.surg.2014.03.024)] [Medline: [24856316](#)]
8. Berg K, Arestedt K, Kjellgren K. Postoperative recovery from the perspective of day surgery patients: a phenomenographic study. *Int J Nurs Stud* 2013 Dec;50(12):1630-1638. [doi: [10.1016/j.ijnurstu.2013.05.002](https://doi.org/10.1016/j.ijnurstu.2013.05.002)] [Medline: [23726224](#)]
9. Gilmartin J. Contemporary day surgery: patients' experience of discharge and recovery. *J Clin Nurs* 2007 Jun;16(6):1109-1117. [doi: [10.1111/j.1365-2702.2007.01548.x](https://doi.org/10.1111/j.1365-2702.2007.01548.x)] [Medline: [17518885](#)]
10. Larsson F, Strömbäck U, Rysst Gustafsson S, Engström Å. Postoperative recovery: experiences of patients who have undergone orthopedic day surgery. *J Perianesth Nurs* 2022 Aug;37(4):515-520 [FREE Full text] [doi: [10.1016/j.jopan.2021.10.012](https://doi.org/10.1016/j.jopan.2021.10.012)] [Medline: [35279387](#)]
11. Mottram A. 'They are marvellous with you whilst you are in but the aftercare is rubbish': a grounded theory study of patients' and their carers' experiences after discharge following day surgery. *J Clin Nurs* 2011 Nov;20(21-22):3143-3151. [doi: [10.1111/j.1365-2702.2011.03763.x](https://doi.org/10.1111/j.1365-2702.2011.03763.x)] [Medline: [21762418](#)]
12. Vonk Noordegraaf A, Anema JR, van Mechelen W, Knol DL, van Baal WM, van Kesteren PJM, et al. A personalised eHealth programme reduces the duration until return to work after gynaecological surgery: results of a multicentre randomised trial. *BJOG* 2014 Aug;121(9):1127-35; discussion 1136. [doi: [10.1111/1471-0528.12661](https://doi.org/10.1111/1471-0528.12661)] [Medline: [24511914](#)]
13. De La Cruz Monroy MFI, Mosahebi A. The use of smartphone applications (apps) for enhancing communication with surgical patients: a systematic review of the literature. *Surg Innov* 2019 Apr;26(2):244-259. [doi: [10.1177/1553350618819517](https://doi.org/10.1177/1553350618819517)] [Medline: [30602332](#)]
14. Timmers T, Janssen L, Kool RB, Kremer JA. Educating patients by providing timely information using smartphone and tablet apps: systematic review. *J Med Internet Res* 2020 Apr 13;22(4):e17342 [FREE Full text] [doi: [10.2196/17342](https://doi.org/10.2196/17342)] [Medline: [32281936](#)]
15. Willems SJ, Coppieters MW, Pronk Y, Diks MJF, van der Heijden KWAP, Rooker S, et al. A clinical journey mobile health app for perioperative patients: cross-sectional study. *JMIR Hum Factors* 2021 Feb 08;8(1):e20694 [FREE Full text] [doi: [10.2196/20694](https://doi.org/10.2196/20694)] [Medline: [33555262](#)]
16. den Bakker CM, Schaafsma FG, Consten ECJ, Schraffordt Koops SE, van der Meij E, van de Ven PM, et al. Personalised electronic health programme for recovery after major abdominal surgery: a multicentre, single-blind, randomised, placebo-controlled trial. *Lancet Digit Health* 2023 Aug;5(8):e485-e494 [FREE Full text] [doi: [10.1016/S2589-7500\(23\)00084-5](https://doi.org/10.1016/S2589-7500(23)00084-5)] [Medline: [37419843](#)]
17. Bouwsma EVA, Bosmans JE, van Dongen JM, Brölmann HAM, Anema JR, Huirne JAF. Cost-effectiveness of an internet-based perioperative care programme to enhance postoperative recovery in gynaecological patients: economic evaluation alongside a stepped-wedge cluster-randomised trial. *BMJ Open* 2018 Jan 21;8(1):e017782 [FREE Full text] [doi: [10.1136/bmjopen-2017-017782](https://doi.org/10.1136/bmjopen-2017-017782)] [Medline: [29358423](#)]
18. van der Meij E, Anema J, Leclercq W, Bongers M, Consten E, Schraffordt Koops S, et al. Personalised perioperative care by e-health after intermediate-grade abdominal surgery: a multicentre, single-blind, randomised, placebo-controlled trial. *Lancet* 2018 Jul 07;392(10141):51-59. [doi: [10.1016/S0140-6736\(18\)31113-9](https://doi.org/10.1016/S0140-6736(18)31113-9)] [Medline: [29937195](#)]
19. Ha JF, Longnecker N. Doctor-patient communication: a review. *Ochsner J* 2010;10(1):38-43 [FREE Full text] [Medline: [21603354](#)]
20. Kvarnström K, Westerholm A, Airaksinen M, Liira H. Factors contributing to medication adherence in patients with a chronic condition: a scoping review of qualitative research. *Pharmaceutics* 2021 Jul 20;13(7):1100 [FREE Full text] [doi: [10.3390/pharmaceutics13071100](https://doi.org/10.3390/pharmaceutics13071100)] [Medline: [34371791](#)]
21. Praatplaat belemmeringen opschaling telemonitoring. Nederlandse Vereniging van Ziekenhuizen. URL: <https://nvz-ziekenhuizen.nl/sites/default/files/2022-12/Belemmeringen%20opschaling%20telemonitoring.pdf> [accessed 2024-02-19]
22. Steckler A, Linnan L. *Process Evaluation for Public Health Interventions and Research*. Hoboken, NJ: Jossey-Bass; 2002.
23. den Bakker CM, Schaafsma FG, van der Meij E, Meijerink WJ, van den Heuvel B, Baan AH, et al. Electronic health program to empower patients in returning to normal activities after general surgical and gynecological procedures: intervention

- mapping as a useful method for further development. *J Med Internet Res* 2019 Feb 06;21(2):e9938 [FREE Full text] [doi: [10.2196/jmir.9938](https://doi.org/10.2196/jmir.9938)] [Medline: [30724740](https://pubmed.ncbi.nlm.nih.gov/30724740/)]
24. van der Meij E, Huirne JA, Ten Cate AD, Stockmann HB, Scholten PC, Davids PH, et al. A perioperative eHealth program to enhance postoperative recovery after abdominal surgery: process evaluation of a randomized controlled trial. *J Med Internet Res* 2018 Jan 02;20(1):e1 [FREE Full text] [doi: [10.2196/jmir.8338](https://doi.org/10.2196/jmir.8338)] [Medline: [29295808](https://pubmed.ncbi.nlm.nih.gov/29295808/)]
 25. Greef M, Deursen A, Tubbing M, Bohnenn E. Development of the Diagnostic Illiteracy Scale in order to reveal illiteracy among adults. *Andragogic Stud J Stu Adult Edu Learn* 2013;1(1):1-48 [FREE Full text]
 26. Quickscan digitale vaardigheden. Pharos. URL: https://www.pharos.nl/wp-content/uploads/2024/08/Quickscan_digitale-vaardigheden_082024.pdf [accessed 2022-05-02]
 27. Bouwsma EVA, Vonk Noordegraaf A, Szlávík Z, Brölmann HAM, Emanuel MH, Lips JP, et al. Process evaluation of a multidisciplinary care program for patients undergoing gynaecological surgery. *J Occup Rehabil* 2014 Sep;24(3):425-438 [FREE Full text] [doi: [10.1007/s10926-013-9475-4](https://doi.org/10.1007/s10926-013-9475-4)] [Medline: [24057871](https://pubmed.ncbi.nlm.nih.gov/24057871/)]
 28. Venkatesh V, Thong JYL, Xu X. Consumer acceptance and use of information technology: extending the unified theory of acceptance and use of technology. *MIS Q* 2012;36(1):157-178. [doi: [10.2307/41410412](https://doi.org/10.2307/41410412)]
 29. van Deursen A, van Dijk J. Modeling traditional literacy, internet skills and internet usage: an empirical study. *Interact Comput* 2014 Jul 16;28(1):13-26. [doi: [10.1093/iwc/iwu027](https://doi.org/10.1093/iwc/iwu027)]
 30. Clayton M, Verow P. Advice given to patients about return to work and driving following surgery. *Occup Med (Lond)* 2007 Oct;57(7):488-491. [doi: [10.1093/occmed/kqm063](https://doi.org/10.1093/occmed/kqm063)] [Medline: [17906266](https://pubmed.ncbi.nlm.nih.gov/17906266/)]
 31. Nygaard IE, Hamad NM, Shaw JM. Activity restrictions after gynecologic surgery: is there evidence? *Int Urogynecol J* 2013 May;24(5):719-724 [FREE Full text] [doi: [10.1007/s00192-012-2026-2](https://doi.org/10.1007/s00192-012-2026-2)] [Medline: [23340879](https://pubmed.ncbi.nlm.nih.gov/23340879/)]
 32. Peng W, Kanthawala S, Yuan S, Hussain SA. A qualitative study of user perceptions of mobile health apps. *BMC Public Health* 2016 Nov 14;16(1):1158 [FREE Full text] [doi: [10.1186/s12889-016-3808-0](https://doi.org/10.1186/s12889-016-3808-0)] [Medline: [27842533](https://pubmed.ncbi.nlm.nih.gov/27842533/)]
 33. Santos WJ, Graham ID, Lalonde M, Demery Varin M, Squires JE. The effectiveness of champions in implementing innovations in health care: a systematic review. *Implement Sci Commun* 2022 Jul 22;3(1):80 [FREE Full text] [doi: [10.1186/s43058-022-00315-0](https://doi.org/10.1186/s43058-022-00315-0)] [Medline: [35869516](https://pubmed.ncbi.nlm.nih.gov/35869516/)]
 34. Groeneveld PW, Sonnad SS, Lee AK, Asch DA, Shea JE. Racial differences in attitudes toward innovative medical technology. *J Gen Intern Med* 2006 Jun;21(6):559-563 [FREE Full text] [doi: [10.1111/j.1525-1497.2006.00453.x](https://doi.org/10.1111/j.1525-1497.2006.00453.x)] [Medline: [16808736](https://pubmed.ncbi.nlm.nih.gov/16808736/)]
 35. National Academies of Sciences, Engineering, and Medicine. *Health-Care Utilization as a Proxy in Disability Determination*. Washington, DC: The National Academies Press; 2018.
 36. Salganicoff A, Ranji U, Beamesderfer A, Kurani N. Women and health care in the early years of the ACA: key findings from the 2013 Kaiser Women's Health Survey. KFF. 2014 May 15. URL: <https://www.kff.org/womens-health-policy/report/women-and-health-care-in-the-early-years-of-the-aca-key-findings-from-the-2013-kaiser-womens-health-survey/> [accessed 2025-07-01]
 37. Hopman P, Heins M, Rijken M, Schellevis F. Health care utilization of patients with multiple chronic diseases in the Netherlands: differences and underlying factors. *Eur J Intern Med* 2015 Apr;26(3):190-196 [FREE Full text] [doi: [10.1016/j.ejim.2015.02.006](https://doi.org/10.1016/j.ejim.2015.02.006)] [Medline: [25704328](https://pubmed.ncbi.nlm.nih.gov/25704328/)]
 38. van Elburg FRT, Klaver NS, Nieboer AP, Askari M. Gender differences regarding intention to use mHealth applications in the Dutch elderly population: a cross-sectional study. *BMC Geriatr* 2022 May 24;22(1):449 [FREE Full text] [doi: [10.1186/s12877-022-03130-3](https://doi.org/10.1186/s12877-022-03130-3)] [Medline: [35610577](https://pubmed.ncbi.nlm.nih.gov/35610577/)]

Abbreviations

UTAUT2: unified theory of acceptance and use of technology 2

Edited by N Rohatgi; submitted 27.03.24; peer-reviewed by H Karim, A Santiago, D Poenaru, M van der Velde, A Leshner; comments to author 11.09.24; revised version received 06.12.24; accepted 16.12.24; published 14.01.25.

Please cite as:

Toben D, de Wind A, van der Meij E, Huirne JAF, Anema JR

A Patient-Oriented Implementation Strategy for a Perioperative mHealth Intervention: Feasibility Cohort Study

JMIR Perioper Med 2025;8:e58878

URL: <https://periop.jmir.org/2025/1/e58878>

doi: [10.2196/58878](https://doi.org/10.2196/58878)

PMID:

©Daan Toben, Astrid de Wind, Eva van der Meij, Judith A F Huirne, Johannes R Anema. Originally published in JMIR Perioperative Medicine (<http://periop.jmir.org>), 14.01.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in JMIR Perioperative Medicine, is properly cited. The complete bibliographic information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Original Paper

Development and Validation of a Routine Electronic Health Record-Based Delirium Prediction Model for Surgical Patients Without Dementia: Retrospective Case-Control Study

Emma Holler¹, PhD; Christina Ludema², PhD; Zina Ben Miled³, PhD; Molly Rosenberg², PhD; Corey Kalbaugh², PhD; Malaz Boustani⁴, MD; Sanjay Mohanty¹, MD

¹Department of Surgery, Indiana University School of Medicine, Indianapolis, IN, United States

²Department of Epidemiology & Biostatistics, Indiana University Bloomington, Bloomington, United States

³Department of Electrical & Computer Engineering, Lamar University, Beaumont, TX, United States

⁴Department of Medicine, Indiana University School of Medicine, Indianapolis, IN, United States

Corresponding Author:

Emma Holler, PhD

Department of Surgery

Indiana University School of Medicine

545 Barnhill Drive

Indianapolis, IN, 46202

United States

Phone: 1 317 944 5376

Email: emorone@iu.edu

Abstract

Background: Postoperative delirium (POD) is a common complication after major surgery and is associated with poor outcomes in older adults. Early identification of patients at high risk of POD can enable targeted prevention efforts. However, existing POD prediction models require inpatient data collected during the hospital stay, which delays predictions and limits scalability.

Objective: This study aimed to develop and externally validate a machine learning-based prediction model for POD using routine electronic health record (EHR) data.

Methods: We identified all surgical encounters from 2014 to 2021 for patients aged 50 years and older who underwent an operation requiring general anesthesia, with a length of stay of at least 1 day at 3 Indiana hospitals. Patients with preexisting dementia or mild cognitive impairment were excluded. POD was identified using Confusion Assessment Method records and delirium International Classification of Diseases (ICD) codes. Controls without delirium or nurse-documented confusion were matched to cases by age, sex, race, and year of admission. We trained logistic regression, random forest, extreme gradient boosting (XGB), and neural network models to predict POD using 143 features derived from routine EHR data available at the time of hospital admission. Separate models were developed for each hospital using surveillance periods of 3 months, 6 months, and 1 year before admission. Model performance was evaluated using the area under the receiver operating characteristic curve (AUROC). Each model was internally validated using holdout data and externally validated using data from the other 2 hospitals. Calibration was assessed using calibration curves.

Results: The study cohort included 7167 delirium cases and 7167 matched controls. XGB outperformed all other classifiers. AUROCs were highest for XGB models trained on 12 months of preadmission data. The best-performing XGB model achieved a mean AUROC of 0.79 (SD 0.01) on the holdout set, which decreased to 0.69-0.74 (SD 0.02) when externally validated on data from other hospitals.

Conclusions: Our routine EHR-based POD prediction models demonstrated good predictive ability using a limited set of preadmission and surgical variables, though their generalizability was limited. The proposed models could be used as a scalable, automated screening tool to identify patients at high risk of POD at the time of hospital admission.

(*JMIR Perioper Med* 2025;8:e59422) doi:[10.2196/59422](https://doi.org/10.2196/59422)

KEYWORDS

delirium; machine learning; prediction; postoperative; algorithm; electronic health records; surgery; risk prediction

Introduction

Postoperative delirium (POD) is a common and serious surgical complication that affects 15%-50% of older surgical patients [1-3]. POD is characterized by acute fluctuations in consciousness and has a complex etiology thought to be caused by interactions between predisposing (eg, individual vulnerability) and precipitating (eg, acute illness or surgery) factors [4]. Common predisposing factors include older age, preexisting cognitive impairment, poor physical functioning, alcohol abuse, smoking, and depression [5-8]. Risk factors unique to surgical settings include the type of surgery (eg, major vascular procedures), emergent status, case complexity, and perioperative medications [6,7,9,10]. Despite being an acute condition, delirium is associated with long-term cognitive and physical impairment, institutionalization, and death [4,11]. However, up to 40% of cases may be preventable, and multicomponent, nonpharmacologic interventions may be effective in reducing incidence and health care costs [12,13].

Early and accurate POD risk prediction can inform prevention and enable targeted intervention and resource planning efforts. Fortunately, the widespread availability of electronic health record (EHR) data and advancements in machine learning offer an opportunity to develop accurate, low-cost, and scalable screening tools for POD risk. Several machine learning-based POD prediction models have been developed, reporting areas under the curve (AUROCs) ranging from 0.71 to 0.86 [14-26]. However, the models with the highest AUROCs have important limitations that hinder their practical application. First, they focus on specific patient subsets (ie, intensive care unit (ICU) patients, cardiac surgery), which restricts their generalizability to general surgical populations. Second, population-specific models necessitate separate models for each subpopulation, making implementation cumbersome and resource intensive. Finally, many of these models require inpatient data that take hours or days to accumulate, delaying risk assessment and potential interventions. A small number of studies have developed POD prediction models for general surgical populations; however, these models still incorporate nonroutine clinical data (eg, inpatient nursing assessments) that require time to collect and may not be universally available [14-18,27].

These limitations highlight the need for a model that can predict POD in a diverse surgical population using readily available preoperative data, as it could provide an early, inexpensive, and scalable prescreening tool to identify patients who may benefit from additional monitoring or preventative measures. In this study, we developed and externally validated a machine learning model that can accurately predict POD in surgical patients at the time of hospital admission using only routine EHR data. We also identified preoperative EHR-based predictors of POD and determined how preoperative surveillance length affected model performance.

Methods

Ethical Considerations

This study was approved by the Indiana University (IU) Institutional Review Board (#15767) and adhered to the

reporting standards described in the Transparent Reporting of Individual Prognosis or Diagnosis (TRIPOD) guidelines [27].

Study Data and Cohort Selection

Diagnoses, medication orders, surgery, and other inpatient clinical records (eg, nursing assessments) were extracted from the IU Health electronic data warehouse. IU Health, a nonprofit health system with the largest physician network in the state of Indiana, includes 17 hospitals and dozens of outpatient facilities and performs approximately 115,000 surgeries per year [28]. We identified all surgical hospitalizations for patients aged 50 years and older who underwent surgery requiring general anesthesia at an IU Health facility between January 1, 2014, and December 31, 2021; had a length of stay of at least 1 day; and did not have preexisting dementia. Hospitalizations of patients with preexisting dementia (defined as having a dementia diagnosis code or an order for an antidementia medication before admission; see Table S1 in [Multimedia Appendix 1](#)) were excluded because dementia is known to be the single-strongest predictor of delirium [6]; models are not needed to forecast risk. For a hospitalization to be eligible, the patient had to have at least 1 IU Health encounter (defined as any interaction with an IU Health facility, eg, outpatient, inpatient, or emergency department visits) in the year before admission and have at least 1 diagnosis or medication record during that period. If no sex, race, or age data were available across all of a given patient's hospitalizations, that patient was excluded.

This study followed a retrospective case-control design where nondelirium (ie, control) hospitalizations were matched to delirium (ie, case) hospitalizations by sex, race, age within 3 years, and admission year within 3 years. We matched on these variables to ensure the age distribution for cases and controls was equalized across race and sex groups. As a result, age was less important to the model, and biases within strata of race and sex were minimized. Because matching was done at the hospitalization level rather than the patient-level, it was possible for case and control hospitalizations belonging to the same patient to be matched.

Hospitalizations where the patient developed POD were designated as cases. POD was defined as at least 1 positive Confusion Assessment Method (CAM) [29] nursing assessment or a delirium *International Classification of Diseases, Ninth Revision (ICD-9)/International Classification of Diseases, Tenth Revision, Clinical Modification (ICD-10-CM)* code (see Table S2 in [Multimedia Appendix 1](#)) recorded during the hospital stay. The CAM is a validated diagnostic algorithm with an overall sensitivity of 94% and a specificity of 89% [30]. Hospitalizations where delirium was present at the time of admission were excluded because the model is intended to predict POD. Hospitalizations without delirium or any nurse-documented confusion (ie, cognitive assessments reporting that the patient was disoriented, confused, or did not follow commands) were eligible to be selected as controls. Visits that did not have documented delirium (ie, delirium ICD code or positive CAM) but did have nurse-documented confusion were excluded from the control pool to ensure controls were not actually misclassified cases; confusion (without delirium) could possibly represent subsyndromal delirium. If a case had more

than 1 potential control, a control was randomly selected. For each eligible visit, the index date was defined as the date of hospital admission. We used the following set of sociodemographic, surgery, diagnosis, and medication variables to build our predictive models.

Variables

Sociodemographic variables included age, patient-reported sex, and patient-reported race (categorized as Black, White, Asian, other, or unknown for analytic purposes), and insurance type. The insurance type was ascertained during each index visit and categorized as commercial, government (Medicare or Medicaid), self-pay, or other/unknown. Smoking status at the time of surgery was extracted from the EHR and categorized as “current,” “former,” or “never smoker.” The BMI was obtained from the visit nearest to the index. The initial American Society of Anesthesiologists (ASA) class and emergency surgery status (defined as operations with an ASA class of 5 or E) were also included. Surgical specialty was assigned based on National Surgical Quality Improvement Program inclusion and exclusion criteria [31]. If a patient underwent 4 or more procedures falling under 2 or more distinct specialties, the visit was categorized as “multispecialty.”

Diagnosis variables were generated using ICD-9/ICD-10-CM codes. Binary variables were created for each of the 31 Elixhauser disease groups using Quan et al [32] coding scheme and Elixhauser mortality scores were calculated for each patient using van Walraven weights [32-34]. We also created binary variables for other diagnoses potentially associated with increased risk of delirium, including previous delirium, cerebrovascular disease (CVD), previous traumatic brain injury (TBI), and sensory impairment (Table S3 in [Multimedia Appendix 1](#)). We derived a composite variable representing the total comorbidity burden by calculating the sum of the number of unique ICD codes (at the 3-digit level) a patient had prior to each index date. Variables for the number of ICD codes belonging to the ICD-10 group Z00-Z99 (factors influencing health status and contact with health services) and their ICD-9 equivalents were also included based on prior literature [14], grouped as follows: Z00-Z13, Z16, Z17, Z18, Z20-29, Z30-39, Z40-53, Z55-65, Z69-76, and Z77-99.

Medication variables were generated using medication order data. Anticholinergic (ACh) medications were identified using the Anticholinergic Cognitive Burden (ACB) scale, a well-established tool that categorizes medications based on the strength of their ACh activity [35]. Three ACh medication variables were developed representing the total number of orders for drugs with an ACB score of 1, 2, and 3, respectively. We also included other non-ACh medication variables as predictors. Since medication orders were retrieved from multiple health care institutions, a unified mapping of medication names to a drug taxonomy was not available. Instead, we mapped each medication in the medication orders to the Anatomical Therapeutic Chemical (ATC) classification codes [36]. The ATC drug classification system is hierarchical with multiple sublevels and maintained by the World Health Organization. For this study, all 14 main groups (eg, A: alimentary tract and metabolism; B: blood and blood-forming organs; C:

cardiovascular system) and the first-level subgroup were included (eg, A01: stomatological preparations; A02: drugs for acid-related disorders). For each patient, the count of medication orders (excluding AChs, which were derived separately, as described before) associated with a given ATC subgroup was calculated over the preindex assessment period. We also created a variable summing the total number of medication orders before each admission to capture polypharmacy.

Model Development and Evaluation

Three IU Health institutions were selected for this study. Institutions A, B, and C had the first-, second-, and third-greatest number of delirium cases, respectively. Institution-specific models were developed using data derived from the following preindex surveillance periods: 3 months before admission, 6 months before admission, and 1 year before admission. The purpose of training these separate models was to provide an understanding of how the training data and surveillance period impact the models' ability to predict POD and generalizability. Prior to training, each model's data were split into training (80%) and holdout (20%) sets, while maintaining a 1:1 ratio of cases and controls to avoid class imbalance. Imbalanced data are problematic in classification tasks because the model will focus on learning the characteristics of the majority class. As a result, the model may achieve high accuracy but fail to accurately identify the minority class.

In this study, 6 demographic variables, 4 surgical variables, 49 diagnosis variables, and 84 medication variables were included for a total of 143 features. Categorical variables were one-hot encoded (ie, converted into dummy variables), and continuous variables were standardized such that they each had a mean of 0 and an SD of 1. We initially explored several different machine learning models to predict whether patients would develop POD after surgery. In addition to traditional logistic regression, a parametric model, we also tried random forest, extreme gradient boosting (XGB), and a multilayer neural network because they can learn complex nonlinear relationships between variables. Optimal hyperparameters for each model were selected using a grid search with 5-fold cross-validation. Each candidate model was evaluated by calculating the area under the receiver operating characteristic curve (AUROC) on its holdout set using data from 1 year before hospital admission, and the model with the highest AUROC was selected as the final model. XGB outperformed the other candidate classifiers in all cases.

After model selection, XGB models trained on data from institution A (referred to as XGB_A) were internally validated on holdout data from institution A and externally validated using holdout data from institutions B and C. Similarly, models trained on data from institutions B and C (referred to as XGB_B and XGB_C, respectively) were internally validated on holdout data from institutions B and C and externally validated using data from institutions A and C and A and B, respectively. The predictive performance of each model was evaluated on the holdout and external validation data by creating 1000 bootstrapped samples without replacement, calculating the AUROC, sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) in each sample and then

averaging them across all samples. We also generated predictions for nondelirium visits with nurse-documented confusion (which were excluded from training) to examine how the models handle patients with possible subsyndromal delirium. The default threshold of 0.50 was used for predictions. Shapley Additive Explanation (SHAP) [37] was used to determine the most important features, and model calibration was assessed using calibration curves. All analyses were completed using R version 4.3.2 (R Foundation for Statistical Computing).

Results

Study Cohort

Figure 1 depicts the workflow used for model development, internal validation, and external validation for the model trained

on data from institution A. Between 2014 and 2022, at the 3 institutions of interest, there were 39,968 surgical visits for 30,131 unique patients aged 50 years and older. Of the identified visits, 431 (1.4%) were excluded for not having any previous diagnosis or medication order data, and 120 (0.4%) were excluded for missing sex, race, or the ASA class. The 6250 (20.7%) visits with nurse-documented confusion (but no delirium) were excluded from the training and holdout sets but reserved for later analyses. After matching, the final analytic sample included 7167 (23.8%) delirium cases and 7167 (23.8%) matched controls (Figure 2).

Figure 1. Workflow for the development and validation of the model using data from institution A. XGB: extreme gradient boosting.

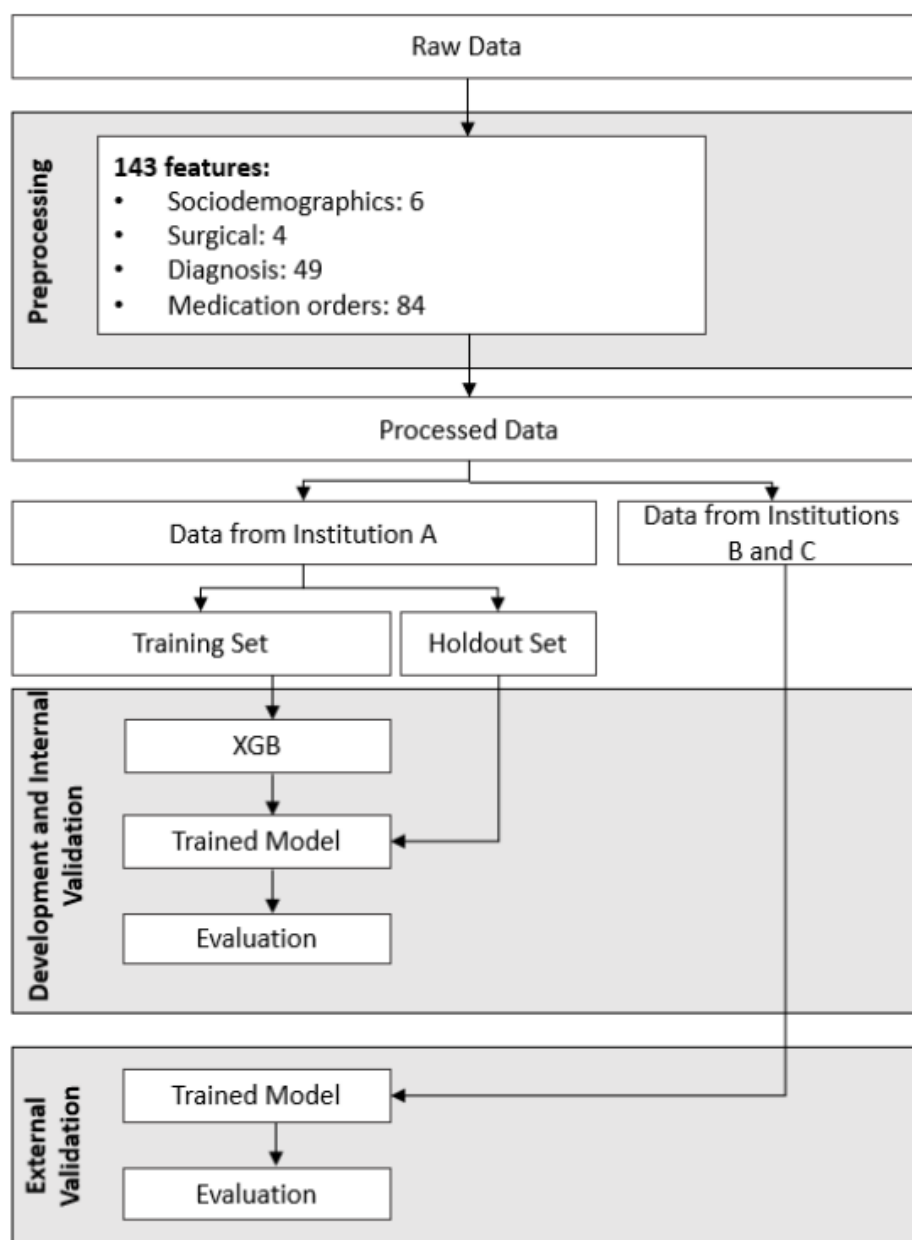
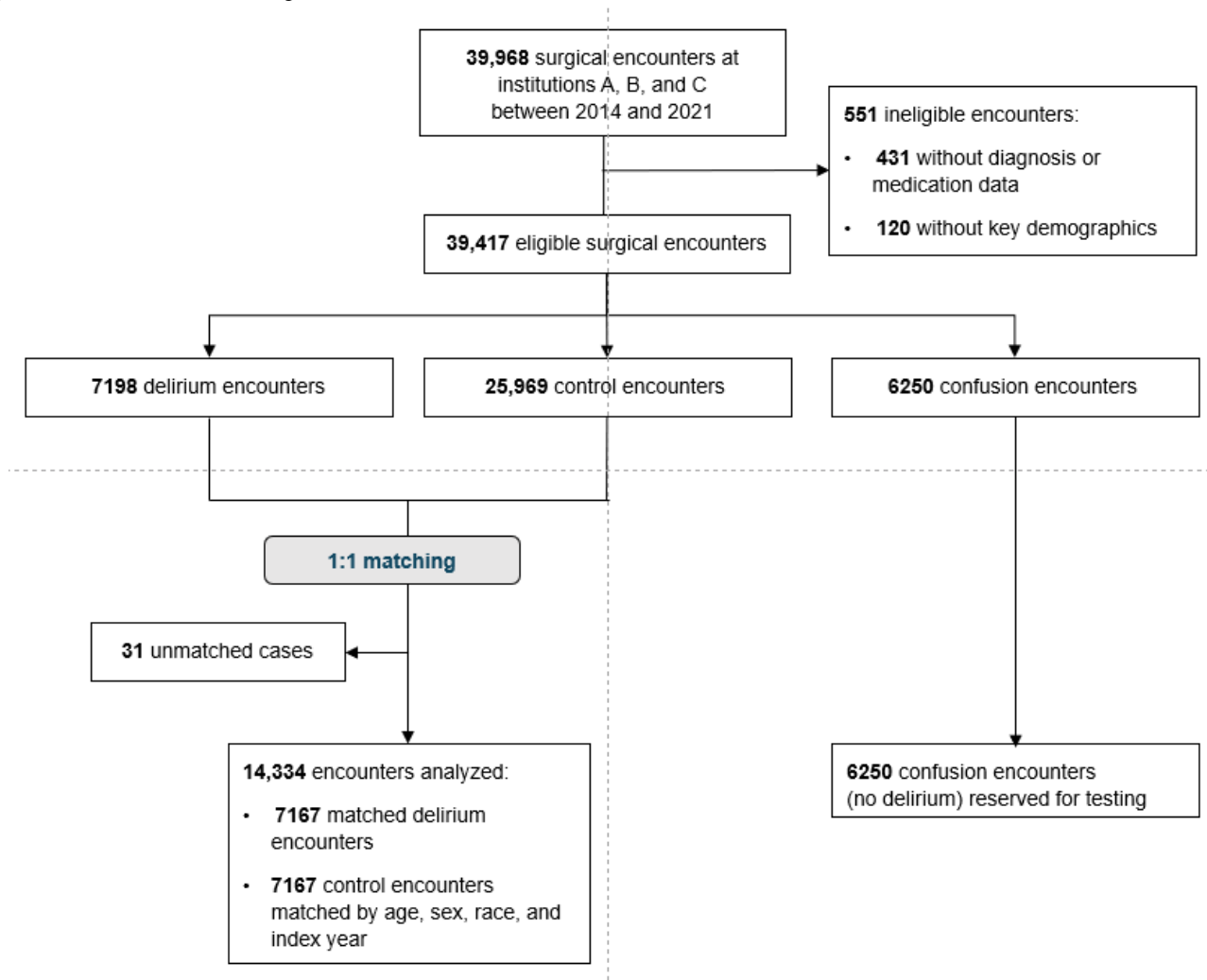


Figure 2. Patient inclusion flow diagram.

Pooling across institutions, the median age was 68 (IQR 61-76) years, and most patients were male ($n=7412$, 51.7%), White ($n=12,276$, 85.6%), and had public insurance ($n=11,523$, 80.4%). The most common surgical specialty was general surgery ($n=3600$, 25.1%), and 11.5% ($n=1644$) of operations were classified as emergencies (Table 1 and Table S4 in Multimedia Appendix 1).

As shown in Table 2, the 3 most common comorbidities in the general cohort were hypertension ($n=9998$, 69.8%), diabetes ($n=5189$, 36.2%), and nonmetastatic cancer ($n=5222$, 29.6%). Delirium cases differed from controls in several respects.

Delirium cases had a greater comorbidity burden than controls and were more likely to have previous delirium (Table 2 and Table S5 in Multimedia Appendix 1).

Of the 6250 (20.7%) visits with nurse-documented confusion but without delirium, 3185 (51%) belonged to institution A, 1328 (21.2%) to institution B, and 1737 (27.8%) to institution C. Patients with confusion were more likely to have had delirium in the past year than controls but less likely than cases. Their comorbidity burden also fell in between that of cases and controls (Tables S6 and S7 in Multimedia Appendix 1).

Table 1. Characteristics of delirium cases and controls by institution.

Variables ^a	Institution A		Institution B		Institution C	
	Controls (n=3739)	Cases (n=3739)	Controls (n=1928)	Cases (n=1928)	Controls (n=1500)	Cases (n=1500)
Age (years), median (IQR)	68 (61-76)	68 (61-76)	66 (59-73)	66 (59-73)	72 (63-80)	72 (63-80)
Sex: female, n (%)	1840 (49.2)	1840 (49.2)	861 (44.7)	861 (44.7)	760 (50.7)	760 (50.7)
Race, n (%)						
Asian	12 (0.3)	12 (0.3)	13 (0.7)	13 (0.7)	1 (0.1)	1 (0.1)
Black	758 (20.3)	758 (20.3)	162 (8.4)	162 (8.4)	59 (3.9)	59 (3.9)
Other	4 (0.1)	4 (0.1)	3 (0.2)	3 (0.2)	4 (0.3)	4 (0.3)
White	2959 (79.1)	2959 (79.1)	1747 (90.6)	1747 (90.6)	1432 (95.5)	1432 (95.5)
Unknown	6 (0.2)	6 (0.2)	3 (0.2)	3 (0.2)	4 (0.3)	4 (0.3)
Insurance, n (%)						
Private	857 (22.9)	572 (15.3)	547 (28.4)	391 (20.3)	239 (15.9)	124 (8.3)
Public	2861 (76.5)	3137 (83.9)	1376 (71.4)	1530 (79.4)	1253 (83.5)	1366 (91.1)
Uninsured	21 (0.6)	30 (0.8)	5 (0.3)	7 (0.4)	8 (0.5)	10 (0.7)
BMI, median (IQR)	28.5 (24.3-33.7)	27.5 (23.1-32.7)	27.2 (23.2-32.0)	27.0 (22.7-32.0)	28.0 (23.9-33.6)	27.2 (22.9-33.2)
Smoking status, n (%)						
Current	505 (13.5)	561 (15.0)	173 (9.0)	263 (13.6)	213 (14.2)	280 (18.7)
Former	1609 (43.0)	1805 (48.3)	799 (41.4)	901 (46.7)	624 (41.6)	689 (45.9)
Never	1625 (43.5)	1373 (36.7)	956 (49.6)	764 (39.6)	663 (44.2)	531 (35.4)
ASA^b class, n (%)						
1-2	421 (11.3)	143 (3.8)	126 (6.5)	37 (1.9)	250 (16.7)	81 (5.4)
3-4	3102 (83.0)	2875 (76.9)	1722 (89.3)	1649 (85.5)	1132 (75.5)	1152 (76.8)
5 or E	216 (5.8)	721 (19.3)	80 (4.1)	242 (12.6)	118 (7.9)	267 (17.8)
Surgical specialty, n (%)						
Cardiothoracic (CT)	536 (14.3)	577 (15.4)	183 (9.5)	160 (8.3)	72 (4.8)	142 (9.5)
Ears, nose, and throat (ENT)	48 (1.3)	80 (2.1)	76 (3.9)	98 (5.1)	17 (1.1)	77 (5.1)
General	498 (13.3)	490 (13.1)	952 (49.4)	981 (50.9)	309 (20.6)	370 (24.7)
Multiple	97 (2.6)	614 (16.4)	78 (4.0)	322 (16.7)	15 (1.0)	74 (4.9)
Neurology	666 (17.8)	672 (18.0)	3 (0.2)	10 (0.5)	169 (11.3)	128 (8.5)
Orthopedics	907 (24.3)	620 (16.6)	103 (5.3)	68 (3.5)	560 (37.3)	370 (24.7)
Other	28 (0.7)	28 (0.7)	57 (3.0)	61 (3.2)	11 (0.7)	22 (1.5)
Plastic surgery	165 (4.4)	111 (3.0)	31 (1.6)	17 (0.9)	77 (5.1)	95 (6.3)
Urology/gynecology	276 (7.4)	172 (4.6)	440 (22.8)	209 (10.8)	153 (10.2)	131 (8.7)
Vascular	518 (13.9)	375 (10.0)	5 (0.3)	2 (0.1)	117 (7.8)	91 (6.1)

^aContinuous variables are summarized as the median (IQR) and categorical variables as n (%).

^bASA: American Society of Anesthesiologists.

Table 2. Clinical characteristics of cases and controls by institution.

Variable ^a	Institution A		Institution B		Institution C	
	Controls (n=3739)	Cases (n=3739)	Controls (n=1928)	Cases (n=1928)	Controls (n=1500)	Cases (n=1500)
ECI ^b score, median (IQR)	5 (0-13)	8 (2-18)	9 (4-17)	13 (5-22)	5 (0-12)	9 (2-18)
Number of ICD ^c codes, median (IQR)	21 (12-33)	24 (12-40)	21 (11-34)	26 (13-41)	17 (80-29)	22 (11-38)
Congestive heart failure (CHF), n (%)	713 (19.1)	1040 (27.8)	203 (10.5)	304 (15.8)	267 (17.8)	445 (29.7)
Arrhythmia, n (%)	969 (25.9)	1203 (32.2)	397 (20.6)	485 (25.2)	393 (26.2)	471 (31.4)
Valvular disease, n (%)	639 (17.1)	724 (19.4)	148 (7.7)	188 (9.8)	115 (7.7)	178 (11.9)
Peripheral vascular disorder (PVD), n (%)	977 (26.1)	1138 (30.4)	217 (11.3)	259 (13.4)	316 (21.1)	378 (25.2)
Hypertension, n (%)	2767 (74.0)	2696 (72.1)	1217 (63.1)	1255 (65.1)	997 (66.5)	1066 (71.1)
Chronic obstructive pulmonary disorder (COPD), n (%)	962 (25.7)	1227 (32.8)	444 (23.0)	506 (26.2)	398 (26.5)	542 (36.1)
Diabetes, n (%)	1295 (34.6)	1502 (40.2)	558 (28.9)	717 (37.2)	481 (32.1)	636 (42.4)
Hypothyroidism, n (%)	659 (17.6)	630 (16.8)	347 (18.0)	339 (17.6)	249 (16.6)	310 (20.7)
Renal failure, n (%)	891 (23.8)	1198 (32.0)	506 (26.2)	639 (33.1)	336 (22.4)	474 (31.6)
Liver disease, n (%)	266 (7.1)	336 (9.0)	415 (21.5)	573 (29.7)	73 (4.9)	129 (8.6)
Lymphoma, n (%)	69 (1.8)	85 (2.3)	75 (3.9)	71 (3.7)	33 (2.2)	26 (1.7)
Cancer, n (%)	986 (26.4)	1040 (27.8)	1273 (66.0)	1184 (61.4)	339 (22.6)	400 (26.7)
Coagulopathy, n (%)	264 (7.1)	393 (10.5)	164 (8.5)	336 (17.4)	100 (6.7)	153 (10.2)
Obesity, n (%)	720 (19.3)	758 (20.3)	303 (15.7)	372 (19.3)	333 (22.2)	374 (24.9)
Weight loss, n (%)	240 (6.4)	371 (9.9)	220 (11.4)	349 (18.1)	76 (5.1)	173 (11.5)
Fluid/electrolyte disorders, n (%)	761 (20.4)	1171 (31.3)	440 (22.8)	716 (37.1)	334 (22.3)	543 (36.2)
Deficiency anemia, n (%)	460 (12.3)	659 (17.6)	244 (12.7)	335 (17.4)	211 (14.1)	296 (19.7)
Alcohol abuse, n (%)	135 (3.6)	219 (5.9)	67 (3.5)	129 (6.7)	30 (2.0)	74 (4.9)
Drug abuse, n (%)	171 (4.6)	213 (5.7)	58 (3.0)	80 (4.1)	42 (2.8)	72 (4.8)
Psychoses, n (%)	20 (0.5)	84 (2.2)	13 (0.7)	34 (1.8)	12 (0.8)	38 (2.5)
Depression, n (%)	905 (24.2)	1022 (27.3)	343 (17.8)	514 (26.7)	275 (18.3)	406 (27.1)
CVD ^d , n (%)	527 (14.1)	668 (17.9)	111 (5.8)	141 (7.3)	142 (9.5)	231 (15.4)
Previous TBI ^e , n (%)	35 (0.9)	74 (2.0)	12 (0.6)	19 (1.0)	17 (1.1)	23 (1.5)
Sensory impairment, n (%)	212 (5.7)	203 (5.4)	81 (4.2)	91 (4.7)	75 (5.0)	118 (7.9)
Previous delirium, n (%)	215 (5.8)	615 (16.4)	103 (5.3)	304 (15.8)	85 (5.7)	278 (18.5)

^aContinuous variables are summarized as the median (IQR) and categorical variables as n (%).

^bECI: Elixhauser comorbidity index.

^cICD: *International Classification of Diseases*.

^dCVD: cerebrovascular disease.

^eTBI: traumatic brain injury.

Model Evaluation

XGB had the highest AUROC out of the 4 candidate classifiers (AUROC=0.79), followed by the neural network (AUROC=0.78), the random forest (AUROC=0.78), and logistic regression (AUROC=0.72). Based on this AUROC evaluation, the XGB model was retained for further analysis. For institution A, the training set included 5234 visits (n=2617, 50%, cases and n=2617, 50%, controls) and the holdout set included 1503 visits (n=752, 50%, cases and n=751, 50%, controls). For institution B, the training and holdout data sets included 2699 visits (n=1350, 50%, cases and n=1349, 50%, controls) and 775 visits (n=387, 49.9%, cases and n=388, 50.1%, controls), respectively. The training and holdout data sets for institution C included 2100 visits (n=1050, 50%, cases and n=1050, 50%,

controls) and 603 visits (n=302, 50.1%, cases and n=301, 49.9%, controls), respectively.

The models trained on institution A (ie, XGB_A) had the best performance, achieving AUROCs of 0.77-0.79 on institution A holdout data and 0.68-0.74 when externally validated on data from institutions B and C. Models trained on institution B (ie, XGB_B) were the least robust, achieving a maximum AUROC of 0.71 on holdout data from institution B and 0.72-0.74 when externally validated on data from institutions A and C. Models trained on institution C (ie, XGB_C) performed better than XGB_B but worse than XGB_A, with a maximum AUROC of 0.77 on holdout data from institution C and 0.64-0.75 when externally validated on data from institutions A and B (Table 3).

Table 3. XGB^a model performance metrics^b by surveillance period and holdout data.

Surveillance period, models, and institutions	AUROC ^c , mean (SD)	Sensitivity, mean (SD)	Specificity, mean (SD)	PPV ^d , mean (SD)	NPV ^e , mean (SD)
1 year, XGB_A					
Institution A	0.79 (0.01)	0.70 (0.02)	0.72 (0.02)	0.72 (0.02)	0.71 (0.02)
Institution B	0.69 (0.02)	0.49 (0.03)	0.78 (0.02)	0.69 (0.03)	0.61 (0.02)
Institution C	0.74 (0.02)	0.70 (0.03)	0.66 (0.03)	0.67 (0.03)	0.69 (0.03)
1 year, XGB_B					
Institution A	0.74 (0.01)	0.76 (0.02)	0.57 (0.02)	0.64 (0.02)	0.70 (0.02)
Institution B	0.71 (0.02)	0.57 (0.03)	0.75 (0.02)	0.69 (0.03)	0.64 (0.02)
Institution C	0.73 (0.02)	0.65 (0.03)	0.68 (0.03)	0.67 (0.03)	0.66 (0.03)
1 year, XGC_C					
Institution A	0.75 (0.01)	0.75 (0.02)	0.60 (0.02)	0.66 (0.02)	0.71 (0.02)
Institution B	0.69 (0.02)	0.47 (0.03)	0.77 (0.02)	0.67 (0.03)	0.59 (0.02)
Institution C	0.77 (0.02)	0.66 (0.03)	0.69 (0.03)	0.69 (0.03)	0.67 (0.03)
6 months, XGB_A					
Institution A	0.78 (0.01)	0.56 (0.03)	0.73 (0.02)	0.67 (0.03)	0.62 (0.02)
Institution B	0.68 (0.02)	0.45 (0.03)	0.79 (0.02)	0.68 (0.03)	0.59 (0.02)
Institution C	0.74 (0.02)	0.67 (0.03)	0.66 (0.03)	0.67 (0.03)	0.67 (0.03)
6 months, XGB_B					
Institution A	0.73 (0.01)	0.78 (0.02)	0.54 (0.02)	0.63 (0.02)	0.71 (0.02)
Institution B	0.71 (0.02)	0.56 (0.03)	0.73 (0.02)	0.67 (0.03)	0.62 (0.02)
Institution C	0.74 (0.02)	0.66 (0.03)	0.68 (0.03)	0.68 (0.03)	0.67 (0.03)
6 months, XGC_C					
Institution A	0.73 (0.01)	0.76 (0.02)	0.55 (0.02)	0.63 (0.02)	0.70 (0.02)
Institution B	0.65 (0.02)	0.52 (0.03)	0.70 (0.02)	0.64 (0.03)	0.60 (0.02)
Institution C	0.76 (0.02)	0.71 (0.03)	0.66 (0.03)	0.68 (0.03)	0.69 (0.03)
3 months, XGB_A					
Institution A	0.77 (0.01)	0.70 (0.02)	0.70 (0.02)	0.70 (0.02)	0.70 (0.02)
Institution B	0.69 (0.02)	0.47 (0.03)	0.78 (0.02)	0.68 (0.03)	0.60 (0.02)
Institution C	0.74 (0.02)	0.68 (0.03)	0.67 (0.03)	0.67 (0.03)	0.68 (0.03)
3 months, XGB_B					
Institution A	0.72 (0.01)	0.75 (0.02)	0.55 (0.02)	0.63 (0.02)	0.69 (0.02)
Institution B	0.70 (0.02)	0.56 (0.03)	0.74 (0.02)	0.68 (0.03)	0.63 (0.02)
Institution C	0.74 (0.02)	0.65 (0.03)	0.68 (0.03)	0.67 (0.03)	0.66(0.03)
3 months, XGC_C					
Institution A	0.73 (0.01)	0.75 (0.02)	0.57 (0.02)	0.64 (0.02)	0.70 (0.02)
Institution B	0.64 (0.02)	0.50 (0.03)	0.71 (0.02)	0.63 (0.03)	0.58 (0.02)
Institution C	0.76 (0.02)	0.73 (0.03)	0.64 (0.03)	0.67 (0.03)	0.70 (0.03)

^aXGB: extreme gradient boosting.

^bMean (SD) metrics presented were obtained using bootstrap resampling on the held-out patients from institutions A, B, and C.

^cAUROC: area under the receiver operating curve.

^dPPV: positive predictive value.

^eNPV: negative predictive value.

Performance became marginally worse with shorter surveillance periods. All models were relatively well calibrated (Figures S1-S3 in [Multimedia Appendix 1](#)). The top 5 most important features for XGB_A, XGB_B, and XGB_C by evaluation data set and surveillance period are presented in [Table 4](#) and Tables

S8-S9 in [Multimedia Appendix 1](#). The ASA class was frequently the most important predictor.

Across all surveillance periods, the models predicted between 40% and 60% of the patients with confusion as cases or controls (Table S10 in [Multimedia Appendix 1](#)).

Table 4. Top 5 most influential variables used by XGB^a models (1-year surveillance period).^b

Model and rank	Holdout data		
	Institution A	Institution B	Institution C
XGB_A			
1	ASA ^c class	ASA class	ASA class
2	ICD ^d group: Z00-Z13 ^e	ICD group: Z00-Z13	ICD group: Z00-Z13
3	Multispecialty surgery	Multispecialty surgery	Service: hospitalist ^f
4	Service: hospitalist	Service: hospitalist	Multispecialty surgery
5	Emergency surgery	Previous delirium	Emergency surgery
XGB_B			
1	ASA class	ASA class	ASA class
2	Multispecialty surgery	Multispecialty surgery	Multispecialty surgery
3	Previous delirium	Previous delirium	Previous delirium
4	BMI	Urology/gynecology surgery	Service: orthopedics ^g
5	Emergency surgery	BMI	BMI
XGB_C			
1	ASA class	ASA class	ASA class
2	Service: hospitalist	Service: hospitalist	Service: orthopedics
3	Service: orthopedics	Service: orthopedics	Service: hospitalist
4	Previous delirium	Previous delirium	Previous delirium
5	Multispecialty surgery	Multispecialty surgery	ICD group: Z77-Z99 ^h

^aXGB: extreme gradient boosting.

^bFeature importance measured using Shapley Additive Explanation (SHAP) values. XGB_A, XGB_B, and XGB_C were trained on data from institutions A, B, and C, respectively.

^cASA: American Society of Anesthesiologists.

^dICD: *International Classification of Diseases*.

^eICD group Z00-Z13: persons encountering health services for examinations.

^fAdmitted to hospitalist service.

^gAdmitted to orthopedics service.

^hICD group Z77-Z99: persons with potential health hazards related to family and personal history and certain conditions influencing health status.

Discussion

Principal Findings

We developed and externally validated 3 models to predict POD with routine EHR data available at the time of hospital admission. In our experiments, XGB outperformed all other classifiers and demonstrated good discriminative ability on holdout data, achieving a maximum AUROC of 0.79. Generalizability varied by model and the institution used for external validation.

Our models demonstrated good predictive accuracy, with XGB_A outperforming XGB_B and XGB_C across all surveillance periods. Interestingly, longer surveillance periods did not appear to significantly benefit model performance. This is likely because the most important features were surgery-related variables, which were fixed across all surveillance durations. Additionally, surveillance duration did not impact how the models classified patients with confusion but no delirium (ie, potential subsyndromal delirium); approximately half were predicted to be cases, and the other half were predicted to be controls, regardless of the surveillance period. Given that subsyndromal delirium is thought to be on the spectrum between healthy

controls and delirium [38], it was expected that the models would have trouble classifying those patients.

Generalizability varied by model and institution. XGB_A performed relatively well when externally validated using data from institution C, as did XGB_C when validated using data from institution A. However, the AUROCs for both models decreased substantially when validated on data from institution B. In contrast, XGB_B had higher AUROCs when externally validated on institutions A and C than it did on holdout data from the same institution it was trained on. We hypothesize that the observed variation in performance could be due to institution B having a substantially different patient population than institutions A and C. Institutions A and C are trauma centers that perform a comparatively large number of orthopedic surgeries, and their populations have fewer comorbidities. Institution A also cares for complex vascular and cardiac patients, while the other 2 institutions generally do not. Conversely, institution B is not a trauma center and performs mostly general and urologic/gynecologic surgeries. It also largely services frail, high-acuity patients with chronic illnesses, and the general surgical complexity is higher. The comparatively low AUROC of XGB_B could reflect the model having difficulty discriminating between cases and controls, because it was trained on patients who were more ill, regardless of delirium status. These results highlight the importance of selecting an appropriate training population when a generalizable prediction model is desired; if a hospital has a patient population that differs significantly from the training data set, a localized model may be needed, even within the same hospital system.

The ASA class, a subjective measure of a patient's physiologic status [39], was frequently the most important feature. This supports previous literature linking a higher ASA class to a greater risk of POD [40]. The Elixhauser comorbidity index (ECI) did not appear in the list of top features despite the strong association of comorbidities with delirium, possibly because the ASA class summarizes health information beyond mortality risk and additionally identifies emergency cases. However, the subjectivity of the ASA class [41] may harm model generalizability compared to more objective measures, such as comorbidity scores. Other surgical variables, including admitting service and surgical specialty, were frequently among the top 5 features. Notably, both these variables have been associated with an increased risk of POD, particularly surgical specialty [6]. Multispecialty surgery was particularly important across models, suggesting that surgical complexity may be an important risk factor for delirium. The type of admitting service and individual surgical specialties that were most predictive differed by model, potentially because the distributions were different between institutions. For example, urologic/gynecologic surgery was frequently a top predictor in XGB_B models but not in others. This could be because proportionally more controls had that type of surgery than cases at institution B but not at institutions A and C. Reducing the cardinality of these variables is likely to improve generalizability but potentially at the cost of reduced discriminative ability. For XGB_A, the number of ICD codes belonging to ICD-10 group Z00-Z13 ("persons encountering health services for examinations") was a top feature, and higher

values negatively influenced model predictions. This may be because this ICD group captures routine health examinations, which are often undertaken by healthier individuals. The fact that the top features are supported by the literature suggests that the models are clinically explainable.

Several delirium prediction models have been developed, reporting AUROCs ranging from 0.56 to 0.94 [42]. The models with the highest AUROCs focus on specific patient subsets (ie, ICU patients, cardiac surgery) and include variables collected during the hospital stay, such as the APACHE score (which must be calculated), surgery duration (often not reliably recorded), and inpatient laboratory values. In-hospital variables may, indeed, be the strongest predictors of delirium and explain why our model failed to outperform previous ones; however, they were intentionally excluded from this study as that would preclude our models from being used at the time of hospitalization. Fewer models have been developed that are both her based and intended to be used at or shortly after admission. In their 2022 paper, Bishara et al [14] developed a POD prediction model for the general surgical population using different machine learning approaches and preoperative EHR data. They found that an XGB model outperforms other classifiers, similar to our findings, and reported an internal validation AUROC of 0.85 [14]. In contrast to our study, matching was not performed, and patients with dementia were included in the study population. Fifty-nine variables derived from inpatient (but preoperative) nursing assessments were also included as predictors. Some of these assessments (eg, Braden Scale score [43]) captured patients' functional status, which is highly correlated to delirium [5,6] and may explain why their model had a higher AUROC. Wong et al [44] developed a model to predict delirium in a general inpatient population without known cognitive impairment using an XGB model and reported an AUROC of 0.86. Their model used 796 features collected within 24 hours of admission and included inpatient neurologic examination data, which were highly predictive of delirium. These factors could explain, at least in part, the difference in performance between these previous models and our models.

In summary, our findings suggest that a machine learning model trained on routine EHR data can achieve clinically useful accuracy when predicting POD. Unlike previous models, the models presented in this study can be used to make predictions at the time of hospital admission, which could quickly inform preventive and resource-planning efforts. The models were also externally validated, providing critical information about generalizability when using a limited set of prehospital and surgery variables. These models can be readily integrated into EHR systems to provide a scalable, automated prescreening tool to flag patients who are at risk of developing POD and would benefit from targeted preventative measures.

Strengths and Limitations

Our study has several strengths. First, we used both the CAM method and ICD codes to maximize case identification; because delirium ICD codes are extremely specific but less sensitive [45], false negatives are unlikely. Second, we compared different surveillance periods to determine how surveillance duration influences accuracy. Third, we examined how the models

classify patients with confusion but no delirium, which could potentially capture subsyndromal delirium. Finally, we trained our models on data from 3 different institutions and externally validated them against each other to determine their transportability.

This study also has several limitations. Although we attempted to maximize delirium detection by using both the CAM method and ICD codes, a small number of patients did not have any CAM data available. As mentioned previously, delirium ICD codes tend to have high specificity but lower sensitivity [45], so some cases may have been missed. Patients were intentionally matched on age, sex, and race to limit biases related to these variables; however, discriminative ability was likely reduced as a result. Because patients with preexisting dementia or confusion during the inpatient visit (but no documented delirium) were excluded, the models may not generalize well to those types of patients. However, we chose to exclude those patients because their high risk of delirium was evident; our models focused on patients with a less clear delirium risk, which could partially explain the lower performance compared to

previous models. Finally, although the models were externally validated, the hospitals were within the same health care system, which may present more optimistic generalizability relative to uses of the models in outside systems.

Conclusion

Routine EHR data can be used for early delirium prediction in a diverse cohort of surgery patients without dementia. Although our models slightly underperformed relative to some of the previously published classifiers that use inpatient data, our routine EHR-based models serve a distinct purpose of enabling predictions at the time of admission, while being highly scalable. Generalizability varied depending on the training data, so institution-specific models may be necessary when using only a limited set of preadmission and surgery variables with distributions that substantially differ between institutions. The proposed models could be used in clinical practice as an automated prescreening tool for the early identification of high-risk patients, enabling clinicians to immediately adjust their care strategies and inform targeted delirium prevention measures and resource planning.

Acknowledgments

This study was supported by the National Institute on Aging (#K23AG071945).

Authors' Contributions

All authors contributed to study conception and design. EH performed all analyses and drafted the manuscript. All authors critically revised and reviewed the final manuscript.

Conflicts of Interest

ZBM has a financial interest in DigiCare Realized and could benefit from the results of this research. MB serves as a chief scientific officer and cofounder of BlueAgilis; and the chief health officer of DigiCare Realized, Inc. He has equity interest in Blue Agilis, Inc DigiCare Realized, Inc; Preferred Population Health Management LLC; and MyShift, Inc (previously known as RestUp, LLC). He serves as an advisory board member for Acadia Pharmaceuticals; Eisai, Inc; Biogen; and Genentech. These conflicts have been reviewed by Indiana University and have been appropriately managed to maintain objectivity. The remaining authors declare no competing interests.

Multimedia Appendix 1

Calibration curves for XGB; ICD codes for preexisting Alzheimer's disease, related dementias, delirium, and additional variables; sociodemographic and surgical characteristics of patients and controls; clinical characteristics of patients and controls; XGB model predictions for confusion encounters; and top 5 most influential variables used by XGB models. ICD: International Classification of Diseases; XGB: extreme gradient boosting.

[[DOCX File, 271 KB - periop_v8i1e59422_app1.docx](#)]

References

1. Marcantonio ER, Goldman L, Mangione CM, Ludwig LE, Muraca B, Haslauer CM, et al. A clinical prediction rule for delirium after elective noncardiac surgery. *JAMA* 1994 Jan 12;271(2):134-139. [Medline: [8264068](#)]
2. Marcantonio ER, Flacker JM, Wright RJ, Resnick NM. Reducing delirium after hip fracture: a randomized trial. *J Am Geriatr Soc* 2001 May;49(5):516-522. [doi: [10.1046/j.1532-5415.2001.49108.x](#)] [Medline: [11380742](#)]
3. Rudolph JL, Jones RN, Levkoff SE, Rockett C, Inouye SK, Sellke FW, et al. Derivation and validation of a preoperative prediction rule for delirium after cardiac surgery. *Circulation* 2009 Jan 20;119(2):229-236 [FREE Full text] [doi: [10.1161/CIRCULATIONAHA.108.795260](#)] [Medline: [19118253](#)]
4. Inouye SK, Westendorp RGJ, Saczynski JS. Delirium in elderly people. *Lancet* 2014 Mar 08;383(9920):911-922 [FREE Full text] [doi: [10.1016/S0140-6736\(13\)60688-1](#)] [Medline: [23992774](#)]
5. Marcantonio ER. In the clinic. Delirium. *Ann Intern Med* 2011 Jun 07;154(11):ITC6-1, ITC6. [doi: [10.7326/0003-4819-154-11-201106070-01006](#)] [Medline: [21646553](#)]

6. Vasilevskis EE, Han JH, Hughes CG, Ely EW. Epidemiology and risk factors for delirium across hospital settings. *Best Pract Res Clin Anaesthesiol* 2012 Sep;26(3):277-287 [FREE Full text] [doi: [10.1016/j.bpa.2012.07.003](https://doi.org/10.1016/j.bpa.2012.07.003)] [Medline: [23040281](https://pubmed.ncbi.nlm.nih.gov/23040281/)]
7. Brouquet A, Cudennec T, Benoist S, Moulias S, Beauchet A, Penna C, et al. Impaired mobility, ASA status and administration of tramadol are risk factors for postoperative delirium in patients aged 75 years or more after major abdominal surgery. *Ann Surg* 2010 Apr;251(4):759-765. [doi: [10.1097/SLA.0b013e3181c1cfc9](https://doi.org/10.1097/SLA.0b013e3181c1cfc9)] [Medline: [20224380](https://pubmed.ncbi.nlm.nih.gov/20224380/)]
8. Greene NH, Attix DK, Weldon BC, Smith PJ, McDonagh DL, Monk TG. Measures of executive function and depression identify patients at risk for postoperative delirium. *Anesthesiology* 2009 Apr;110(4):788-795 [FREE Full text] [doi: [10.1097/aln.0b013e31819b5ba6](https://doi.org/10.1097/aln.0b013e31819b5ba6)] [Medline: [19326494](https://pubmed.ncbi.nlm.nih.gov/19326494/)]
9. Noimark D. Predicting the onset of delirium in the post-operative patient. *Age Ageing* 2009 Jul;38(4):368-373. [doi: [10.1093/ageing/afp024](https://doi.org/10.1093/ageing/afp024)] [Medline: [19297372](https://pubmed.ncbi.nlm.nih.gov/19297372/)]
10. Koebrugge B, van Wensen RJA, Bosscha K, Dautzenberg PLJ, Koning OHJ. Delirium after emergency/elective open and endovascular aortoiliac surgery at a surgical ward with a high-standard delirium care protocol. *Vascular* 2010;18(5):279-287. [doi: [10.2310/6670.2010.00052](https://doi.org/10.2310/6670.2010.00052)] [Medline: [20822723](https://pubmed.ncbi.nlm.nih.gov/20822723/)]
11. Witlox J, Eurelings LSM, de Jonghe JFM, Kalisvaart KJ, Eikelenboom P, van Gool WA. Delirium in elderly patients and the risk of postdischarge mortality, institutionalization, and dementia: a meta-analysis. *JAMA* 2010 Jul 28;304(4):443-451. [doi: [10.1001/jama.2010.1013](https://doi.org/10.1001/jama.2010.1013)] [Medline: [20664045](https://pubmed.ncbi.nlm.nih.gov/20664045/)]
12. Inouye SK, Bogardus ST, Charpentier PA, Leo-Summers L, Acampora D, Holford TR, et al. A multicomponent intervention to prevent delirium in hospitalized older patients. *N Engl J Med* 1999 Mar 04;340(9):669-676. [doi: [10.1056/NEJM199903043400901](https://doi.org/10.1056/NEJM199903043400901)] [Medline: [10053175](https://pubmed.ncbi.nlm.nih.gov/10053175/)]
13. Hshieh TT, Yang T, Gartaganis SL, Yue J, Inouye SK. Hospital elder life program: systematic review and meta-analysis of effectiveness. *Am J Geriatr Psychiatry* 2018 Oct;26(10):1015-1033 [FREE Full text] [doi: [10.1016/j.jagp.2018.06.007](https://doi.org/10.1016/j.jagp.2018.06.007)] [Medline: [30076080](https://pubmed.ncbi.nlm.nih.gov/30076080/)]
14. Bishara A, Chiu C, Whitlock EL, Douglas VC, Lee S, Butte AJ, et al. Postoperative delirium prediction using machine learning models and preoperative electronic health record data. *BMC Anesthesiol* 2022 Jan 03;22(1):8 [FREE Full text] [doi: [10.1186/s12871-021-01543-y](https://doi.org/10.1186/s12871-021-01543-y)] [Medline: [34979919](https://pubmed.ncbi.nlm.nih.gov/34979919/)]
15. Hu X, Liu H, Zhao X, Sun X, Zhou J, Gao X, et al. Automated machine learning-based model predicts postoperative delirium using readily extractable perioperative collected electronic data. *CNS Neurosci Ther* 2022 Apr;28(4):608-618 [FREE Full text] [doi: [10.1111/cns.13758](https://doi.org/10.1111/cns.13758)] [Medline: [34792857](https://pubmed.ncbi.nlm.nih.gov/34792857/)]
16. Davoudi A, Ebadi A, Rashidi P, Ozrazgat-Baslanti T, Bihorac A, Bursian AC. Delirium prediction using machine learning models on preoperative electronic health records data. *Proc IEEE Int Symp Bioinformatics Bioeng* 2017 Oct;2017:568-573 [FREE Full text] [doi: [10.1109/BIBE.2017.00014](https://doi.org/10.1109/BIBE.2017.00014)] [Medline: [30393788](https://pubmed.ncbi.nlm.nih.gov/30393788/)]
17. Racine AM, Tommet D, D'Aquila ML, Fong TG, Gou Y, Tabloski PA, RISE Study Group. Machine learning to develop and internally validate a predictive model for post-operative delirium in a prospective, observational clinical cohort study of older surgical patients. *J Gen Intern Med* 2021 Feb;36(2):265-273 [FREE Full text] [doi: [10.1007/s11606-020-06238-7](https://doi.org/10.1007/s11606-020-06238-7)] [Medline: [33078300](https://pubmed.ncbi.nlm.nih.gov/33078300/)]
18. Xue B, Li D, Lu C, King CR, Wildes T, Avidan MS, et al. Use of machine learning to develop and evaluate models using preoperative and intraoperative data to identify risks of postoperative complications. *JAMA Netw Open* 2021 Mar 01;4(3):e212240 [FREE Full text] [doi: [10.1001/jamanetworkopen.2021.2240](https://doi.org/10.1001/jamanetworkopen.2021.2240)] [Medline: [33783520](https://pubmed.ncbi.nlm.nih.gov/33783520/)]
19. Zhao H, You J, Peng Y, Feng Y. Machine learning algorithm using electronic chart-derived data to predict delirium after elderly hip fracture surgeries: a retrospective case-control study. *Front Surg* 2021;8:634629 [FREE Full text] [doi: [10.3389/fsurg.2021.634629](https://doi.org/10.3389/fsurg.2021.634629)] [Medline: [34327210](https://pubmed.ncbi.nlm.nih.gov/34327210/)]
20. Matsumoto K, Nohara Y, Sakaguchi M, Takayama Y, Fukushima S, Soejima H, et al. Temporal generalizability of machine learning models for predicting postoperative delirium using electronic health record data: model development and validation study. *JMIR Perioper Med* 2023 Oct 26;6:e50895 [FREE Full text] [doi: [10.2196/50895](https://doi.org/10.2196/50895)] [Medline: [37883164](https://pubmed.ncbi.nlm.nih.gov/37883164/)]
21. Mufti HN, Hirsch GM, Abidi SR, Abidi SSR. Exploiting machine learning algorithms and methods for the prediction of agitated delirium after cardiac surgery: models development and validation study. *JMIR Med Inform* 2019 Oct 23;7(4):e14993 [FREE Full text] [doi: [10.2196/14993](https://doi.org/10.2196/14993)] [Medline: [31558433](https://pubmed.ncbi.nlm.nih.gov/31558433/)]
22. Jung JW, Hwang S, Ko S, Jo C, Park HY, Han H, et al. A machine-learning model to predict postoperative delirium following knee arthroplasty using electronic health records. *BMC Psychiatry* 2022 Jun 27;22(1):436 [FREE Full text] [doi: [10.1186/s12888-022-04067-y](https://doi.org/10.1186/s12888-022-04067-y)] [Medline: [35761274](https://pubmed.ncbi.nlm.nih.gov/35761274/)]
23. Luo Y, Wu X, Song Y, Wang X, Liu K, Shi C, et al. Development and validation of a nomogram to predict postoperative delirium in older patients after major abdominal surgery: a retrospective case-control study. *Perioper Med (Lond)* 2024 May 16;13(1):41 [FREE Full text] [doi: [10.1186/s13741-024-00399-3](https://doi.org/10.1186/s13741-024-00399-3)] [Medline: [38755693](https://pubmed.ncbi.nlm.nih.gov/38755693/)]
24. Geßele C, Saller T, Smolka V, Dimitriadis K, Amann U, Strobach D. Development and validation of a new drug-focused predictive risk score for postoperative delirium in orthopaedic and trauma surgery patients. *BMC Geriatr* 2024 May 13;24(1):422 [FREE Full text] [doi: [10.1186/s12877-024-05005-1](https://doi.org/10.1186/s12877-024-05005-1)] [Medline: [38741037](https://pubmed.ncbi.nlm.nih.gov/38741037/)]
25. Fan Y, Yang T, Liu Y, Gan H, Li X, Luo Y, et al. Nomogram for predicting the risk of postoperative delirium in elderly patients undergoing orthopedic surgery. *Perioper Med (Lond)* 2024 May 04;13(1):34 [FREE Full text] [doi: [10.1186/s13741-024-00393-9](https://doi.org/10.1186/s13741-024-00393-9)] [Medline: [38702728](https://pubmed.ncbi.nlm.nih.gov/38702728/)]

26. Nagata C, Hata M, Miyazaki Y, Masuda H, Wada T, Kimura T, et al. Development of postoperative delirium prediction models in patients undergoing cardiovascular surgery using machine learning algorithms. *Sci Rep* 2023 Nov 30;13(1):21090 [FREE Full text] [doi: [10.1038/s41598-023-48418-5](https://doi.org/10.1038/s41598-023-48418-5)] [Medline: [38036664](https://pubmed.ncbi.nlm.nih.gov/38036664/)]
27. Collins GS, Reitsma JB, Altman DG, Moons K. Transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD): the TRIPOD statement. *BMC Med* 2015 Jan 06;13(1):1 [FREE Full text] [doi: [10.1186/s12916-014-0241-z](https://doi.org/10.1186/s12916-014-0241-z)] [Medline: [25563062](https://pubmed.ncbi.nlm.nih.gov/25563062/)]
28. IU Health: about our system. Indiana University Health. URL: <https://iuhealth.org/about-our-system> [accessed 2024-04-15]
29. Inouye SK, van Dyck CH, Alessi CA, Balkin S, Siegel AP, Horwitz RI. Clarifying confusion: the Confusion Assessment Method. A new method for detection of delirium. *Ann Intern Med* 1990 Dec 15;113(12):941-948. [doi: [10.7326/0003-4819-113-12-941](https://doi.org/10.7326/0003-4819-113-12-941)] [Medline: [2240918](https://pubmed.ncbi.nlm.nih.gov/2240918/)]
30. Wei LA, Fearing MA, Sternberg EJ, Inouye SK. The Confusion Assessment Method: a systematic review of current usage. *J Am Geriatr Soc* 2008 May;56(5):823-830 [FREE Full text] [doi: [10.1111/j.1532-5415.2008.01674.x](https://doi.org/10.1111/j.1532-5415.2008.01674.x)] [Medline: [18384586](https://pubmed.ncbi.nlm.nih.gov/18384586/)]
31. Khuri SF, Henderson WG, Daley J, Jonasson O, Jones RS, Campbell DA, Principal Investigators of the Patient Safety in Surgery Study. Successful implementation of the Department of Veterans Affairs' National Surgical Quality Improvement Program in the private sector: the Patient Safety in Surgery study. *Ann Surg* 2008 Aug;248(2):329-336. [doi: [10.1097/SLA.0b013e3181823485](https://doi.org/10.1097/SLA.0b013e3181823485)] [Medline: [18650645](https://pubmed.ncbi.nlm.nih.gov/18650645/)]
32. Quan H, Sundararajan V, Halfon P, Fong A, Burnand B, Luthi J, et al. Coding algorithms for defining comorbidities in ICD-9-CM and ICD-10 administrative data. *Med Care* 2005 Nov;43(11):1130-1139. [doi: [10.1097/01.mlr.0000182534.19832.83](https://doi.org/10.1097/01.mlr.0000182534.19832.83)] [Medline: [16224307](https://pubmed.ncbi.nlm.nih.gov/16224307/)]
33. Elixhauser A, Steiner C, Harris DR, Coffey RM. Comorbidity measures for use with administrative data. *Med Care* 1998 Jan;36(1):8-27. [doi: [10.1097/00005650-199801000-00004](https://doi.org/10.1097/00005650-199801000-00004)] [Medline: [9431328](https://pubmed.ncbi.nlm.nih.gov/9431328/)]
34. van Walraven C, Austin PC, Jennings A, Quan H, Forster AJ. A modification of the Elixhauser comorbidity measures into a point system for hospital death using administrative data. *Med Care* 2009 Jun;47(6):626-633. [doi: [10.1097/MLR.0b013e31819432e5](https://doi.org/10.1097/MLR.0b013e31819432e5)] [Medline: [19433995](https://pubmed.ncbi.nlm.nih.gov/19433995/)]
35. Campbell N, Maidment I, Fox C, Khan B, Boustani M. The 2012 update to the anticholinergic cognitive burden scale. *J Am Geriatr Soc* 2013 Apr;61(S1):S142-S143. [doi: [10.1111/JGS.2013.61.ISSUE-S1](https://doi.org/10.1111/JGS.2013.61.ISSUE-S1)]
36. Anatomical therapeutic chemical (ATC) classification. World Health Organization. URL: <https://www.who.int/tools/atc-ddd-toolkit/atc-classification> [accessed 2023-09-04]
37. Lundberg SM, Lee LSI. A unified approach to interpreting model predictions. arXiv. Preprint posted online 2012. [doi: [10.48550/arXiv.1705.07874](https://doi.org/10.48550/arXiv.1705.07874)]
38. Ouimet S, Riker R, Bergeron N, Cossette M, Kavanagh B, Skrobik Y. Subsyndromal delirium in the ICU: evidence for a disease spectrum. *Intensive Care Med* 2007 Jun 3;33(6):1007-1013. [doi: [10.1007/s00134-007-0618-y](https://doi.org/10.1007/s00134-007-0618-y)] [Medline: [17404704](https://pubmed.ncbi.nlm.nih.gov/17404704/)]
39. Doyle DJ, Hendrix JM, Garmon EH. American Society of Anesthesiologists Classification. Treasure Island, FL: StatPearls Publishing; 2023.
40. Oh E, Li M, Fafowora T, Inouye S, Chen C, Rosman L, et al. Preoperative risk factors for postoperative delirium following hip fracture repair: a systematic review. *Int J Geriatr Psychiatry* 2015 Sep;30(9):900-910 [FREE Full text] [doi: [10.1002/gps.4233](https://doi.org/10.1002/gps.4233)] [Medline: [25503071](https://pubmed.ncbi.nlm.nih.gov/25503071/)]
41. Sankar A, Johnson SR, Beattie WS, Tait G, Wijeyesundera DN. Reliability of the American Society of Anesthesiologists physical status scale in clinical practice. *Br J Anaesth* 2014 Sep;113(3):424-432 [FREE Full text] [doi: [10.1093/bja/aeu100](https://doi.org/10.1093/bja/aeu100)] [Medline: [24727705](https://pubmed.ncbi.nlm.nih.gov/24727705/)]
42. Lindroth H, Bratzke L, Purvis S, Brown R, Coburn M, Mrkobrada M, et al. Systematic review of prediction models for delirium in the older adult inpatient. *BMJ Open* 2018 Apr 28;8(4):e019223 [FREE Full text] [doi: [10.1136/bmjopen-2017-019223](https://doi.org/10.1136/bmjopen-2017-019223)] [Medline: [29705752](https://pubmed.ncbi.nlm.nih.gov/29705752/)]
43. Bergstrom N, Braden BJ, Laguzza A, Holman V. The Braden Scale for predicting pressure sore risk. *Nurs Res* 1987;36(4):205-210. [Medline: [3299278](https://pubmed.ncbi.nlm.nih.gov/3299278/)]
44. Wong A, Young AT, Liang AS, Gonzales R, Douglas VC, Hadley D. Development and validation of an electronic health record-based machine learning model to estimate delirium risk in newly hospitalized patients without known cognitive impairment. *JAMA Netw Open* 2018 Aug 03;1(4):e181018 [FREE Full text] [doi: [10.1001/jamanetworkopen.2018.1018](https://doi.org/10.1001/jamanetworkopen.2018.1018)] [Medline: [30646095](https://pubmed.ncbi.nlm.nih.gov/30646095/)]
45. Kim D, Lee J, Kim C, Huybrechts K, Bateman B, Paterno E, et al. Evaluation of algorithms to identify delirium in administrative claims and drug utilization database. *Pharmacoepidemiol Drug Saf* 2017 Aug;26(8):945-953 [FREE Full text] [doi: [10.1002/pds.4226](https://doi.org/10.1002/pds.4226)] [Medline: [28485014](https://pubmed.ncbi.nlm.nih.gov/28485014/)]

Abbreviations

- ACB:** Anticholinergic Cognitive Burden
- ACh:** anticholinergic
- ASA:** American Society of Anesthesiologists
- ATC:** Anatomical Therapeutic Chemical

AUROC: area under the receiver operating characteristic curve
CAM: Confusion Assessment Method
CVD: cerebrovascular disease
ECI: Elixhauser comorbidity index
EHR: electronic health record
ICD: International Classification of Diseases
ICD-9: International Classification of Diseases, Ninth Revision
ICD-10-CM: International Classification of Diseases, Tenth Revision, Clinical Modification
IU: Indiana University
NPV: negative predictive value
POD: postoperative delirium
PPV: positive predictive value
SHAP: Shapley Additive Explanation
TBI: traumatic brain injury
XGB: extreme gradient boosting

Edited by N Rohatgi; submitted 11.04.24; peer-reviewed by SR Pagali; comments to author 26.07.24; revised version received 15.10.24; accepted 01.11.24; published 09.01.25.

Please cite as:

Holler E, Ludema C, Ben Miled Z, Rosenberg M, Kalbaugh C, Boustani M, Mohanty S
Development and Validation of a Routine Electronic Health Record-Based Delirium Prediction Model for Surgical Patients Without Dementia: Retrospective Case-Control Study
JMIR Perioper Med 2025;8:e59422
URL: <https://periop.jmir.org/2025/1/e59422>
doi: [10.2196/59422](https://doi.org/10.2196/59422)
PMID:

©Emma Holler, Christina Ludema, Zina Ben Miled, Molly Rosenberg, Corey Kalbaugh, Malaz Boustani, Sanjay Mohanty. Originally published in *JMIR Perioperative Medicine* (<http://periop.jmir.org>), 09.01.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in *JMIR Perioperative Medicine*, is properly cited. The complete bibliographic information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Original Paper

Agreement Between Provider-Completed and Patient-Completed Preoperative Frailty Screening Using the Clinical Risk Analysis Index: Cross-Sectional Questionnaire Study

Mehraneh Khalighi^{1,2*}, MD; Amy C Thomas^{3,4*}, MD; Karl J Brown^{4*}, MS; Katherine C Ritchey^{3,4*}, MPH, DO

¹Division of General Internal Medicine, Department of Medicine, University of Washington, Seattle, WA, United States

²Hospital and Specialty Medicine, VA Puget Sound Health Care System, Seattle, WA, United States

³Division of Geriatrics and Gerontology, Department of Medicine, University of Washington, Seattle, WA, United States

⁴Geriatric Research, Education and Clinical Center, VA Puget Sound Health Care System, Seattle, WA, United States

* all authors contributed equally

Corresponding Author:

Mehraneh Khalighi, MD

Hospital and Specialty Medicine

VA Puget Sound Health Care System

1660 South Columbian Way

S-112-SDU

Seattle, WA, 98108

United States

Phone: 1 206 764 2183

Fax: 1 206 277 6478

Email: mehraneh.khalighi@va.gov

Abstract

Background: Frailty is associated with postoperative morbidity and mortality. Preoperative screening and management of persons with frailty improves postoperative outcomes. The Clinical Risk Analysis Index (RAI-C) is a validated provider-based screening tool for assessing frailty in presurgical populations. Patient self-screening for frailty may provide an alternative to provider-based screening if resources are limited; however, the agreement between these 2 methods has not been previously explored.

Objective: The objective of our study was to examine provider-completed versus patient-completed RAI-C assessments to identify areas of disagreement between the 2 methods and inform best practices for RAI-C screening implementation.

Methods: Orthopedic physicians and physician assistants completed the RAI-C assessment on veterans aged 65 years and older undergoing elective total joint arthroplasty (eg, total hip or knee arthroplasty) and documented scores into the electronic health record during their preoperative clinic evaluation. Participants were then mailed the same RAI-C form after preoperative evaluation and returned responses to study coordinators. Agreement between provider-completed and patient-completed RAI-C assessments and differences within individual domains were compared.

Results: A total of 49 participants aged 65 years and older presenting for total joint arthroplasty underwent RAI-C assessment between November 2022 and August 2023. In total, 41% (20/49) of participants completed and returned an independent postvisit RAI-C assessment before surgery and within 180 days of their initial evaluation. There was a moderate but statistically significant correlation between provider-completed and patient-completed RAI-C assessments ($r=0.62$; 95% CI 0.25-0.83; $P=.003$). Provider-completed and patient-completed RAI-C assessments resulted in the same frailty classification in 60% (12/20) of participants, but 40% (8/20) of participants were reclassified to a more frail category based on patient-completed assessment. Agreement was the lowest between provider-completed and patient-completed screening questions regarding memory and activities of daily living.

Conclusions: RAI-C had moderate agreement when completed by providers versus the participants themselves, with more than a third of patient-completed screens resulting in a higher frailty classification. Future studies will need to explore the differences between and accuracy of RAI-C screening approaches to inform best practices for preoperative RAI-C assessment implementation.

(*JMIR Perioper Med* 2025;8:e66440) doi:[10.2196/66440](https://doi.org/10.2196/66440)

KEYWORDS

Risk Analysis Index; preoperative screening; questionnaire; frailty; self-reported; veteran; hip; knee; arthroplasty; elective surgery; cross-sectional; quality improvement

Introduction

Frailty is a multidimensional syndrome characterized by decreased physiological reserve reducing recovery from stressors including surgery and is associated with increased postoperative morbidity and mortality [1]. Frailty screening and multidisciplinary management of persons with frailty before elective surgery improve perioperative functional performance, decrease postoperative mortality, and may improve postoperative morbidity [2,3]. While numerous patient-completed frailty screening tools (eg, FRAIL Scale, Edmonton Frail Scale, and Vulnerable Elders Survey) have been used to predict surgical morbidity and mortality in different surgical populations, few have undergone as extensive validation in the presurgical population as the Clinical Risk Analysis Index (RAI-C) [4,5]. The RAI-C is a validated 14-item health and functioning questionnaire developed to distinguish between frail and robust persons in the preoperative setting. It calculates a score between 0 and 81 from information provided by a person or surrogate with scores ≥ 37 indicating frailty [5-7]. Higher RAI-C scores have been associated with postoperative mortality across surgical specialties suggesting its use as an easily administered preoperative risk-stratification tool [6-8]. RAI-C has been adopted by the Veterans Health Administration (VHA) as the preferred tool for presurgical frailty assessment with the goal to optimize the care of at-risk persons [9].

Validation studies suggest that persons can complete the RAI-C independently, which is advantageous if provider time is limited [6-8]. However, review of study methods indicates that providers modified participant responses as needed, suggesting that screening was not entirely patient-led [6,7]. It is uncertain how often providers changed participant responses, which domains were modified, and how modifications affected frailty classifications. Therefore, we sought to examine provider-completed versus patient-completed RAI-C assessments to identify areas of disagreement between the 2 methods and inform best practices for RAI-C screening implementation.

Methods

Screening Procedures

Overview

As part of a quality improvement initiative, we designed and implemented a cross-sectional pilot examination to screen participants aged 65 years and older referred to an outpatient, VHA orthopedic clinic for elective total joint arthroplasty (TJA; eg, total hip or knee arthroplasty) for frailty between November 2022 and August 2023. The primary aim was to examine the agreement between provider-completed and patient-completed RAI-C assessments to inform frailty screening practices at our institution.

Orthopedic physicians and physician assistants underwent training on the use of an electronic health record (EHR)-embedded web-based RAI-C questionnaire. During preoperative evaluations, providers screened participants for frailty using the EHR-embedded assessment and recorded the RAI-C scores. Robust (RAI-C < 30), prefrail (RAI-C 30-36), and frail (RAI-C ≥ 37) classifications were based on cutoffs defined in a large recalibration and external validation study of patients undergoing major elective noncardiac surgery. In that study, the 180-day postoperative mortality rate for RAI-C ≥ 30 was 2.0%, surpassing the overall mean mortality rate of 1.8%, and 4.3% for RAI-C ≥ 37 , which is greater than twice the mean mortality rate of the population [5]. All participants also underwent screening for dementia with the Mini-Cog, a validated cognitive screen combining 3-item word memory and clock drawing [10]. Scores range from 0 to 5, with scores < 3 indicating significant risk for dementia [11]. After the visit, participants were mailed a paper version of the RAI-C with a letter explaining the purpose of the screening tool and instructions on how to send back completed forms to study coordinators.

Participants were excluded from the study if surgery was performed before the participant responses to the RAI-C were received for analysis to mitigate possible confounding effects of surgery on patient-completed RAI-C responses. In addition, we excluded participant responses that were received more than 180 days from the date of provider-completed RAI-C to avoid confounding effects of progressive loss of function and osteoarthritis-related pain on the patient-completed RAI-C results. We chose an exclusion cutoff of 180 days based on findings that in individuals awaiting TJA for more than 180 days, worsening patient-reported outcome measures (ie, joint-specific function and health-related quality of life) were associated with increased levels of clinical frailty [12].

Analysis of Intervention and Measures

Patient-completed RAI-C responses were compared with provider-completed EHR-RAI-C results and analyzed for discrepancies between their total RAI-C and individual domain scores. The study authors performed a detailed EHR review to verify accuracy of provider and participant responses pertaining to health conditions (ie, presence of renal failure, heart failure, weight loss, or cancer). The provider completing the RAI-C also performed Mini-Cog screening for dementia to identify persons who would benefit from geriatric consultation (eg, scores < 3), but results of this screening did not inform the subjective participant responses to the RAI-C question on loss of memory. The accuracy of participant responses to subjective questions (ie, limitations in activities of daily living [ADLs], loss of appetite, or memory problems) was not verified.

The primary outcome measure was the degree of concordance between provider-completed and patient-completed total RAI-C scores. Secondary outcome measures were degree of concordance between the responses for individual domains and

the effect of time elapsed between provider-completed and patient-completed responses on the degree of concordance between scores. The Pearson product-moment correlation coefficient (r) was used to determine the linear relationship between provider-completed and patient-completed total RAI-C and individual RAI-C domain scores and time elapsed in days from provider to participant completion of the RAI-C and the absolute difference in scores obtained, respectively. Quantile-quantile plots and histograms of both the provider-completed and patient-completed total RAI-C scores indicated that the distributions of both variables were approximately normal. All analyses were performed in R (version 4.3.1; R Foundation for Statistical Computing).

Ethical Considerations

The Human Research Protection Program, Associate Chief of Staff for Research and Development, and Quality, Safety, and Values department reviewed this project in accordance with the Veterans Health Administration Program Guide 1200.21 and determined that it was a nonresearch, operations activity. Thus, approval by an institutional review board and consent to participate were not needed. Participant data were anonymized to ensure privacy and confidentiality. Participants were not offered compensation.

Results

Forty-nine participants aged 65 years and older presenting for TJA underwent RAI-C screening between November 2022 and August 2023. In total, 61% (30/49) of participants returned a postvisit RAI-C assessment, but 9 participants underwent surgery before completion and were excluded from analysis. An additional participant who returned a postvisit RAI-C assessment more than 180 days from orthopedic clinic evaluation was excluded. Therefore, 41% (20/49) of participants who returned a completed postvisit RAI-C assessment before surgery within 180 days from their initial evaluation were included in our analysis and their characteristics are summarized in [Table 1](#). The number of positive responses to RAI-C questions reported in [Table 2](#) show all responses. Identical result counts between provider and patient responses do not necessarily indicate agreement between their respective responses.

We used RAI-C score without cancer in our analysis since none of the participants met RAI-C definition of cancer (ie, unresectable cancer, metastatic cancer with poor prognosis, chemotherapy within 30 days, or radiotherapy within 90 days). There was statistically significant, moderate correlation between provider-completed and patient-completed RAI-C ($N=20$, $r=0.62$, 95% CI 0.25-0.83; $P=.003$; [Figure 1](#)).

Table 1. Participant characteristics (N=20).

Characteristics	Values
Gender, n (%)	
Men	19 (95)
Average age, years (range)	74 (66-83)
Race, n (%)^a	
White	17 (85)
Black	2 (10)
Preferred language, n (%)^b	
English	18 (90)
Mini-Cog score ≥ 3 , n (%)	19 (95)

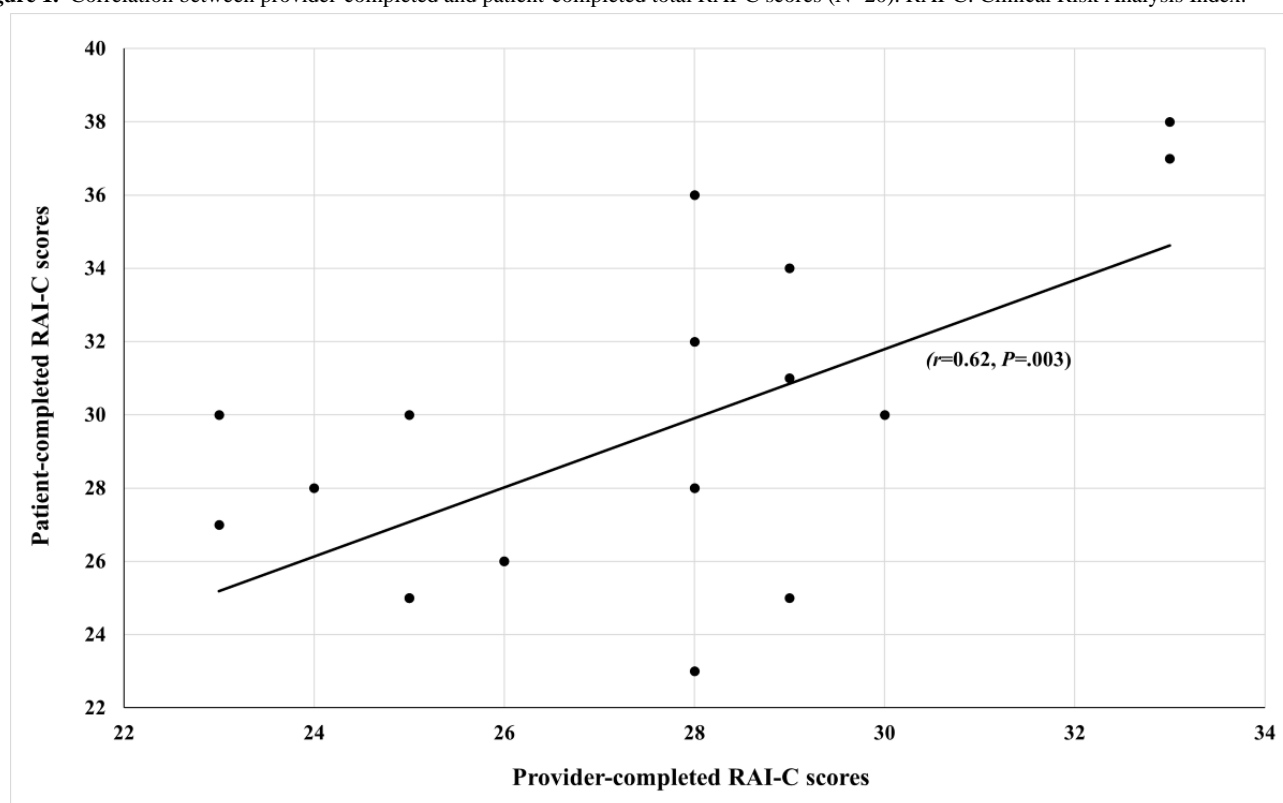
^aOne participant declined to respond.

^bTwo participants declined to respond.

Table 2. Patients' and providers' responses.

Factors	Patient-completed	Provider-completed
Medical conditions per RAI-C^a definition, n (%)		
Kidney disease	0 (0)	0 (0)
Heart failure	3 (15)	0 (0)
Shortness of breath	0 (0)	0 (0)
Cancer within 5 years	0 (0)	0 (0)
Nutrition, n (%)		
Loss of weight	3 (15)	1 (5)
Loss of appetite	1 (5)	0 (0)
Cognition, n (%)		
Loss of memory	4 (20)	3 (15)
Limitations in activities of daily living, n (%)		
Mobility	10 (50)	10 (50)
Eating	3 (15)	1 (5)
Toileting	2 (10)	0 (0)
Personal hygiene	2 (10)	0 (0)
Total RAI-C score, n (%)		
RAI-C <30 (Robust)	11 (55)	17 (85)
RAI-C 30-36 (Prefrail)	7 (35)	3 (15)
RAI-C ≥ 37 (Frail)	2 (10)	0 (0)

^aRAI-C: Clinical Risk Analysis Index.

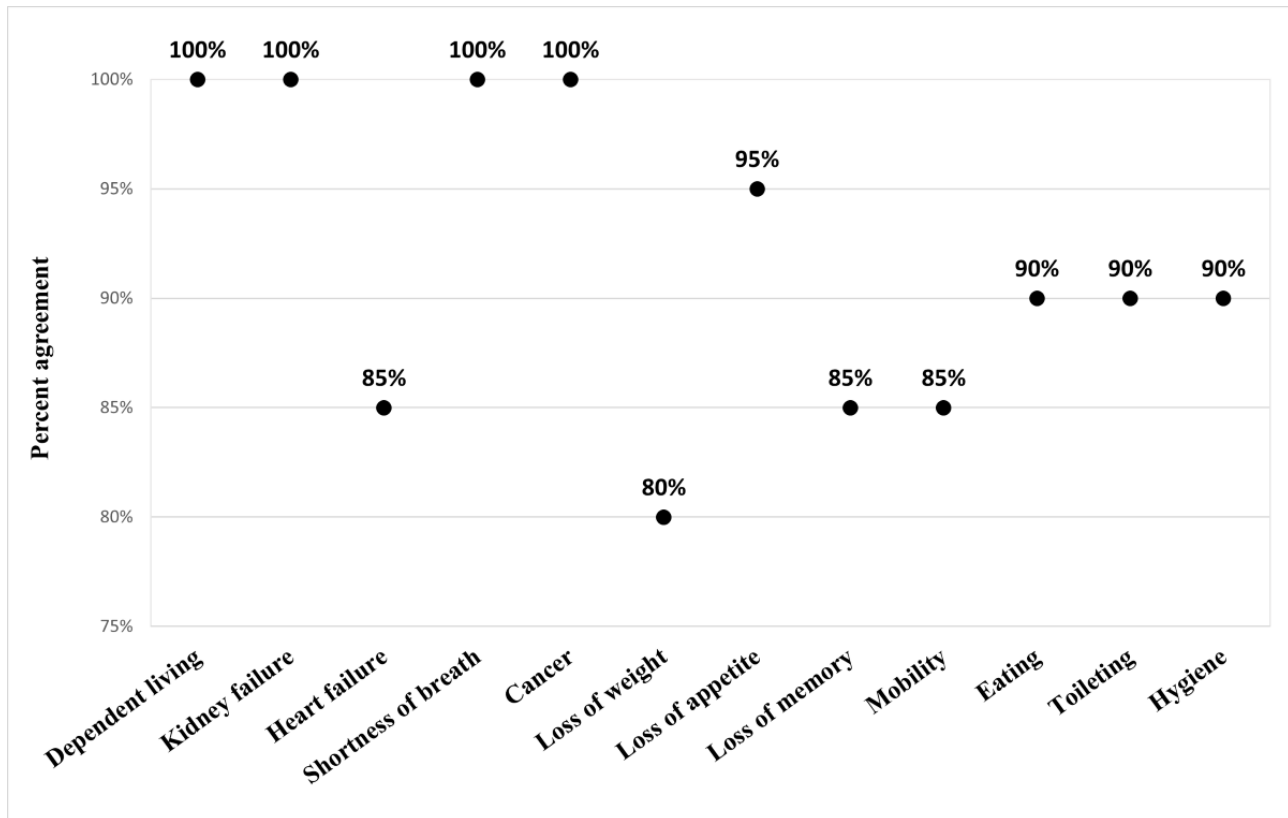
Figure 1. Correlation between provider-completed and patient-completed total RAI-C scores (N=20). RAI-C: Clinical Risk Analysis Index.

Frailty classification was identical in 60% (12/20) of participants. The remaining 40% (8/20) of participants were reclassified to a higher level of frailty based on patient-completed RAI-C scores. In addition, 30% (6/20) of

participants were reclassified from robust to prefrail and 10% (2/20) from prefrail to frail (Multimedia Appendix 1).

Agreement between questions concerning chronic health conditions such as kidney disease and cancer was relatively high (Figure 2).

Figure 2. Percentage agreement between provider-completed and patient-completed responses to individual domains of the Clinical Risk Analysis Index (N=20).



The domains with lowest agreements included heart failure, loss of weight, loss of memory, and the mobility subcategory of ADLs. Neither participant nor provider responses to weight loss (ie, loss of ≥ 10 lb in the past 3 months without trying) were accurate as they were not supported by EHR-documented weights. Although participant responses to weight loss compared with provider responses differed in 20% (4/20) of participants, this disagreement did not affect their respective frailty classification.

In responding to questions on loss of appetite, loss of memory, and limitations in ADLs, 45% (9/20) of participants assigned lower scores than providers, which reclassified 6 of these participants to a higher level of frailty. Therefore, participant responses to questions pertaining to loss of appetite, loss of memory, and ADLs accounted for 75% (6/8) of observed reclassifications to a higher level of frailty. The remaining 2 observed reclassifications to a higher level of frailty were based on participant responses indicating presence of heart failure, which was supported on review of EHR documentation of heart failure symptoms or consistent findings on transthoracic echocardiography.

On average, participants returned self-assessments within 41 days of the date the forms were mailed to them (median 28, range 21-68 days) with an average time between completion of

provider and participant RAI-C forms of 65 (median 65, range 25-118) days. Time elapsed between assessments did not correlate with the differences observed between RAI-C scores (N=20, $r=0.38$; $P=.10$).

Discussion

Principal Findings

The RAI-C is preferred for preoperative frailty screening in VHA and has been validated in presurgical populations [5-7]. These prior validation studies have not fully explored the relationship between provider and patient-completed assessments as a method to increase screening efficiency. We showed that our population of older veterans with low concern for cognitive impairment presenting for elective orthopedic TJA could complete RAI-C assessments independently. However, the correlation between provider-completed and patient-completed RAI-C scores was only moderate and more than a third of participants were reclassified to higher levels of frailty based on self-assessment. While other studies comparing provider versus participant perceptions of frailty also observed moderate correlation between the 2 methods, their study populations and settings were different (emergency room vs preoperative setting), they used a different screening tool (Clinical Frail Scale vs RAI-C), and they found that providers

assigned higher levels of frailty than participants [13,14]. Our study is one of the first to highlight areas of discrepancy between provider-completed and patient-completed RAI-C, suggesting challenges to the predictive validity of this tool and considerations for clinical implementation.

We found that disagreement between provider and participant responses and reclassifications were mainly based on participant-perceived decline in appetite, memory, and performance of ADLs, or heart failure. Notably, all participants accurately recognized their heart failure diagnosis, while providers missed the diagnosis in 3 cases. Disagreement between provider and participant responses to these domains (ie, heart failure, loss of appetite, memory loss, and limitations in ADLs) and provider underclassification of frailty has potentially significant clinical ramifications. Although optimal management of frailty is ill-defined, expert consensus suggests that persons with frailty should undergo comprehensive assessments to identify and address rehabilitative, nutritional, and psychosocial needs preoperatively [15]. Emerging data suggest that multimodal interventions can improve postsurgical outcomes for persons with frailty undergoing elective surgeries [3,16,17]. High-risk surgical candidates with frailty should have exploration of their health care priorities, postsurgical goals, and care preferences to avoid potentially deleterious postoperative outcomes [18]. Clarification of goals of care in the context of surgical risk and expected clinical outcomes, termed “surgical pause,” increases receipt of goal-concordant care and avoids unwanted surgery [19]. Thus, adequately and accurately identifying level of functional ability, cognition, and ultimately frailty of preoperative persons is important for unbiased care planning and resource allocation.

However, disuse or incorrect use of frailty screening tools can contribute to misclassification of frailty, potentially limiting access to interventions and significantly impacting quality of life and function. Elective TJA is rarely lifesaving but significantly impacts functional ability and preservation of independence [20]. Without consistent use of validated tools to screen for frailty, ageism and other implicit biases may contribute to overclassification of frailty by health care professionals and increase their reluctance to offer therapies simply based on biological age or “old” appearance [21]. Alternatively, concerns about surgical candidacy, unaddressed pain, and further loss of function may contribute to social desirability and response biases that encourage underclassification of frailty by participants who are reluctant to report functional or other limitations when responding to provider questions assessing for presurgical frailty [22,23]. Similar to responses to sensitive questions, where perceptions of anonymity and privacy increase the accuracy of self-reported answers, written responses to questions on performance of ADLs may be more accurate than verbal responses to providers, especially during the first encounter when participants have not yet built rapport with their providers [24,25].

In addition, the lived experiences of older adults and their perception of health may influence frailty classification and related health outcomes [26]. The person’s perception of decline in one domain (eg, performance of ADLs) may affect performance in other domains (eg, decline in appetite or memory) with a cumulative effect on level of frailty [26]. Therefore, the participants’ responses could be considered a more accurate reflection of subjective symptoms or functional ability, as they represent the individuals’ perceptions of their health.

When participants respond to the same questions without provider oversight, the effect of these biases may be minimized, and the accuracy of the screening tool might improve.

Limitations

Our evaluation was limited to a small population of mainly English-speaking men with low concern for cognitive impairment within 1 VHA orthopedic surgery clinic which may not relate to other presurgical populations (eg, peripheral vascular surgery or general surgery) with different prevalences of frailty and cognitive impairment. In addition, worsening joint-specific function and health-related quality of life with longer wait times before TJA or surgical intervention between provider and patient-completed RAI-C can influence participants’ responses. Therefore, we attempted to mitigate possible confounding effects of prolonged wait times before surgery by excluding participant-completed RAI-C results that were completed more than 180 days from provider-completed surveys. We attempted to mitigate the effect of surgery on patient-completed RAI-C by excluding those participants who underwent surgery before completing the self-reported RAI-C. Nonetheless, our study was strengthened by the high participant response rate of more than 40%. In most cases of disagreement (ie, cognition and limitations in ADLs), participants’ responses resulted in a higher frailty classification, which could not be verified for accuracy. Furthermore, we could not assess for the role of selection bias on our findings. It is possible that self-reported responses to the RAI-C were predominantly completed and returned by participants who disagreed with provider-completed responses to the RAI-C. Finally, participant completion of the RAI-C relies on the ability to read and understand the questions. We were unable to assess the effects of health literacy or educational level on assessment disagreements.

Conclusions

Frailty screening with the RAI-C can be done by providers or patients before elective orthopedic TJA. The level of disagreement observed between provider-completed and patient-completed assessments suggests that these methods are not interchangeable. Future studies exploring screening methods in larger, more diverse populations who are undergoing a variety of surgeries may clarify challenges to screening accuracy and validity of patient-completed screening approaches.

Acknowledgments

Partial financial support was received from Veterans Integrated Service Network (VISN) 20 for clinical demonstration and innovation programs.

Authors' Contributions

MK, AT, and KR contributed to the concept and design of the project; MK and KR took the lead in drafting the manuscript; and MK and KB conducted the data analysis. All authors provided critical feedback and helped shape this manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Frailty classification based on provider-completed versus patient-completed RAI-C scores (N=20). RAI-C: Clinical Risk Analysis Index.

[PNG File, 51 KB - [periop_v8i1e66440_app1.png](#)]

References

1. Shinall MC, Arya S, Youk A, Varley P, Shah R, Massarweh NN, et al. Association of preoperative patient frailty and operative stress with postoperative mortality. *JAMA Surg* 2020;155(1):e194620 [FREE Full text] [doi: [10.1001/jamasurg.2019.4620](https://doi.org/10.1001/jamasurg.2019.4620)] [Medline: [31721994](https://pubmed.ncbi.nlm.nih.gov/31721994/)]
2. Hall DE, Arya S, Schmid KK, Carlson MA, Lavedan P, Bailey TL, et al. Association of a frailty screening initiative with postoperative survival at 30, 180, and 365 Days. *JAMA Surg* 2017;152(3):233-240 [FREE Full text] [doi: [10.1001/jamasurg.2016.4219](https://doi.org/10.1001/jamasurg.2016.4219)] [Medline: [27902826](https://pubmed.ncbi.nlm.nih.gov/27902826/)]
3. Hall DE, Youk A, Allsup K, Kennedy K, Byard TD, Dhupar R, et al. Preoperative rehabilitation is feasible in the weeks prior to surgery and significantly improves functional performance. *J Frailty Aging* 2023;12(4):267-276 [FREE Full text] [doi: [10.14283/jfa.2022.42](https://doi.org/10.14283/jfa.2022.42)] [Medline: [38008976](https://pubmed.ncbi.nlm.nih.gov/38008976/)]
4. Nidadavolu LS, Ehrlich AL, Sieber FE, Oh ES. Preoperative evaluation of the frail patient. *Anesth Analg* 2020;130(6):1493-1503 [FREE Full text] [doi: [10.1213/ANE.0000000000004735](https://doi.org/10.1213/ANE.0000000000004735)] [Medline: [32384339](https://pubmed.ncbi.nlm.nih.gov/32384339/)]
5. Arya S, Varley P, Youk A, Borrebach JD, Perez S, Massarweh NN, et al. Recalibration and external validation of the risk analysis index: a surgical frailty assessment tool. *Ann Surg* 2020;272(6):996-1005 [FREE Full text] [doi: [10.1097/SLA.0000000000003276](https://doi.org/10.1097/SLA.0000000000003276)] [Medline: [30907757](https://pubmed.ncbi.nlm.nih.gov/30907757/)]
6. Hall DE, Arya S, Schmid KK, Blaser C, Carlson MA, Bailey TL, et al. Development and initial validation of the risk analysis index for measuring frailty in surgical populations. *JAMA Surg* 2017;152(2):175-182 [FREE Full text] [doi: [10.1001/jamasurg.2016.4202](https://doi.org/10.1001/jamasurg.2016.4202)] [Medline: [27893030](https://pubmed.ncbi.nlm.nih.gov/27893030/)]
7. Shah R, Borrebach JD, Hodges JC, Varley PR, Wisniewski MK, Shinall MC, et al. Validation of the risk analysis index for evaluating frailty in ambulatory patients. *J Am Geriatr Soc* 2020;68(8):1818-1824 [FREE Full text] [doi: [10.1111/jgs.16453](https://doi.org/10.1111/jgs.16453)] [Medline: [32310317](https://pubmed.ncbi.nlm.nih.gov/32310317/)]
8. George EL, Hall DE, Youk A, Chen R, Kashikar A, Trickey AW, et al. Association between patient frailty and postoperative mortality across multiple noncardiac surgical specialties. *JAMA Surg* 2021;156(1):e205152 [FREE Full text] [doi: [10.1001/jamasurg.2020.5152](https://doi.org/10.1001/jamasurg.2020.5152)] [Medline: [33206156](https://pubmed.ncbi.nlm.nih.gov/33206156/)]
9. The surgical pause practice adopted as national program. US Department of Veterans Affairs. 2024 Feb 13. URL: <https://www.hsrd.research.va.gov/impacts/surgical-pause.cfm> [accessed 2024-07-13]
10. Borson S, Scanlan JM, Chen P, Ganguli M. The mini-cog as a screen for dementia: validation in a population-based sample. *J Am Geriatr Soc* 2003;51(10):1451-1454 [FREE Full text] [doi: [10.1046/j.1532-5415.2003.51465.x](https://doi.org/10.1046/j.1532-5415.2003.51465.x)] [Medline: [14511167](https://pubmed.ncbi.nlm.nih.gov/14511167/)]
11. Borson S, Scanlan J, Brush M, Vitaliano P, Dokmak A. The mini-cog: a cognitive 'vital signs' measure for dementia screening in multi-lingual elderly. *Int J Geriatr Psychiatry* 2000;15(11):1021-1027. [doi: [10.1002/1099-1166\(200011\)15:11<1021::aid-gps234>3.0.co;2-6](https://doi.org/10.1002/1099-1166(200011)15:11<1021::aid-gps234>3.0.co;2-6)] [Medline: [11113982](https://pubmed.ncbi.nlm.nih.gov/11113982/)]
12. Bayram JM, Wickramasinghe NR, Scott CEH, Clement ND. Clinical frailty is independently associated with joint-specific function and health-related quality of life in patients awaiting a total hip or knee arthroplasty. *Bone Jt Open* 2023 Apr 7;4(4):241-249. [doi: [10.1302/2633-1462.44.bjo-2023-0020.r1](https://doi.org/10.1302/2633-1462.44.bjo-2023-0020.r1)]
13. Shah SP, Penn K, Kaplan SJ, Vrablik M, Jablonowski K, Pham TN, et al. Comparison of bedside screening methods for frailty assessment in older adult trauma patients in the emergency department. *Am J Emerg Med* 2019;37(1):12-18. [doi: [10.1016/j.ajem.2018.04.028](https://doi.org/10.1016/j.ajem.2018.04.028)] [Medline: [29728285](https://pubmed.ncbi.nlm.nih.gov/29728285/)]
14. Dresden SM, Platts-Mills TF, Kandasamy D, Walden L, Betz ME. Patient versus physician perceptions of frailty: a comparison of clinical frailty scale scores of older adults in the emergency department. *Acad Emerg Med* 2019;26(9):1089-1092 [FREE Full text] [doi: [10.1111/acem.13825](https://doi.org/10.1111/acem.13825)] [Medline: [31265194](https://pubmed.ncbi.nlm.nih.gov/31265194/)]

15. Alvarez-Nebreda ML, Bentov N, Urman RD, Setia S, Huang JC, Pfeifer K, et al. Recommendations for preoperative management of frailty from the Society for Perioperative Assessment and Quality Improvement (SPAQI). *J Clin Anesth* 2018;47:33-42. [doi: [10.1016/j.jclinane.2018.02.011](https://doi.org/10.1016/j.jclinane.2018.02.011)] [Medline: [29550619](https://pubmed.ncbi.nlm.nih.gov/29550619/)]
16. Pouwels S, Stokmans RA, Willigendael EM, Nienhuijs SW, Rosman C, van Ramshorst B, et al. Preoperative exercise therapy for elective major abdominal surgery: a systematic review. *Int J Surg* 2014;12(2):134-140 [FREE Full text] [doi: [10.1016/j.ijsu.2013.11.018](https://doi.org/10.1016/j.ijsu.2013.11.018)] [Medline: [24325942](https://pubmed.ncbi.nlm.nih.gov/24325942/)]
17. Cabilan CJ, Hines S, Munday J. The effectiveness of prehabilitation or preoperative exercise for surgical patients: a systematic review. *JBI Database System Rev Implement Rep* 2015;13(1):146-187. [doi: [10.11124/jbisrir-2015-1885](https://doi.org/10.11124/jbisrir-2015-1885)] [Medline: [26447015](https://pubmed.ncbi.nlm.nih.gov/26447015/)]
18. Reuben DB, Jennings LA. Putting goal-oriented patient care into practice. *J Am Geriatr Soc* 2019;67(7):1342-1344 [FREE Full text] [doi: [10.1111/jgs.15885](https://doi.org/10.1111/jgs.15885)] [Medline: [30882888](https://pubmed.ncbi.nlm.nih.gov/30882888/)]
19. Oyekan AA, Lee JY, Hodges JC, Chen SR, Wilson AE, Fourman MS, et al. Increasing quality and frequency of goals-of-care documentation in the highest-risk surgical candidates: one-year results of the surgical pause program. *JB JS Open Access* 2023;8(2):e22.00107 [FREE Full text] [doi: [10.2106/JBJS.OA.22.00107](https://doi.org/10.2106/JBJS.OA.22.00107)] [Medline: [37101601](https://pubmed.ncbi.nlm.nih.gov/37101601/)]
20. Neuprez A, Neuprez AH, Kaux JF, Kurth W, Daniel C, Thirion T, et al. Total joint replacement improves pain, functional quality of life, and health utilities in patients with late-stage knee and hip osteoarthritis for up to 5 years. *Clin Rheumatol* 2020;39(3):861-871 [FREE Full text] [doi: [10.1007/s10067-019-04811-y](https://doi.org/10.1007/s10067-019-04811-y)] [Medline: [31720892](https://pubmed.ncbi.nlm.nih.gov/31720892/)]
21. Chang ES, Kanno S, Levy S, Wang SY, Lee JE, Levy BR. Global reach of ageism on older persons' health: a systematic review. *PLoS One* 2020;15(1):e0220857 [FREE Full text] [doi: [10.1371/journal.pone.0220857](https://doi.org/10.1371/journal.pone.0220857)] [Medline: [31940338](https://pubmed.ncbi.nlm.nih.gov/31940338/)]
22. Bispo JP. Social desirability bias in qualitative health research. *Rev Saude Publica* 2022;56:101 [FREE Full text] [doi: [10.11606/s1518-8787.2022056004164](https://doi.org/10.11606/s1518-8787.2022056004164)] [Medline: [36515303](https://pubmed.ncbi.nlm.nih.gov/36515303/)]
23. Tay Swee Cheng R, Klainin-Yobas P, Hegney D, Mackey S. Factors relating to perioperative experience of older persons undergoing joint replacement surgery: an integrative literature review. *Disabil Rehabil* 2015;37(1):9-24. [doi: [10.3109/09638288.2014.906663](https://doi.org/10.3109/09638288.2014.906663)] [Medline: [24689440](https://pubmed.ncbi.nlm.nih.gov/24689440/)]
24. Durant LE, Carey MP. Self-administered questionnaires versus face-to-face interviews in assessing sexual behavior in young women. *Arch Sex Behav* 2000;29(4):309-322. [doi: [10.1023/a:1001930202526](https://doi.org/10.1023/a:1001930202526)] [Medline: [10948721](https://pubmed.ncbi.nlm.nih.gov/10948721/)]
25. Ong AD, Weiss DJ. The Impact of Anonymity on Responses to Sensitive Questions. *J Applied Social Psychol* 2006 Jul 31;30(8):1691-1708. [doi: [10.1111/j.1559-1816.2000.tb02462.x](https://doi.org/10.1111/j.1559-1816.2000.tb02462.x)]
26. Khalil AH, Gobbens RJJ. What If the clinical and older adults' perspectives about frailty converge? A call for a mixed conceptual model of frailty: a traditional literature review. *Healthcare (Basel)* 2023;11(24):3174 [FREE Full text] [doi: [10.3390/healthcare11243174](https://doi.org/10.3390/healthcare11243174)] [Medline: [38132064](https://pubmed.ncbi.nlm.nih.gov/38132064/)]

Abbreviations

ADLs: activities of daily living
EHR: electronic health record
RAI-C: Clinical Risk Analysis Index
TJA: total joint arthroplasty
VHA: Veterans Health Administration

Edited by J Shiffmiller; submitted 12.09.24; peer-reviewed by J Hejkal, V Aznar-Tortonda; comments to author 24.10.24; revised version received 13.12.24; accepted 17.01.25; published 10.02.25.

Please cite as:

Khalighi M, Thomas AC, Brown KJ, Ritchey KC

Agreement Between Provider-Completed and Patient-Completed Preoperative Frailty Screening Using the Clinical Risk Analysis Index: Cross-Sectional Questionnaire Study

JMIR Perioper Med 2025;8:e66440

URL: <https://periop.jmir.org/2025/1/e66440>

doi: [10.2196/66440](https://doi.org/10.2196/66440)

PMID: [39928399](https://pubmed.ncbi.nlm.nih.gov/39928399/)

©Mehraneh Khalighi, Amy C Thomas, Karl J Brown, Katherine C Ritchey. Originally published in *JMIR Perioperative Medicine* (<http://periop.jmir.org>), 10.02.2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work, first published in *JMIR Perioperative Medicine*, is properly cited. The complete bibliographic

information, a link to the original publication on <http://periop.jmir.org>, as well as this copyright and license information must be included.

Publisher:
JMIR Publications
130 Queens Quay East.
Toronto, ON, M5A 3Y5
Phone: (+1) 416-583-2040
Email: support@jmir.org

<https://www.jmirpublications.com/>