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Original Research Article

Intraoperative forced-air warming, thermal trajectories, and postoperative recovery: a retrospective cohort study

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ABSTRACT

Background: Inadvertent perioperative hypothermia is common during surgery and may contribute to delayed postanesthesia recovery. We evaluated the association between intraoperative forced-air warming and postoperative recovery time and characterized intraoperative temperature trajectories according to surgical procedure.
Methods: This retrospective comparative cohort included 77 adults undergoing surgery under general anesthesia at ISSSTE Hospital General "Dr. Fernando Quiroz Gutiérrez" from July to August 2024. Thirty-nine patients received active forced-air warming with a 3M Bair Hugger® warming blanket and 38 received conventional thermal management. The primary outcome was postanesthesia care unit recovery time. Patient-level serial temperatures were analyzed with linear mixed-effects models. Recovery time was evaluated in analyzable treatment-by-procedure strata, and exploratory analyses assessed time to hypothermia, a proxy minimum-temperature outcome, and potential resource savings.
Results: Active warming was associated with 105.6 fewer minutes of recovery than conventional management (95% CI 51.2-160.0; p=0.002) in the adjusted aggregate model. Among the 39 actively warmed patients, 451 temperature measurements showed no significant overall linear change (-0.005°C per 20 minutes; 95% CI -0.014 to 0.004; p=0.262). Exploratory laparotomy had a more negative thermal slope, whereas resection procedures had a more positive slope relative to other general surgery. Twenty-six of 39 patients developed hypothermia; procedure category was not significantly associated with time to hypothermia.
Conclusions: Active warming was associated with shorter postoperative recovery, while thermal trajectories varied by procedure. Because the study was observational and the recovery analysis was based on aggregated strata, the findings should be interpreted as associations and confirmed prospectively.

Keywords: Body temperature, Forced-air warming, Postanesthesia recovery, Perioperative hypothermia, Surgery

INTRODUCTION

Inadvertent perioperative hypothermia, commonly defined as a core temperature below 36°C, remains frequent during surgery. In a prospective study of 2015 patients undergoing general anesthesia, perioperative hypothermia occurred in 78.6%, and prolonged anesthesia and larger volumes of intravenous fluid were important risk factors.[1] A more recent multicenter cohort of 4516 adults reported an overall intraoperative hypothermia incidence of 23.82%, with a higher proportion among patients who were already hypothermic at baseline.[2] A systematic review likewise identified anesthesia lasting more than 2 hours and intravenous fluid administration above 1000 mL as relevant risk factors.[3]

After induction of anesthesia, redistribution of heat from the core to the peripheral compartment, vasodilation, impaired thermoregulatory responses, and reduced

metabolic heat production promote early temperature decline.[4] Surgical exposure, evaporation, irrigation, blood loss, and a cool operating room may further increase heat loss.[4,5] During abdominal surgery, perioperative hypothermia can develop rapidly when effective warming is not used.[6] Hypothermia is clinically important because it may impair coagulation and platelet function, alter anesthetic drug metabolism, prolong neuromuscular blockade, and increase shivering.[4] A randomized trial in major abdominal surgery also demonstrated longer time to readiness for discharge from the postanesthesia care unit in hypothermic patients.[7]

Forced-air warming is among the most widely studied active warming strategies. A systematic review supports active body surface warming for maintaining normothermia and reducing postoperative shivering.[8] In a randomized trial, adding forced-air warming during anesthetic induction reduced intraoperative and postoperative hypothermia compared with passive insulation during induction; both groups subsequently received intraoperative warming.[9] Blanket location also influenced thermal outcomes in prone spinal surgery.[10] A trial in orthopedic surgery under spinal anesthesia compared resistive warming, forced-air warming, and their combination, without demonstrating a clear advantage of combining the two devices.[11] Prewarming may help preserve perioperative normothermia.[12] However, one randomized trial found no incremental benefit when a strict intraoperative temperature-management protocol was already applied.[13] In a randomized trial of laparoscopic thoracic or abdominal surgery, forced-air warming improved temperature control and reduced postoperative shivering levels compared with passive insulation.[14] In patients undergoing lung lobectomy, postoperative forced-air warming shortened the time to reach 37°C compared with cotton blankets.[15]

Thermal response is also influenced by the procedure itself and by correlated perioperative factors such as body mass index, baseline temperature, fasting, intravenous and irrigation volumes, blood loss, anesthesia duration, positioning, operating-room temperature, and humidity.[16] The operational consequences may extend beyond temperature alone. Budget-impact and health-technology assessments suggest that effective normothermia protocols can reduce resource use and potentially lower costs, although such estimates depend strongly on local practice and costing assumptions.[17,18]

The present study therefore evaluated the association between intraoperative forced-air warming and postoperative recovery time in a retrospective clinical cohort. Secondary objectives were to describe longitudinal intraoperative temperature trajectories, explore heterogeneity by surgical procedure, assess time to hypothermia, and estimate the potential operational implications of differences in recovery time.

We hypothesized that active warming would be associated with shorter recovery and that thermal trajectories would vary across surgical procedures.

METHODS

Study design and setting

We performed an observational, analytic, retrospective comparative cohort study of adults undergoing general, orthopedic, or gynecologic surgical procedures at ISSSTE Hospital General "Dr. Fernando Quiroz Gutiérrez", Mexico, from July to August 2024. Patients were classified according to the thermal-management strategy actually received during surgery: active forced-air warming or conventional management without active warming.

The study is reported in accordance with the STROBE recommendations for observational studies.[19]

Participants and surgical categories

The analytic sample included 77 patients aged up to 80 years; 39 received active warming and 38 constituted the conventional-management group. All eligible consecutive cases with sufficient clinical and perioperative information to determine thermal-management strategy and outcomes were included. Procedures were grouped into seven mutually exclusive categories: cholecystectomy, abdominal wall repair or hernioplasty, orthopedic surgery, hysterectomy, exploratory laparotomy, resection procedures, and other general surgery. The grouping was based on anatomic region, degree of surgical exposure, cavity opening, expected procedural magnitude and duration, and the number of observations available. "Other general surgery" was used as the reference category in procedure-specific models and should not be interpreted as a lower-risk or less complex group.

Eligibility and exclusion criteria

Patients were eligible if they were adults aged 80 years or younger and underwent a general, orthopedic, or gynecologic surgical procedure at the study hospital during the study period.

Patients were excluded if they were younger than 18 years or older than 80 years, underwent a procedure outside the prespecified surgical scope, or had insufficient clinical or perioperative documentation to determine the thermal-management strategy or ascertain the study outcomes.

Of the 88 records screened, 11 were excluded because the patients did not meet the age eligibility criteria. The remaining 77 patients were included in the analytic cohort: 39 received active forced-air warming and 38 received conventional thermal management.

Exposure and temperature assessment

The exposure of interest was intraoperative active warming with the 3M Bair Hugger® forced-air warming system using a disposable warming blanket. The comparator was conventional thermal management without active forced-air warming. The investigators did not determine the clinical indication for the device.

Baseline variables included age, sex, and surgical category. Perioperative hypothermia was defined as body temperature <36.0°C. Thermal outcomes included initial, minimum, and final temperature; absolute temperature change; any episode of hypothermia; time to the first measurement <36.0°C; proportion of observed time below 36.0°C; and the individual thermal slope. Serial temperatures were recorded at approximately 20-minute intervals. Hypothermia burden was expressed as degree-minutes below 36°C, calculated by linear interpolation and the trapezoidal rule.

Patient-level serial intraoperative temperatures were available for the 39 actively warmed patients. For the conventional group, thermal information used in the exploratory proxy analysis was available as category-level summaries rather than reconstructed patient-level trajectories. Accordingly, longitudinal mixed-model analyses describe the actively warmed cohort, whereas between-strategy thermal estimates based on summarized comparator information were treated as exploratory proxy analyses.

Recovery and resource outcomes

Perioperative intervals included the time from the end of surgery to admission to recovery, from admission to discharge from the postanesthesia care unit, and from recovery discharge to hospitalization. The principal operational outcome was time between admission to and discharge from the postanesthesia care unit.

Potential resource savings were estimated from the observed or modeled reduction in recovery time and the local cost-per-minute parameters used in the source analysis. These estimates were intended to describe operational magnitude and were not treated as a formal cost-effectiveness evaluation.

Data collection and ethics

Data were obtained retrospectively from clinical records, anesthesia records, perioperative nursing documentation, intraoperative temperature records, postanesthesia care unit records, and administrative documentation related to time and costs. Trained personnel extracted data using a standardized format. Information was anonymized before analysis and used exclusively for scientific purposes.

The protocol was reviewed and approved by the ethics committee. The study was conducted in accordance with the Declaration of Helsinki and applicable national regulations. Informed consent was obtained from all participants

Statistical analysis

Continuous variables were summarized as mean±standard deviation (SD) and median (interquartile range) as appropriate; categorical variables were summarized as n (%). Distributional assumptions were assessed with histograms, Q-Q plots, and the Shapiro-Wilk test. Between-group comparisons used Welch's t test or the Mann-Whitney U test for continuous variables and Pearson's χ^2 test or Fisher's exact test for categorical variables. Baseline balance was additionally assessed with absolute standardized mean differences (SMDs), using 0.10 and 0.20 as descriptive thresholds for small and moderate imbalance.

Longitudinal temperature was analyzed with linear mixed-effects models in which repeated measurements were nested within patients and a random intercept accounted for within-patient correlation. The principal model included standardized time, surgical category, and a time-by-category interaction, with other general surgery as the reference category. Coefficients were re-expressed in clinically interpretable 20-minute intervals. Models were estimated by maximum likelihood with Satterthwaite approximation for degrees of freedom.

Postanesthesia recovery time was evaluated in 13 analyzable strata defined by thermal-management strategy and surgical category. The adjusted aggregate model included warming strategy, mean age, proportion of women, and summarized minimum temperature for each stratum. Because this analysis used aggregated strata rather than individual patients, its coefficient for warming strategy represents a between-stratum association and not an individual-level treatment effect.

Time to the first episode of hypothermia was assessed among the 39 actively warmed patients using Kaplan-Meier methods and Cox proportional-hazards models adjusted for age, sex, and surgical category. An exploratory proxy regression evaluated the summarized minimum-temperature outcome after adjustment for baseline temperature, age, sex, and surgical duration.

For the operational analysis, differences in recovery time and potential savings were estimated by surgical category. Uncertainty was evaluated with 5000 nonparametric bootstrap resamples.

All tests were two-sided with $\alpha=0.05$. Nominal p values and multiple-comparison adjustments using the Benjamini-Hochberg false-discovery-rate method and Bonferroni method were calculated where specified in the source analysis. Complete-case denominators were used for each model.

RESULTS

Baseline characteristics

Seventy-seven patients were included: 39 (50.6%) received active warming and 38 (49.4%) received conventional thermal management (Table 1). Mean age was 60.3±12.9 years in the active-warming group and 56.6±14.5 years in the comparator group (mean difference 3.73 years; 95% CI -2.51 to 9.96; p=0.237; SMD=0.272). Women represented 59.0% (23/39) of the active-warming group and 81.6% (31/38) of the comparator group (nominal p=0.030; false-discovery-rate-adjusted p=0.114; SMD=0.495). Because of this baseline imbalance, sex was included in adjusted analyses. The distribution of surgical categories did not differ globally between groups (Fisher's exact p=0.982).

Table 1: Baseline characteristics.

Characteristics	Total (n=77) (%)	Active warming (n=39) (%)	Conventional management (n=38) (%)	SMD	P value
Age, years, mean±SD	58.5±13.7	60.3±12.9	56.6±14.5	0.272	0.237
Sex					0.030
Female	54 (70.1)	23 (59.0)	31 (81.6)	0.495	
Male	23 (29.9)	16 (41.0)	7 (18.4)	0.495	
Surgical category					0.982
Other general surgery	17 (22.1)	8 (20.5)	9 (23.7)	0.076	
Orthopedic surgery	9 (11.7)	6 (15.4)	3 (7.9)	0.234	
Cholecystectomy	20 (26.0)	10 (25.6)	10 (26.3)	0.015	
Hysterectomy	6 (7.8)	3 (7.7)	3 (7.9)	0.008	
Exploratory laparotomy	6 (7.8)	3 (7.7)	3 (7.9)	0.008	
Abdominal wall repair	15 (19.5)	7 (17.9)	8 (21.1)	0.078	
Resection	4 (5.2)	2 (5.1)	2 (5.3)	0.006	

Data are presented as mean±SD or N (%). SMD: standardized mean difference; SD: standard deviation. Age was compared with Welch's t test, sex with Pearson's χ^2 test, and the distribution of surgical categories with Fisher's exact test.

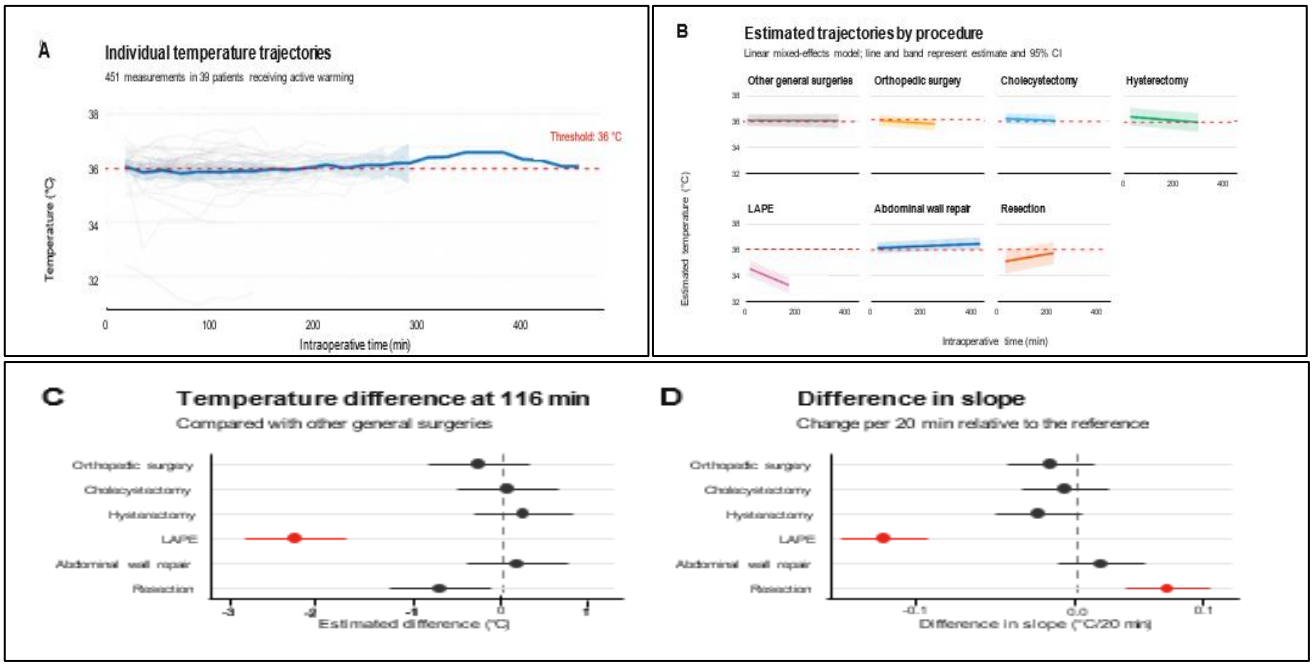

Figure 1: Longitudinal evolution of intraoperative temperature in patients receiving active warming: A) individual thermal trajectories of 39 patients, corresponding to 451 intraoperative measurements. Gray lines represent individual patients; the solid line and shaded band show the observed mean and its 95% confidence interval (CI). The dashed line indicates the 36°C hypothermia threshold; B) estimated thermal trajectories by surgical category from a linear mixed-effects model with a random intercept for patient. Lines and bands represent population estimates and 95% CIs; C) differences in estimated temperature level at the mean observation time (approximately 116 minutes) relative to other general surgery; D) differences in thermal slope, expressed as °C per 20 minutes, relative to the reference category.

Points show coefficients and lines show 95% CIs; statistically significant estimates are highlighted in the source artwork. CI: confidence interval.

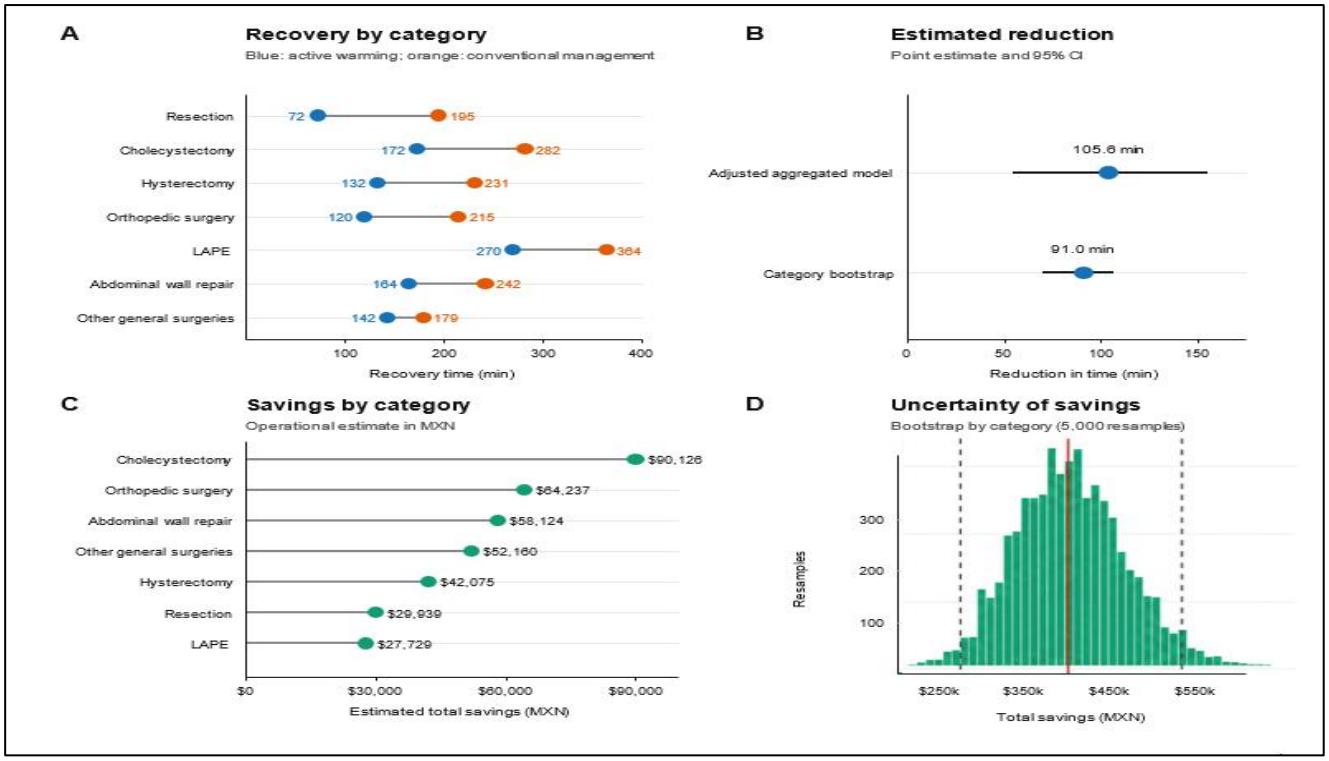

Figure 2: Postoperative recovery and potential operational savings according to thermal-management strategy: A) summarized time between admission to and discharge from the recovery area for active warming and conventional management, stratified by surgical category. Lines connect the two estimates within each category; B) reduction in recovery time estimated by the adjusted aggregate model and by category-level bootstrap. Points represent estimates and lines represent 95% Cis; C) potential total operational saving by category, calculated from time saved and the cost-per-minute parameter used in the analysis; D) distribution of total savings from 5000 category-level bootstrap resamples.
The vertical line indicates the observed saving of MXN $364,390 and dashed lines delimit the bootstrap 95% CI. Recovery and cost analyses are aggregate estimates and should be interpreted as exploratory operational associations. CI: confidence interval; MXN: Mexican pesos.

Longitudinal temperature during active warming

The longitudinal analysis included 451 temperature measurements from the 39 actively warmed patients (Figure 1). The mixed-effects model did not identify a significant overall linear temperature change during follow-up. After re-expression in 20-minute intervals, the estimated change was -0.005°C per 20 minutes (95% CI -0.014 to 0.004; p=0.262). The estimated temperature at the mean observation time of approximately 116 minutes was 35.89°C (95% CI 35.62-36.17). The SD of the patient-level random intercept was 0.84°C and the residual SD was 0.36°C; the intraclass correlation coefficient was 0.845, indicating substantial between-patient heterogeneity.

Variation in thermal trajectory by procedure

In the model including surgical category and the time-by-category interaction, other general surgery was the reference group. Its estimated slope was -0.001°C per 20 minutes (95% CI -0.019 to 0.016; p=0.870). At the mean observation time, exploratory laparotomy was associated with a temperature 2.29°C lower than the reference category (β=-2.288; 95% CI -3.157 to -1.419; p<0.001) and with a slope 0.126°C per 20 minutes more negative (95% CI -0.174 to -0.077; p<0.001). Resection procedures did not differ significantly in temperature level (β=-0.669°C; p=0.187), but their slope was 0.060°C per 20 minutes more positive than the reference category (95% CI 0.014-0.105; p=0.010). No significant differences in level or slope were identified for orthopedic surgery, cholecystectomy, hysterectomy, or abdominal wall repair. Because only three patients underwent exploratory laparotomy and two underwent resection in the actively warmed cohort, these procedure-specific findings are exploratory.

Association between active warming and postoperative recovery

The adjusted recovery model was based on 13 treatment-by-procedure strata and was statistically significant [$F(4,8)=11.29$; p=0.002; $R^2=0.850$; adjusted $R^2=0.774$]. After adjustment for mean age, proportion of women, and summarized minimum temperature, the absence of active warming was associated with 105.6 additional minutes of recovery compared with active warming (β=105.58

minutes; 95% CI 51.20-159.97; p=0.002). This coefficient represents an aggregate between-stratum association rather than an individual causal effect.

Within the same model, each 1°C increase in summarized minimum temperature was associated with 36.4 fewer recovery minutes (β=-36.36; 95% CI -69.10 to -3.62; p=0.034). A 10-percentage-point increase in the proportion of women within a stratum was associated with 14.8 fewer recovery minutes (95% CI -24.36 to -5.28; p=0.007). Mean age was not significantly associated with recovery time (β=0.64 minutes/year; 95% CI -2.53 to 3.80; p=0.655). Because minimum temperature may lie on the causal pathway between warming and recovery, adjustment for this variable should not be interpreted as estimating the total effect of warming.

Exploratory hypothermia and proxy temperature analyses

Among the 39 actively warmed patients, 26 developed hypothermia during follow-up. The Cox model adjusted for age, sex, and surgical category did not show a significant global association between procedure category and time to hypothermia (likelihood-ratio χ^2=9.76, 8 df; p=0.282). Compared with other general surgery, the hazard ratio (HR) was 2.74 for orthopedic surgery (95% CI 0.68-10.99; p=0.154), 2.18 for exploratory laparotomy (95% CI 0.50-9.58; p=0.302), and 1.37 for resection (95% CI 0.18-10.35; p=0.762). Confidence intervals were wide and these estimates were considered exploratory (Appendix Figure S2).

In the proxy analysis of summarized minimum temperature, baseline temperature was the strongest predictor: each 1°C higher baseline temperature was associated with a 1.145°C higher estimated minimum temperature (95% CI 0.918-1.371; p<0.001). After adjustment for baseline temperature, age, sex, and surgical duration, the active-warming indicator was not significantly associated with the proxy minimum-temperature outcome (β=-0.613°C versus conventional management; 95% CI -1.314 to 0.088; p=0.086). Surgical duration had a small negative association that did not reach statistical significance (β=-0.002°C/minute; 95% CI -0.0042 to 0.0001; p=0.068). The model explained 65.0% of outcome variability (R^2=0.650; adjusted R^2=0.624). Because comparator thermal values were based on procedure-level summaries, this analysis cannot reconstruct individual variability and should not be interpreted causally.

Potential operational savings

Summarized time between admission to and discharge from recovery was lower with active warming in all seven surgical categories (Figure 2). In 5000 category-level bootstrap resamples, the mean reduction was 91.0 minutes (95% CI 70.4-107.6) and the median reduction was 95.4 minutes (95% CI 78.0-110.0). The largest category-specific differences were observed in resection (123 minutes), cholecystectomy (110 minutes), hysterectomy (99 minutes), orthopedic surgery (95 minutes), and exploratory laparotomy (94 minutes).

Using the local operational cost-per-minute assumptions from the source analysis, the observed potential saving in the cohort was MXN $364,390. The bootstrap mean total saving was MXN $365,219 (95% CI $263,941-$477,284), with a mean net-saving ratio of 0.300 (95% CI 0.223-0.387). These figures are descriptive operational estimates derived from local time and costing parameters and are not a formal economic evaluation.

DISCUSSION

This retrospective cohort generated three principal findings. First, among actively warmed patients, there was no significant overall linear decline in body temperature, but the high intraclass correlation showed substantial between-patient heterogeneity. Second, thermal trajectories differed across some procedure categories, particularly exploratory laparotomy and resection, although these subgroup estimates were based on very small numbers. Third, active warming was associated with substantially shorter postanesthesia recovery in the aggregate treatment-by-procedure model, with a corresponding potential reduction in local recovery-area resource use.

The absence of a significant population-average thermal slope should not be interpreted as evidence that temperature remained stable in every patient. A mixed model estimates an average trajectory while allowing repeated measurements to cluster within individuals. The large patient-level random component in this cohort is consistent with the recognized multifactorial nature of perioperative temperature regulation, in which patient characteristics, anesthesia, exposure, fluid management, and environmental conditions interact.[20,21] Longitudinal analysis therefore provides information that cannot be captured by a single final temperature measurement.

Procedure-specific differences were most apparent for exploratory laparotomy, which showed both a lower estimated temperature level and a more negative slope relative to other general surgery. This direction is physiologically plausible because open abdominal exposure can increase evaporative heat loss, while anesthesia simultaneously impairs normal thermoregulatory vasoconstriction and promotes core-to-peripheral redistribution.[21,22] Nevertheless, the present data cannot determine whether the observed trajectory was due to surgical exposure itself, procedure duration, anesthetic management, fluid administration, operating-room conditions, or other correlated factors. The very small numbers in exploratory laparotomy and resection further require that these findings be treated as hypothesis-generating.

The clinically most notable result was the association between active warming and shorter recovery time. However, the analytic level is crucial: the recovery model used aggregated treatment-by-procedure strata rather than individual-patient observations. The 105.6-minute coefficient therefore describes a between-stratum association and cannot be interpreted as an individual treatment effect. In addition, treatment assignment was not randomized, sex differed between groups at baseline, and unmeasured perioperative factors may have influenced both the choice of warming and the duration of recovery. These features create the possibility of residual confounding and ecological bias. Earlier randomized evidence in abdominal surgery supports a relationship between normothermia and faster readiness for postanesthesia care unit discharge, although its recovery criteria and anesthetic regimen differ from those in the present cohort.[7]

Minimum intraoperative temperature was also associated with recovery time in the aggregate model. This relationship is biologically plausible, but its causal interpretation is uncertain because minimum temperature may be an intermediate variable through which warming affects recovery. Adjusting for a mediator can attenuate or otherwise change the estimated total association of the exposure. Future prospective analyses should prespecify the causal estimand and distinguish confounders from mediators and post-exposure variables.

The exploratory proxy temperature analysis did not show a statistically conclusive association between warming strategy and summarized minimum temperature after adjustment. This finding does not necessarily contradict the recovery association or the longitudinal temperature findings. The proxy analysis used procedure-level thermal summaries for the comparator and therefore could not recover individual thermal variability. Similarly, the absence of a significant global procedure effect on time to hypothermia should not be interpreted as equivalence because confidence intervals were wide and the number of events was limited.

The operational analysis suggests that shorter recovery could translate into meaningful local resource savings. The bootstrap distribution supported a consistent reduction in recovery time across the categories analyzed. Nevertheless, the monetary values depend on the local cost-per-minute assumptions and on the validity of the aggregate recovery estimates. They should therefore be viewed as contextual estimates of potentially released capacity rather than as generalizable cost-effectiveness results. Previous budget-impact and technology assessments have likewise suggested that normothermia programs can produce savings, but their magnitude varies by health system and implementation model.[17,18]

This study has several strengths, including repeated temperature measurements, mixed-effects modelling of longitudinal data, explicit evaluation of time-by-procedure interactions, and transparent presentation of exploratory operational estimates. Its limitations are equally important. The retrospective observational design precludes causal inference; the sample was small; several procedure strata were very small; temperature sampling was not necessarily uniform; serial patient-level thermal data were available only for the actively warmed cohort; the comparator thermal proxy relied on procedure-level summaries; and potentially important confounders such as operating-room temperature, fluid volumes, blood loss, anesthetic regimen, and detailed exposure were not completely available. The aggregate recovery analysis further limits individual-level interpretation.

CONCLUSION

In conclusion, intraoperative active forced-air warming was associated with shorter postoperative recovery in this retrospective cohort, while actively warmed patients showed heterogeneous thermal trajectories across surgical procedures. These findings support studying perioperative warming with both longitudinal thermal and clinical recovery outcomes, but they do not establish a causal benefit. Prospective, adequately powered studies with patient-level temperature and recovery data in both treatment groups, detailed perioperative covariates, and, when feasible, randomized allocation are needed to confirm the magnitude and mechanism of the observed associations.

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Ethical approval: The study was approved by the The ISSSTE Hospital General "Dr. Fernando Quiroz Gutiérrez" Ethics Committee

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Appendix

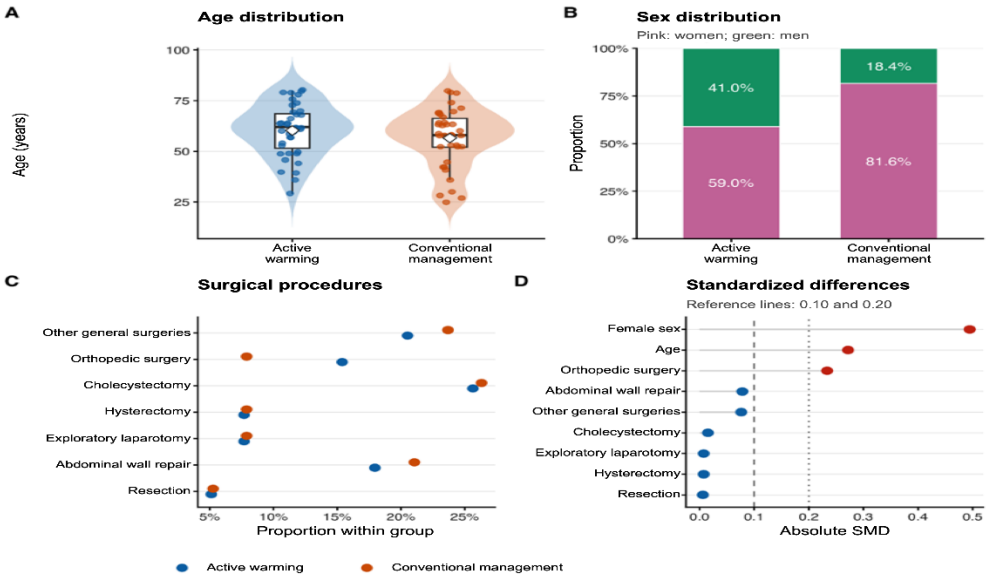

Figure 1: Baseline characteristics and balance between thermal-management strategies: A) age distribution by group. Violin plots represent density, boxes show the median and interquartile range, points show individual observations, and diamonds show the mean; B) proportional sex distribution within each group; C) distribution of surgical categories within each management strategy; D) absolute standardized mean differences for age, sex, and surgical category.
Vertical lines indicate reference values of 0.10 and 0.20. SMD: standardized mean difference.

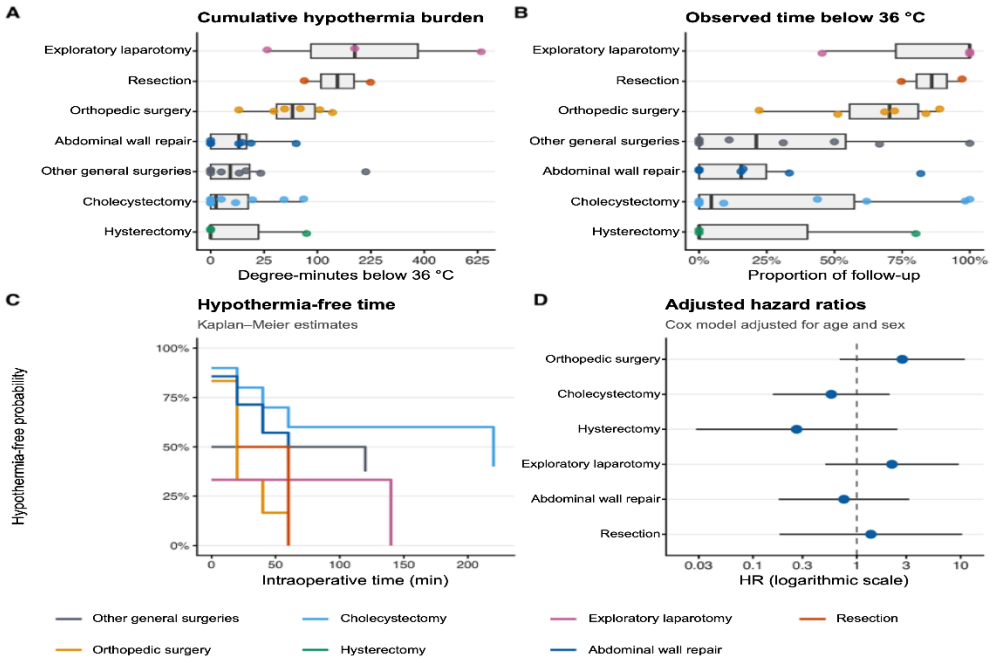

Figure 2: Hypothermia burden and time to the first hypothermia episode: A) cumulative hypothermia burden, expressed as degree-minutes below 36°C, by surgical category. The axis uses a square-root transformation to preserve visibility of small and extreme values; B) Proportion of observed time with temperature <36°C. In both panels, boxes show the median and interquartile range and points represent individual patients; C) Kaplan-Meier curves for hypothermia-free time; D) hazard ratios adjusted for age and sex for time to hypothermia, using other general surgery as the reference.
Points represent HRs and lines show 95% CIs. Because of small strata and wide intervals, these results are exploratory. HR: hazard ratio; CI: confidence interval.