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Airway warming devices in the context of single and multimodal strategies for intraoperative hypothermia: a network meta-analysis

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Abstract

Background: This network meta-analysis (NMA) assessed the relative efficacy of airway warming devices and combined warming strategies for preventing intraoperative hypothermia.

Methods: We searched MEDLINE, EMBASE, CENTRAL, and Google Scholar to identify randomized controlled trials (RCTs) published through November 2025 that compared two or more warming strategies, including airway warming devices, in patients under general anesthesia. The primary outcome was intraoperative core temperature at the end of surgery. To establish the rank order of the evaluated warming strategies, frequentist and Bayesian NMAs were conducted and surface under the cumulative ranking curve (SUCRA) values were used.

Results: The systematic review and NMA included 25 RCTs involving 1,404 patients. At the end of surgery, heated humidifiers (HHs), HH + intravenous fluid warmer (IV), HH + IV + water mattress (WM), and the Mega Acer Kit[®] (MAK)—a heated-humidified breathing circuit with an integrated fluid warming unit—were associated with significantly higher core temperatures than the control group. Based on the SUCRA values, MAK ranked highest at the end of surgery, followed by HH + IV + WM. Multimodal interventions generally ranked higher than single warming methods across all assessed time points, suggesting the superiority of multimodal warming approaches. The SUCRA values from the frequentist and Bayesian models were closely aligned, indicating the robustness of the analysis.

Conclusion: Based on the available evidence, MAK may be the most effective among warming strategies involving airway warming devices. Overall, multimodal warming approaches may offer advantages over single-device strategies for perioperative temperature management, although the certainty of the evidence is limited.

Systematic review registration: PROSPERO CRD42024534439.

Keywords: Body temperature; Closed-circuit anesthesia; General anesthesia; Hypothermia; Network meta-analysis; Warming devices.

Introduction

Intraoperative heat loss is common among surgical patients, placing them at risk of hypothermia without adequate warming measures[1]. Although mild therapeutic hypothermia provides some protection against ischemic injury to vital organs[2], unintended hypothermia may lead to various perioperative complications including coagulopathy, cardiovascular dysfunction, wound infection, and delayed recovery, all of which negatively affect patient outcomes[1,3]. Therefore, prevention of intraoperative hypothermia is crucial for improving the quality of perioperative patient management.

Intraoperative hypothermia occurs through diverse mechanisms. Therefore, various warming strategies have been proposed. These include devices that limit cutaneous heat loss, such as forced-air warmers and passive insulation; tools that restrict conductive cooling, such as circulating water mattresses and intravenous (IV) fluid warmers; and airway warming devices that prevent respiratory heat loss, such as heated-humidified breathing circuits (HHBCs) and passive humidifiers (heat and moisture exchangers)[4].

Because respiratory heat loss accounts for only a small portion of the total intraoperative heat loss[5], the clinical impact of airway warming has been controversial. Our previous meta-analysis showed that active airway warming via heated humidifiers (HHs) significantly reduced the core temperature decline during general anesthesia[6]; however, HH alone was often insufficient to fully prevent hypothermia. These findings highlight the limitations of HH as a standalone strategy and support the need for a multimodal approach that targets multiple heat loss pathways.

Therefore, we conducted a network meta-analysis (NMA) to assess and rank the relative efficacy of airway warming devices and their combinations with other warming modalities that employ different mechanisms to prevent intraoperative hypothermia.

Materials and methods

The protocol for this systematic review and NMA was developed according to the Preferred

Reporting Items for Systematic Review and Meta-Analysis Protocol (PRISMA-P) statement[7] and registered in the PROSPERO network (registration number: CRD42024534439; www.crd.york.ac.uk/PROSPERO) on April 10, 2024. This study was performed in accordance with the recommendations of the Cochrane Collaboration[8] and was reported following the PRISMA extension statement for reporting systematic reviews incorporating NMA of healthcare interventions[9].

Inclusion and exclusion criteria

We included only peer-reviewed randomized controlled trials (RCTs) that compared the effects of two or more warming strategies, particularly airway warming devices, to prevent intraoperative hypothermia in patients undergoing general anesthesia. The PICO-SD information was as follows:

Patients (P): All patients receiving surgery under general anesthesia

Intervention (I): Intraoperative warming strategies including airway warming devices

Comparison (C): No warming intervention (control) or intraoperative warming strategies other than airway warming devices

Outcome measurements (O): The primary outcome of NMA was intraoperative core temperature at the end of surgery. The secondary outcome was intraoperative core temperature at other time points (30, 60, 90, 120, and 180 min after anesthesia induction).

Study design (SD): Peer-reviewed RCTs

Studies involving children (<18 years of age), animals, review articles, letters to the editor, commentaries, proceedings, and irrelevant studies were excluded.

Search strategy

Two independent investigators (JJL and GJC) comprehensively searched MEDLINE, EMBASE, Cochrane Central Register of Controlled Trials (CENTRAL), and Google Scholar databases for relevant articles up to November 2025. Search terms were developed in consultation with a medical librarian and included a combination of free text, Medical Subject Headings, and

EMTREE terms, including 'heat,' 'humidified,' 'circuit,' and 'randomized controlled trial.' The search terms used in MEDLINE and EMBASE are presented in Supplementary Materials. Clinical trial registries were used to identify completed but unpublished RCTs, and the Open Grey System for Information on Grey Literature in Europe (OpenSIGLE) was used to search the gray literature. To ensure that all available studies were searched, reference lists of the original papers were manually scanned until no relevant studies were identified. No restrictions on publication date or language were imposed.

Study selection

The reference lists obtained as described above were imported into EndNote (Clarivate, Philadelphia, PA, USA), and duplicate articles were removed. Two investigators (JJL and OHL) independently reviewed the titles and abstracts of selected studies. If a study was considered eligible based on the title or abstract, the entire manuscript was retrieved and evaluated. Full-text versions of potentially relevant studies identified by at least one investigator and those with an abstract that did not provide sufficient information were retrieved and assessed. The investigators discussed their assessments to reach a consensus on study inclusion. If consensus could not be reached, disagreements were resolved through discussion with a third investigator (HK).

Data extraction

Using a standardized data collection form, two independent investigators (JJL and GJC) extracted and cross-checked all required data from the included studies. If the investigators disagreed, the article was reevaluated by each investigator until a consensus was reached. If no consensus was reached, a third investigator (HK) was consulted.

The following data were extracted: (1) title, (2) first author name, (3) journal name, (4) publication year, (5) study design, (6) country, (7) risk of bias, (8) surgery type, (9) inclusion criteria, (10) exclusion criteria, (11) sex, (12) age, (13) number of patients, (14) intraoperative use of airway heating and humidifying devices and warming manipulations, (15) additional thermal

management, and (16) primary and secondary outcomes.

Core body temperature data were selected for the analysis when a previous study reported multiple types of temperature measurements. The means and standard deviations of the intraoperative core temperatures were primarily obtained from tables or texts. If the data were available only in graphical form, we extracted the values using the open-source software, Plot Digitizer (version 2.6.10; <http://plotdigitizer.sourceforge.net>)[10]. In cases where data were missing or unclear, we contacted the corresponding authors to retrieve the necessary information.

Risk of bias assessment

Two independent investigators (JJL and GJC) critically appraised the quality of each study using the revised Cochrane risk-of-bias tool for randomized trials (RoB 2.0). Initially, the investigators assessed five domains in each study: D1) bias arising from the randomization process, D2) bias due to deviations from the intended interventions, D3) bias due to missing outcome data, D4) bias in outcome measurement, and D5) bias in the selection of reported results. The overall risk of bias was evaluated and classified as low if all domains were judged to have a low risk of bias, high if at least one domain had a high risk of bias or if multiple domains were of some concern; risk of bias was rated as being of “some concern” if the overall judgment was neither low nor high. If no consensus was reached, disagreements were resolved through discussion with a third investigator (HK).

Statistical analyses

We created ad hoc tables to summarize the data from the selected studies, including key characteristics and important questions related to the review objectives. After the data extraction, the investigators determined the feasibility of the meta-analysis.

Multiple-treatment comparison NMA is a meta-analysis generalization method that includes both direct and indirect comparisons of treatments[11]. In this study, we conducted both frequentist and Bayesian random-effects NMAs. In the NMA, the control group was restricted to study arms

without intraoperative thermal management. Arms employing standard care, such as cotton blankets, were categorized separately as passive insulation (PI) interventions rather than controls.

We performed frequentist random-effects NMA using STATA version 15 (StataCorp LP, College Station, TX, USA) based on mvmeta with the NMA graphical tools developed by Chaimani et al.[12]. Before conducting NMA, we determined whether a meta-analysis was possible by evaluating the transitivity assumption. We assessed this assumption for the whole network by visually comparing the distribution of potential effect modifiers across comparisons, including patient eligibility criteria, demographic data (age, sex, and temperature monitoring site), and risk of bias (some concern vs. high risk of bias from the overall risk of bias) as potential treatment effect modifiers across comparisons[13] (Supplementary Fig. 1A–D).

We constructed a network plot linking the included airway warming devices and their combinations with other strategies for preventing intraoperative hypothermia to indicate the types of intraoperative warming strategies, the number of patients receiving different strategies, and the levels of pairwise comparisons. In this plot, the nodes show the warming strategies being compared, whereas the edges show the available direct comparisons between these strategies. Nodes and edges were weighted based on the number of patients and the inverse of the standard error of the effect.

We evaluated the consistency assumption within the entire network using a design-by-treatment interaction model. We also evaluated each closed loop in the network to identify local inconsistencies between direct and indirect effect estimates for the same comparison. For each loop, we estimated the inconsistency factor (IF) as the absolute difference between the direct and indirect estimates and the corresponding 95% confidence interval (CI) for each paired comparison in the loop[13,14]. An IF value with a 95% CI of 0 indicated consistent direct and indirect evidence.

The predictive interval (PrI) plots present the mean summary effects with CIs and their PrIs to facilitate the interpretation of the results, considering the magnitude of heterogeneity. The PrIs provide an interval that is expected to encompass estimates from future studies.

The rankograms and cumulative ranking curves were plotted for each intraoperative warming

strategy. Rankograms represent the probabilities of treatments assuming a possible rank. We used the surface under the cumulative ranking curve (SUCRA) values to determine the hierarchy of warming strategies to prevent intraoperative hypothermia. SUCRA is a relative ranking measure that accounts for uncertainty in the treatment order by considering the location and variance of all relative treatment effects. A higher SUCRA value indicates more positive results for individual interventions [15]. We used comparison-adjusted funnel plots to assess the presence of small-study effects[16].

To test the robustness of the results from the frequentist random NMA, we also conducted Bayesian NMA using fixed and random-effects models, as well as Markov Chain Monte Carlo (MCMC) methods using the R statistical package *gemtc*[17]. Due to the lack of definitive prior evidence regarding comparative efficacy, we used uninformative prior distributions automatically provided by the *gemtc* package.

The MCMC simulations were run using four chains with different initial values for 100,000 iterations after 50,000 burn-ins and thinning to 100. The convergence of fixed and random models derived from MCMC simulations was assessed using trace and density plots and the Gelman–Rubin–Brooks method with a potential scale reduction factor (PSRF) of up to 1.

The fit of the fixed- and random-effects models was assessed using Dbar (posterior mean of the deviance), pD (adequate number of parameters), and DIC (deviance information criterion, sum of Dbar, and pD) statistics. We also calculated SUCRA values from the Bayesian model and compared them with those from the frequentist model.

We also performed a meta-regression analysis, considering the potential influence of risk of bias (some concern vs. high risk), sex, mean age, and temperature measurement site (esophageal vs. non-esophageal) on each outcome. However, after excluding studies that did not provide information on sex, the networks became disconnected. Therefore, we did not perform a meta-regression analysis for sex.

Quality of the evidence

We determined the evidence grade using the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) system, which involves a stepwise evaluation of evidence quality, risk–benefit balance, and a subsequent judgment on the strength of the recommendations[18].

Results

Study selection

A total of 1,396 articles were initially acquired by searching MEDLINE, EMBASE, CENTRAL, and Google Scholar databases, and 11 articles were identified through a manual search. After removing duplicates, 1,109 articles were retained. The titles and abstracts of these articles were reviewed, and 81 met the selection criteria. The kappa value between the two investigators for the initial stage of study selection was 0.943.

The full texts of the remaining 81 articles were reviewed, and 56 were excluded for the following reasons: non-human studies[19,20], review article[6,21-24], non-peer-reviewed article[25-28], non-randomized studies[29,30], no subject of interest[31-44], no intervention of interest[45-54], an unsuitable control group[55-60], and no outcome of interest[61-73]. Finally, 25 RCTs involving 1,404 patients were included in the NMA (Fig. 1). In the second stage of study selection, the kappa value between the two investigators was 0.878.

Study characteristics

The study characteristics are summarized in Table 1. Among the studies selected, South Korea had the highest number of studies[5,74-81], followed by the United States with six [82-87], the United Kingdom with three [88-90], and Japan[91], Taiwan[92], Canada[93], France[94], Sweden[95], Norway[96], and Brazil[97] with one each.

Except for control group (no intervention)[75,79,80,82,84,85,87-90,92-94], 25 different warming strategies were evaluated in the selected studies: HH (or HHBC)[75,76,79-85,87,89,90,92-

94], heat and moisture exchanger (HME)[81,84,90,94], Mega Acer Kit[®] (MAK)[76], Humidistat (H-stat, hygrostatic condenser humidifier)[85], PI[85,95], IV fluid warmer (IV)[83,86,96], water mattress (WM)[83], forced-air warmer (FAW)[85,97], esophageal heat exchanger (EHE)[89], HH + IV[76,96], HH + IV + WM[78,88,96], HH + PI + FAW[5], HH + PI + IV + WM[74], HH + PI + WM[77], HME + FAW[97], HME + IV[86], HME + IV + WM[78,91], HME + PI[95], HME + PI + IV[86], HME + PI + IV + WM[74], MAK + PI + WM[77], IV + WM[91], PI + FAW[5], PI + IV[86], PI + WM[77]. MAK, similar to HH in providing heated and humidified inspired gas, was categorized as an independent airway-warming device because of its integrated fluid-warming component, which may offer additional thermal benefits compared to conventional HH systems. The decision to classify MAK separately from HH + IV was based on a primary RCT by Jung et al.[76], which demonstrated a significant difference in the intraoperative core temperature between MAK and HH + IV, reflecting the need for a distinct categorization.

The surgical types among the patients in the included studies were abdominal surgery[74,84,88,92], gynecological surgery[82,94,97], orthopedic surgery[75,81,89-91], spinal surgery[5,76,85,86], neurosurgery[77], head and neck surgery[91,95], thyroid surgery[80], escharectomy and skin graft[78], cardiac surgery[83,93], vascular surgery[96], and unspecified elective surgery[79,87]. In one study of patients undergoing liver transplantation[74], core temperature data up to 3 h after anesthesia induction (prior to the anhepatic phase) and at the end of the surgery were included in the analysis. Although liver extraction and reperfusion can cause substantial intraoperative thermal shifts, these surgical events were observed equally in both groups. Therefore, despite the procedural complexity and prolonged duration of anesthesia, the end-of-surgery temperature data were considered valid for inclusion. However, owing to network disconnection, this study was ultimately excluded from the final NMA at the end of surgery. In two studies involving patients undergoing cardiac surgery with cardiopulmonary bypass (CPB)[83,93], warming was initiated after the termination of CPB. Although CPB involves distinct thermoregulatory physiology, we included core temperature data exclusively from the post-CPB

period because this phase was no longer influenced by extracorporeal circulation. This period typically exhibits a rapid core temperature decline known as “afterdrop,” which results from redistribution hypothermia due to a core-to-peripheral temperature gradient and resembles the early hypothermic response observed after anesthesia induction[98,99].

The most common measurement site for core body temperature was the esophagus, as reported in 11 studies[75-81,85,94,96,97]. The other measurement sites included the tympanic membrane[5,74,89], nasopharynx[87,92,93], upper pharynx[91], rectum[86,95], and pulmonary artery[74,83]. One study measured the baseline core temperature through the tympanic membrane and recorded the pulmonary arterial temperature after anesthesia induction[74]. Two studies used sublingual[82,84], whereas another two studies used aural canal temperature[88,90] to estimate core body temperature. One of these studies did not report the measured aural canal temperature; instead, it included only body temperature values calculated using the aural canal and mean skin temperatures [88]. Despite the controversy regarding the reliability of these sites in reflecting core body temperature, we included data to conduct a pooled analysis with the most comprehensive dataset possible.

Risk of bias assessment

Risk of bias assessment results are presented in Table 2. Among the 25 studies, 22 were assessed as having a high risk of bias. Three studies were evaluated as having concerns. None of the studies was classified as having a low risk of bias. Risk of bias assessment for each outcome is presented in Supplementary Table 1.

Synthesis of the study results

Regarding the outcomes of each datum, we generated a network plot (Fig. 2), an inconsistency plot (Fig. 3), and a predictive interval plot compared to the control (Fig. 4). The rankograms (Supplementary Fig. 3), cumulative ranking curves (Supplementary Fig. 4), expected mean rankings and SUCRA values for each strategy (Fig. 5), comparison-adjusted funnel plots (Fig. 6), and

comparisons of the SUCRA values between the Bayesian and frequentist models (Fig. 7) are also displayed. Fig. 2-7 and Supplementary Figs. 2-9 (A–F in each figure correspond to the temperatures at the end of surgery and 60, 120, 180, and 30, 90 min after anesthesia induction, respectively) summarize these results.

Primary endpoint: intraoperative core temperature at the end of surgery

A total of 25 studies (1,279 patients) measured core temperature at the end of surgery. Of these, three studies[5,74,77] were separated from the network loops (Supplementary Fig. 2A). After excluding these studies, 22 (1,063 patients) were included in the NMA.

A network plot of all eligible comparisons for this endpoint is shown in Fig. 2A. Although all 19 warming management strategies (nodes) were connected to the network, two comparisons (control and HH) were more directly comparable to the other 17 nodes. We observed no evidence of network inconsistency [$\chi^2(6) = 4.50$, $P = 0.609$].

The network resulting from the comparison of temperatures at the end of surgery comprised 20 closed triangular loops and two closed quadratic loops. Triangular loops were formed by comparing three interventions, while quadratic loops were formed by comparing four interventions, each of which was compared to two other interventions in the loop.

Fourteen loops (Con/H-stat/PI, Con/H-stat/FAW, Con/PI/FAW, HH/H-stat/PI, HH/H-stat/FAW, HH/PI/FAW, H-stat/PI/FAW[85], HH/MAK/HH + IV[76], HH/IV/WM[83], IV/HH + IV/HH + IV + WM[96], IV/HME + IV/HME + PI + IV, IV/HME + IV/PI + IV, IV/HME + PI + IV/PI + IV, and HME + IV/HME + PI + IV/PI + IV[86]) were formed only by multi-arm trials. Although no significant local inconsistencies were observed in most loops, one loop (HH/IV/HH + IV) showed significant local inconsistencies between the direct and indirect point estimates (Fig. 3A).

HH, HH + IV, HH + IV + WM, and MAK showed higher temperatures than the controls only in terms of the 95% CIs. Although MAK ranked the highest, as shown in Fig. 2A, no head-to-head comparisons were made between the MAK and control groups, and the corresponding estimates

were based entirely on indirect comparisons. The lack of significance of the 95% PrIs suggests the need for future RCTs to potentially change the significance of the efficacy of these comparisons (Fig. 4A).

The rankogram in Supplementary Fig. 3A shows that the MAK, HH + IV + WM, HME + FAW, HME + PI + IV, and HME + PI groups exhibited the highest temperatures at the end of surgery. A cumulative ranking plot was drawn and the SUCRA probabilities of the different interventions for this outcome were calculated (Supplementary Fig. 4A). The expected mean rankings and SUCRA values for each intervention are shown in Fig. 5A. According to the SUCRA value, the temperature at the end of surgery was highest in the order of MAK (90.1%), followed by HH + IV + WM (79.8%), HME + PI + IV (77.3%), HME + FAW (76.9%), and HME + PI (69.5%). The comparison-adjusted funnel plots were symmetrical around the zero line, suggesting a low likelihood of publication bias (Fig. 6A).

Secondary endpoint: intraoperative core temperature at prespecified time points

The NMA results at 60, 120, and 180 min following anesthesia induction are presented below, whereas the results at 30 and 90 min along with the corresponding figures are provided in the Supplementary Results section.

At 60 min after anesthesia induction

A total of 18 studies (1,072 patients) measured core temperature 60 min after anesthesia induction; however, three studies[5,74,77] were separated from the network loops (Supplementary Fig. 2B). Therefore, we performed an NMA after excluding these studies, resulting in the analysis of 15 studies (856 patients).

Although all 16 warming management strategies (nodes) were connected to the network, two comparisons (control and HH) were directly comparable with those of the other 14 nodes (Fig. 2B).

We observed no evidence of network inconsistency [$\chi^2(2) = 2.14$, $P = 0.343$]. The closed network at this time point revealed 17 triangular loops.

Thirteen loops (Con/H-stat/PI, Con/H-stat/FAW, Con/PI/FAW, HH/H-stat/PI, HH/H-stat/FAW, HH/PI/FAW, H-stat/PI/FAW[85], HH/MAK/HH + IV[76], IV/HH + IV/HH + IV + WM[96], IV/HME + IV/HME + PI + IV, IV/HME + IV/PI + IV, IV/HME + PI + IV/PI + IV, and HME + IV/HME + PI + IV/PI + IV[86]) were formed only by multi-arm trials. We observed no evidence of significant local inconsistencies between direct and indirect point estimates (Fig. 3B).

HH, HH + IV, HH + IV + WM, and MAK showed higher temperatures than the controls only in terms of the 95% CI (Fig. 4B). Based on the SUCRA values presented in Fig. 5B, the temperature at 60 min was the highest for MAK (90.1%), followed by HH + IV + WM (83.9%), HME + FAW (73.2%), HME + IV + WM (64.5%), and HH + IV (63.4%). The symmetry of the comparison-adjusted funnel plots around the zero line indicates a low likelihood of publication bias (Fig. 6B).

At 120 min after anesthesia induction

Although 15 studies (798 patients) measured the temperature 120 min after anesthesia induction, 11 studies (552 patients) were included in the analysis because four studies[5,74,77,97] were disconnected from the network loops (Supplementary Fig. 2C).

A network plot of all valid comparisons for this endpoint is shown in Fig. 2C. No evidence of network inconsistency was observed [$\chi^2(1) = 1.00$, $P = 0.999$]. We observed six closed triangular loops at this time point, all of which were formed only by multi-arm trials.

As illustrated in Fig. 4C, HH, HH + IV, HH + IV + WM, and MAK demonstrated significantly higher temperatures than the controls, based on the 95% CIs. SUCRA rankings further revealed that MAK achieved the highest temperature at 120 min (90.1%), followed by HH + IV + WM (86.1%), HH + IV (65.3%), HME + IV + WM (56.1%), and IV + WM (56%) (Fig. 5C). None of the studies that were excluded owing to network disconnection evaluated MAK as a single

intervention; therefore, the amount of data contributing to the MAK ranking at these time points was not affected. The comparison-adjusted funnel plots were symmetrical around the zero line, suggesting that publication bias was unlikely (Fig. 6C).

At 180 min after anesthesia induction

Of the 11 studies (592 patients) that measured core temperature 180 min after anesthesia induction, three studies[5,74,77] were disconnected from the network (Supplementary Fig. 2D), resulting in eight studies (376 patients) being included in the analysis.

Fig. 2D shows a network plot of all the comparisons assessed in the analysis for this endpoint. No evidence of network inconsistency was observed [$\chi^2(1) = 1.04$, $P = 0.308$]. We observed six closed triangular loops at this time point, all of which were formed only by multi-arm trials.

According to the 95% CIs, HH, HH + IV, HH + IV + WM, and MAK showed significantly higher temperatures than the controls (Fig. 4D). As indicated by the SUCRA values in Fig. 5D, the temperature at 180 min was highest for MAK (85.3%), followed by HH + IV + WM (84.2%), HH + IV (63.4%), and HME + PI + IV (58.1%). A low likelihood of publication bias was observed in comparison-adjusted funnel plots (Fig. 6D).

Bayesian NMA for robustness assessment and meta-regression

To assess the robustness of our findings, we conducted a Bayesian NMA along with a frequentist approach. Network diagnostics using trace and density plots showed that model convergence was valid in both the fixed- and random-effects models (Supplementary Fig. 5A-F, 6A-F). However, based on the Gelman–Rubin–Brooks method, the random-effects model demonstrated a better fit to the data, as evidenced by lower DIC values and reduced heterogeneity (I^2) compared to those of the fixed-effects model (Supplementary Fig. 7A-F and 8A-F, Supplementary Table 2). Accordingly, the random-effects model was selected for the Bayesian NMA.

As shown in Supplementary Fig. 9A-F and Fig. 7A-F, the SUCRA values and corresponding rankings from the Bayesian model were closely aligned with those of the frequentist model across all time points, including the end of surgery. This consistency demonstrated the robustness of the analysis.

When performing meta-regression analyses across all assessed time points, variables such as risk of bias (some concern vs. high risk), patient age, and temperature measurement site (esophageal vs. non-esophageal) did not improve the model fit or substantially reduce heterogeneity, and none were found to be statistically significant (Supplementary Table 3).

SUCRA-based ranking of interventions over time

Fig. 8 provides an overview of the SUCRA values across different time points for all interventions. MAK consistently ranked the highest, followed by HH + IV + WM in most instances. Overall, multimodal warming strategies tended to rank higher than single interventions at all the assessed time points.

Quality of the evidence

Six outcomes were assessed using the GRADE system (Supplementary Table 4). The quality of the pooled analysis of the intraoperative core temperature at the end of surgery and at 30, 60, 90, and 120 min after anesthesia induction was rated as low, primarily because of the high risk of bias in the majority of the included studies. The quality of evidence for the intraoperative core temperature 180 min after anesthesia induction was rated as very low, reflecting both the predominance of high-risk studies and additional concerns related to imprecision.

Discussion

Based on the available evidence, this systematic review and NMA suggests that, among

interventions utilizing airway warming devices, MAK—an HHBC with a fluid-warming device—may be the most effective warming strategy for preserving core body temperature at the end of surgery in patients undergoing general anesthesia. This was followed by the combination of HH + IV + WM. Notably, multimodal strategies generally outperformed single warming methods in maintaining intraoperative core temperature. According to the SUCRA values, MAK consistently ranked the highest at all measured time points, followed by combinations such as HH + IV + WM and HME + FAW. Among the single warming strategies, MAK was the most effective at the end of surgery, followed by FAW, HH, PI, WM, IV, EHE, and HME. However, because the corresponding estimates rely exclusively on indirect comparisons, the absence of head-to-head comparisons between MAK and the control group limits the certainty of the evidence.

Under general anesthesia, patients experience heat loss via multiple mechanisms[1]. During the first hour after induction, vasodilation causes core body heat to shift toward the periphery, leading to a rapid decrease in core temperature. Before reaching the plateau phase, heat loss through radiation, conduction, convection, and evaporation exceeds metabolic heat production, leading to a gradual decline in core temperature. Among these mechanisms, radiation (caused by the low ambient temperature of the operating room) and convection (caused by the surrounding airflow) are the major sources of heat loss[100]. In comparison, respiratory heat loss represents only approximately 10% of metabolic heat generation[101].

Guidelines on perioperative hypothermia management suggest that core temperature should be monitored during surgery, pre-warming before the induction of anesthesia should be considered, patient exposure should be minimized, and active warming should be applied for procedures expected to last >30 min or in patients at a high risk of hypothermia[102-104]. Most guidelines recommend FAW as the first-line intervention for active warming. They also recommend warming IV fluids when more than 500 mL is administered as well as warming blood products and irrigation fluids. In contrast, active airway warming using HH or HHBC is rarely mentioned in current guidelines[104].

As respiratory heat loss contributes only a minor component to overall heat loss[5], the clinical benefit of airway warming has been debated. However, our previous meta-analysis demonstrated that active airway warming attenuated the initial core temperature drop and maintained a higher intraoperative temperature than conventional breathing circuits or passive warming via an HME[6]. In the present NMA, both HH and MAK ranked relatively high among single intervention strategies, thus supporting their potential clinical utility. Furthermore, combinations, such as HH + IV + WM and HH + IV, outperformed HH alone, thus reinforcing the benefits of multimodal strategies. These findings suggest that integrating active airway warming into broader warming protocols may enhance overall effectiveness.

The MAK is a single device that provides multimodal warming by combining an HHBC with a fluid warming unit embedded in the inspiratory limb. It is equipped with a heated controller, allowing a target temperature of 32–41°C. A 100-cm fluid line with a 5-mL volume is embedded alongside a heating wire wrapped in insulating cotton inside the inspiratory limb[77]. This design effectively warms not only the inspiratory gas, but also the IV fluid delivered to the patient. Studies comparing the fluid warming performance of the MAK and conventional IV fluid warming devices[105-107] have reported that the MAK warms fluids more effectively than conventional IV fluid warmers using dry heat technology, especially at lower flow rates (up to 650 mL/h), whereas conventional devices are more suitable at higher flow rates. However, because the MAK was developed and is primarily used in South Korea, the evidence is limited to a few domestic studies. Therefore, further research is required to establish reliable and generalizable evidence.

This study had some limitations. First, the quality and quantity of available studies were limited. Assessment of risk of bias revealed that most studies had a high risk of bias, with none of the included studies classified as having a low risk of bias. Furthermore, owing to the scarcity of comparisons among different warming strategies, some disconnections occurred within the network loops, limiting the available comparative data. Consequently, predictive intervals could not be calculated for secondary outcomes. In addition, as this NMA focused on warming strategies

involving airway warming devices, studies that did not include any form of airway warming were excluded from the analysis. Second, several sources of heterogeneity were present among the analyzed studies, including differences in patient demographics, surgery types and associated degrees of heat loss, variations in warming device regimens, and inconsistencies in core temperature measurement sites. Although a subgroup analysis by surgery type would have been clinically relevant, it was not feasible because of the limited number and connectivity of the studies in the network. Third, our analysis focused solely on the intraoperative core temperature. Other clinical outcomes such as postoperative complications, recovery profiles, and patient comfort were not assessed. Finally, because MAK is predominantly used in South Korea, the available evidence was derived from a single regional context, which may limit the generalizability of these findings to healthcare systems where MAK is not available. Given these limitations, additional data from well-designed studies with low risk of bias are required to validate our findings. Moreover, owing to the numerous factors that influence heat balance during surgery, further studies exploring various combinations of warming devices in diverse clinical settings are required. Such studies will help to establish efficient context-sensitive warming protocols.

Despite these limitations, this study had several strengths. To our knowledge, this is the first NMA to evaluate and rank the effectiveness of various warming strategies, including those incorporating airway warming devices, in preventing intraoperative hypothermia. The study followed a preplanned registered protocol and employed rigorous methodology. Second, we presented the outcomes according to the time elapsed after anesthesia induction, which may assist clinicians in selecting appropriate warming strategies depending on the expected surgery duration. Third, the NMA employs both frequentist and Bayesian models to ensure the robustness of our findings. Additionally, we conducted a network meta-regression analysis to identify the possible causes of heterogeneity.

Conclusion

Current evidence suggests that, among warming strategies involving airway warming devices, MAK may be the most effective option for preventing intraoperative hypothermia in patients under general anesthesia. Multimodal interventions generally rank higher than single-warming strategies, supporting the potential benefits of multimodal warming approaches.

The certainty of these findings is limited, mainly because of the predominance of the included trials with high risk of bias. Accordingly, the results should be interpreted cautiously, and further well-designed studies are required to strengthen the certainty of the evidence. In addition, because intraoperative heat balance is influenced by multiple factors, future research evaluating different combinations of warming devices within specific surgical contexts is essential to develop more effective and individualized warming strategies, ultimately improving perioperative patient management.

List of abbreviations

NMA, network meta-analysis; RCT, randomized controlled trial; SUCRA, surface under the cumulative ranking curve; HH, heated humidifier; IV, intravenous fluid warmer; WM, water mattress; MAK, Mage Acer Kit; HHBC, heated-humidified breathing circuit; PRISMA-P, Preferred Reporting Items for Systematic Review and Meta-Analysis Protocol; IF, inconsistency factor; CI, confidence interval; PrI, predictive interval; MCMC, Markov Chain Monte Carlo; PSRF, potential scale reduction factor; Dbar, posterior mean of the deviance; pD, adequate number of parameters; DIC, deviance information criterion; GRADE, Grading of Recommendations, Assessment, Development, and Evaluation; HME, heat and moisture exchanger; PI, passive insulation; FAW, forced-air warmer; EHE, esophageal heat exchanger; CPB, cardiopulmonary bypass.

Declarations

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Consent for publication: Not applicable.

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Figure Legends

Figure 1. PRISMA flow diagram of the literature search and selection. PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses; RCT, randomized controlled trial

Figure 2. Network plots illustrating all relevant comparisons included in the analysis, with disconnected loops excluded, for each timepoint: at the end of surgery (A) and 60 (B), 120 (C), and 180 (D) min after anesthesia induction. The nodes show each warming strategy, and the edges show the available direct comparisons among these strategies. The nodes and edges are weighted according to the number of patients and the inverse of the standard error of the effect. Con, control; HH, heated humidifier; HME, heat and moisture exchanger; MAK, Mega Acer Kit; H-stat, humidistat; PI, passive insulation; IV, intravenous fluid warmer; WM, water mattress; FAW, forced air warmer; EHE, esophageal heat exchanger.

Figure 3. Inconsistency plots comparing the direct and indirect effect estimates for each comparison at the end of surgery (A) and 60 (B) min after anesthesia induction. The inconsistency factor (IF), presented as the absolute difference between the direct and indirect estimates with a 95% confidence interval (CI), is shown for each comparison. IF values close to 0

indicate good agreement between the two sources.

Figure 4. Confidence intervals (CI) and predictive intervals (PrI) for each intervention compared with the control at the end of surgery (A) and 60 (B), 120 (C), and 180 (D) min after anesthesia induction. Solid black lines: CIs for each comparison; red lines: corresponding PrIs; blue vertical line: no effect (mean difference = 0). Con, control; HH, heated humidifier; HME, heat and moisture exchanger; MAK, Mega Acer Kit; H-stat, humidistat; PI, passive insulation; IV, intravenous fluid warmer; WM, water mattress; FAW, forced air warmer; EHE, esophageal heat exchanger.

Figure 5. Expected mean rankings and surface under the cumulative ranking curve (SUCRA) values from the frequentist model for each intervention at the end of surgery (A) and 60 (B), 120 (C), and 180 (D) min after anesthesia induction. Y-axis: SUCRA values; X-axis: corresponding expected mean rankings. Con, control; HH, heated humidifier; HME, heat and moisture exchanger; MAK, Mega Acer Kit; H-stat, humidistat; PI, passive insulation; IV, intravenous fluid warmer; WM, water mattress; FAW, forced air warmer; EHE, esophageal heat exchanger.

Figure 6. Comparison-adjusted funnel plots for each timepoint: at the end of surgery (A) and 60 (B), 120 (C), and 180 (D) min after anesthesia induction. A symmetrical distribution around the zero line indicates a low risk of publication bias.

Figure 7. Comparison of the surface under the cumulative ranking curve (SUCRA) values derived from the Bayesian and frequentist models for each timepoint: at the end of surgery (A) and 60 (B), 120 (C), and 180 (D) min after anesthesia induction. X-axis: SUCRA values from the frequentist model; Y-axis: SUCRA values from the Bayesian model. Con, control; HH, heated humidifier; HME, heat and moisture exchanger; MAK, Mega Acer Kit; H-stat, humidistat; PI, passive insulation; IV, intravenous fluid warmer; WM, water mattress; FAW, forced air warmer; EHE, esophageal heat exchanger.

Figure 8. Ranking of interventions based on surface under the cumulative ranking curve

(SUCRA) values over time. MAK consistently ranked the highest at all assessed time points. Con, control; HH, heated humidifier; HME, heat and moisture exchanger; MAK, Mega Acer Kit; H-stat, humidistat; PI, passive insulation; IV, intravenous fluid warmer; WM, water mattress; FAW, forced air warmer; EHE, esophageal heat exchanger.

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Table 1. Study characteristics

Author, year	Region	Surgery	Intervention	N	Patient age, years [†]	Sex (M/F)	Temperature measurement site	Time points of temperature measurements [‡]	Hypothermia Tx and other details.
Carli, 1982[88]	UK	Elective major abdominal surgery	Control	9	70.8±9.6	6/3	Body temperature = $(0.66 \times \text{aural canal } T) + (0.34 \times \text{mean skin } T)$	End of surgery	None.
			HH + IV + WM	11	76.8±5.3	2/9			
Chen, 1994[92]	Taiwan	Elective abdominal surgery	Control	14	56.85±4.72	8/6	Nasopharynx	Baseline / 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180 min after induction	None.
			HH	22	50.68±3.33	12/10			
Conahan, 1987[82]	US	Laparoscopy and ovum harvesting in an ambulatory surgery unit	Control	9	33.8±0.8	0/9	Sublingual	Baseline / 15, 30, 45 min after induction / upon RR arrival	None.
			HH	10	32.1±1.0	0/10			
de Castro, 2011[97]	Brazil	Elective abdominal gynecologic surgeries lasting 120 min or more	FAW	15	50±13	0/15	Esophagus	15, 30, 60, 90, 120 min after respiratory circuit connection	None.
			HME + FAW	15	52±12	0/15			
Deriaz, 1992[94]	France	Gynecological surgery	Control	25	NR	NR	Esophagus	Baseline / 30, 60, 90 min after induction / End of anesthesia	None.
			HME	25	NR	NR			
			HH	25	NR	NR			
Eckerbom, 1990[95]	Sweden	Dental and oral surgery, transsphenoidal hypophysectomy, middle ear surgery, surgery of the pharynx, nose and neck	PI	10	52±14	5/5	Rectum	Baseline / 20 min after the end of anesthesia	None.
			HME + PI	10	32±10	5/5			
Ginsberg, 2000[83]	US	Cardiac surgery involving the use of hypothermic CPB	WM	33	65±13	NR	Pulmonary artery	Baseline (on separation from CPB) / End of case (just before transport to the ICU)	None.
			IV	31	64±9	NR			
			HH	37	67±11	NR			
Goldberg, 1992[84]	US	Lower abdominal procedures under general anesthesia anticipated to last 1-4hrs	Control	16	41.4±10.1	NR	Sublingual	Baseline / 60, 90 min after induction / On arrival in the PACU	Blood warmed to 36°C.
			HME	21	43.2±14.1	NR			
			HH	14	44.7±10.8	NR			
Han, 2013[74]	South Korea	Elective living donor liver transplantation	HME + PI + IV + WM	17	55 (48,60)	15/2	Baseline: Tympanic membrane After induction: Pulmonary artery	Baseline / 60, 120, 180 min after induction (dissection phase) / End of surgery	Blood warmed using a rapid fluid warming machine.
			HH + PI + IV + WM	17	54 (49,57)	12/5			
Jo, 2013[75]	South Korea	Elective arthroscopic shoulder surgery	Control	20	47.5±16.6	14/6	Esophagus	Baseline / 15, 30, 45, 60, 75, 90, 105, 120 min after induction	Warm-cotton blanket applied when core temperature <35°C.
			HH	20	50.4±14.1	12/8			
Jung, 2015[76]	South Korea	Elective spinal surgery with duration of at least 180 min	HH	30	49.1±10.4	12/18	Esophagus	Baseline / 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180 min after induction	FAW (Bair Hugger) applied when core temperature <35°C.
			HH + IV	30	47.2±10.6	16/14			
			MAK	30	49.3±12.1	16/14			
Kim, 2015[77]	South Korea	Elective craniotomy	PI + WM	34	47.9±14.9	16/18	Esophagus	Baseline / 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180 min after induction / End of surgery	FAW applied when core temperature <35.5°C.
			HH + PI + WM	34	50.7±11.3	17/17			
			MAK + PI + WM	34	49.4±12.5	20/14			
Kulkarni, 1995[89]	UK	Elective unilateral total hip replacement	Control	10	69 (59,83)	4/6	Tympanic membrane	Baseline / End of surgery	Blood warmed to 37°C.
			HH	10	70 (58,83)	5/5			
			EHE	10	72 (58, 99)	3/7			
Kwak,	South	Escharectomy	HME + IV +	30	45.6±13.3	24/6	Esophagus	Baseline / 15, 30, 45,	Blood warmed

2013[78]	Korea	and skin graft under general anesthesia	WM					60, 75, 90, 105, 120, 135, 150, 165, 180 min after induction	via fluid heating unit setting at 40°C.
			HH + IV + WM	30	45.4±11.6	25/5			
Lee, 2011[5]	South Korea	Posterior lumbar spinal fusion with metal device instrumentation within two spinal levels	PI + FAW	40	64.7±8.1	22/18	Tympanic membrane	Baseline / 30, 60, 90, 120, 150, 180 min after induction	Blood warmed to 36°C.
			HH + PI + FAW	40	64.2±8.2	28/12			
Ouellette, 1993[85]	US	Elective cervical or lumbar laminectomy with a duration of at least 90 min	Control	12	54±17	NR	Esophagus	Baseline / 30, 60, 90 min after induction / End of anesthesia	None.
			Humidstat (hygrostatic condenser humidifier)	12	54±15	NR			
			PI (reflective space blanket)	12	50±17	NR			
			HH	12	48±7	NR			
			FAW	12	56±17	NR			
Park, 2009[79]	South Korea	Elective surgery under general anesthesia	Control	20	48.4±11.3	5/15	Esophagus	Baseline / 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180 min after induction	None.
			HHBC	20	49.9±14.3	6/14			
Park HJ, 2017[80]	South Korea	Elective thyroidectomy	Control	85	47.3±11.9	16/69	Esophagus	Baseline / 30, 60, 90 min after induction	None.
			HHBC	85	49.2±11.7	22/63			
Park S, 2017[81]	South Korea	Arthroscopic hip surgery	HME	28	38.4±11.5	19/9	Esophagus	Baseline / 120 min after induction	Warming measures (administration of pre-warmed IV fluid, FAW) when core temperature <35°C.
			HHBC	28	41.6±9.7	18/10			
Ralley, 1984[93]	Canada	Uncomplicated valve replacement or aortocoronary bypass surgery with CPB	Control	15	62.3±2.6	13/2	Nasopharynx	Baseline (termination of CPB) / 30, 90, 120, 150, 180, 240 min after CPB termination	NR
			HH	15	58.5±2.4	12/3			
Shanks, 1988[86]	US	Elective spinal surgery	IV	10	50±28	2/8	Rectum	Baseline / 30, 60, 120, 180 min after induction / End of surgery	NR
			HME + IV	10	42±16	4/6			
			PI + IV	10	42±17	3/7			
			HME + PI + IV	10	38±14	5/5			
Stone, 1981[87]	United States	Surgical procedures lasting 3 or more hours	Control	10	NR	10/0	Nasopharynx	Baseline / 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180, 240 min after induction	Warming blankets applied in some patients.
			HH	10	NR	10/0			
Tølløfsrud, 1984[96]	Norway	Abdominal aorta surgery	IV	10	64*	24/6	Esophagus	60, 120, 180 min after induction	None.
			HH + IV	10					
			HH + IV + WM	10					
		Extra-abdominal vascular surgery	IV	10	70*	24/6			
			HH + IV	10					
			HH + IV + WM	10					
Yam, 1990[90]	UK	Elective total hip arthroplasty for osteoarthritis	Control	20	73±8	6/14	Aural canal	Baseline / End of surgery	Blood warmed to 37°C.
			HME	20	70±6	3/17			
			HH	20	68±9	8/12			
Yamashita, 2007[91]	Japan	Orthopedic or head and neck surgery	IV + WM	20	56±17	9/11	Upper pharynx	Baseline (5 min after intubation) / 10, 15, 20, 25, 30, 60, 120 min after induction	FGF 2L/min
			HME + IV + WM	20	64±16	14/6			
			IV + WM	20	58±21	6/9			
			HME + IV + WM	20	64±16	14/6			FGF 4L/min

Abbreviations. N: number of patients; SD: standard deviation; M: male; F: female; Tx: treatment; CPB: cardiopulmonary bypass; HH: heated humidifier; IV: intravenous fluid warmer; WM: water mattress; T: temperature; FAW: forced air warmer; HME: heat and moisture exchanger; PI: passive insulation; HHBC: heated-humidified breathing circuit; MAK: Mega Acer Kit; EHE: esophageal heat exchanger; NR: not reported; FGF: fresh gas flow.

† Data are presented as mean ± SD or median (Q1, Q3).

‡ Timing before and after induction of anesthesia and post-intubation are all included as baseline.

*Only mean values are reported.

Table 2. Risk of bias assessment using the Cochrane risk-of-bias tool for randomized trials, version 2.0

Study	Randomization process	Deviations from the intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall risk of bias
Carli, 1982[88]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Chen, 1994[92]	High risk ^a	Low risk	Low risk	Low risk	Some concerns	High risk
Conahan, 1987[82]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
de Castro, 2011[97]	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns
Deriaz, 1992[94]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Eckerbom, 1990[95]	High risk ^b	Low risk	Low risk	Low risk	Some concerns	High risk
Ginsberg, 2000[83]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Goldberg, 1992[84]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Han, 2013[74]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Jo, 2013[75]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Jung, 2015[76]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Kim, 2015[77]	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Kulkarni, 1995[89]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Kwak, 2013[78]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Lee, 2011[5]	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns
Ouellette, 1993[85]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Park, 2009[79]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Park HJ, 2017[80]	High risk ^c	High risk ^e	Low risk	Low risk	Some concerns	High risk
Park S, 2017[81]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Ralley, 1984[93]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Shanks, 1988[86]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Stone, 1981[87]	High risk ^d	Low risk	Low risk	Low risk	Some concerns	High risk
Tølløfsrud, 1984[96]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Yam, 1990[90]	Some concerns	Low risk	Low risk	Low risk	Some concerns	High risk
Yamashita, 2007[91]	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns

- ^a Allocation concealment: no information; baseline imbalances: substantial differences in group sizes.
- ^b Allocation concealment: no information; baseline imbalances: significant differences in age and fluid administered during surgery.
- ^c Allocation concealment: no information; baseline imbalances: excessive similarity in baseline characteristics due to the matching process.
- ^d Allocation concealment: suspicion that the investigator had knowledge of the allocation (randomly assigned according to surgery duration).
- ^e Substantial impact of failure to analyze participants in the group: all dropouts from the control group (26 of 111 patients).

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PRISMA 2009 Flow Diagram















