

Academic article

Active Warming Technologies for preventing
Perioperative Hypothermia:
A Narrative Review of Evidence and Clinical Practice

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Abstract

Perioperative hypothermia, defined as a core body temperature below 36°C, remains a frequent and preventable complication during anesthesia and surgery. It contributes to adverse outcomes, including increased blood loss, wound infection, delayed anesthetic recovery, and prolonged hospital stay.

This review aims to summarize current evidence regarding active warming technologies—Forced-Air Warming, Warming Mattress, and Intravenous Fluid Warmer—as evidence-based tools for preventing perioperative hypothermia. However, limited evidence is available comparing commonly used warming technologies in routine clinical anesthetic practice. Relevant clinical and experimental studies published over the past decade were reviewed to assess device performance, thermal efficacy, safety, and cost-effectiveness.

Evidence consistently supports Forced-Air Warming as the most validated and effective method for maintaining intraoperative normothermia, supported by multiple randomized controlled trials and meta-analyses. Warming mattresses provide additional conductive heat but are less efficient when used alone; their effectiveness improves when integrated into multimodal warming protocols. Intravenous fluid warmers are particularly valuable in surgeries involving large-volume fluid administration, minimizing heat loss through cold infusions. Despite strong validation, limitations remain, including variations in device design, incomplete standardization of testing methods, and potential safety concerns related to misuse or infection risk.

In clinical practice, selection of warming strategies should consider patient risk factors, surgical duration, and expected fluid administration. Future research should focus on standardizing protocols, optimizing integration with perioperative temperature monitoring systems, and exploring emerging technologies for precise thermal control.

Keywords: Forced-air warming, Intravenous fluid warmer, Perioperative hypothermia, Temperature management, Warming mattress

Introduction

Perioperative hypothermia, defined as a core body temperature below 36°C, is a common yet

preventable complication during surgery.¹ It primarily results from anesthesia-induced impairment of thermoregulation combined with exposure to a cool

operating room environment. Both general and regional anesthesia cause redistribution of heat from the core to the periphery, leading to a rapid decrease in core temperature, particularly within the first hour of anesthesia induction. Without active temperature management, patients remain at high risk of unintended hypothermia and its associated complications.²⁻³

The adverse effects of perioperative hypothermia are well established. Even mild hypothermia can impair coagulation, increase blood loss and transfusion requirements, suppress immune function, and raise the risk of surgical site infections.³⁻⁴ Additionally, hypothermia delays drug metabolism, prolongs anesthetic recovery, and causes post-operative shivering and discomfort.⁵ These consequences often extend post-anesthesia care unit stays and increase overall healthcare costs, making perioperative normothermia a critical quality indicator in modern practice.⁶⁻⁷

Relevant studies published within the past 10 years were identified through literature search in major medical databases. To reduce these risks, active warming technologies such as Forced-Air Warming (FAW) systems, Warming Mattresses (WM), and Intravenous Fluid Warmers (IVFW) are widely used. FAW devices provide convective warming, warming mattresses deliver conductive heat, and IVFW systems prevent heat loss from infused fluids. Each modality contributes uniquely to maintaining thermal balance.

Although several clinical guidelines and systematic reviews have addressed the prevention of perioperative hypothermia, most recommendations focus on general temperature management rather than direct comparison of commonly used active warming technologies in routine anesthetic practice.⁷⁻⁸ In addition, the optimal selection of single versus combined warming techniques in different surgical conditions remains unclear. Therefore, this narrative review aims to summarize current evidence on active warming technologies, including forced-air warming, warming mattresses, and intravenous fluid warmers, for prevention of perioperative hypothermia in patients undergoing anesthesia. This review focuses on clinical

effectiveness, safety, and cost-effectiveness of each technique and discusses the role of single and combined warming strategies in different surgical settings.

Mechanisms and Principles of Active Warming Technologies (*Table 1*)

Maintaining perioperative normothermia requires effective temperature management strategies to counteract multiple mechanisms of heat loss, including radiation, convection, conduction, and evaporation.^{3,5,8} Among these, redistribution of core heat to peripheral tissues following anesthesia induction is the most significant contributor, often causing a core temperature decrease of 1 - 1.5°C within the first hour. Active warming technologies aim to reduce this thermal gradient by providing external heat or preventing internal heat loss from unwarmed infusions. The three most validated systems—Forced-Air Warming (FAW), Warming Mattresses (WM), and Intravenous Fluid Warmers (IVFW)—operate on distinct thermodynamic principles, each offering specific advantages and limitations.^{4,8-9}

Forced-Air Warming (FAW) is the most widely used and extensively validated perioperative warming method. It functions through convective heat transfer, circulating warmed air (typically 37 - 43°C) over the patient's skin via a disposable perforated blanket connected to a heater/blower unit.^{4,9} The warm air layer formed adjacent to the skin enhances heat transfer while reducing convective and radiative heat loss. FAW blankets are available in various configurations, allowing flexibility across surgical positions and procedures.^{4,8-9} Numerous studies demonstrate FAW's effectiveness in maintaining core temperature across diverse surgical populations. When properly used, FAW provides uniform heating with a low risk of thermal injury, although concerns regarding operating room air contamination persist, with inconclusive evidence of increased infection risk.^{4,10,13}

Warming Mattresses (WM) provide conductive heat through direct contact between the patient and a heated surface, typically integrated into the operating table. These systems use electrically heated or water-circulating pads regulated by thermostats to maintain safe temperatures, usually between 37–42°C. The effectiveness of WM depends on contact surface area, patient positioning, and skin perfusion.^{4,9-10} As only posterior body surfaces are warmed, conductive heating alone is often insufficient for total-body temperature maintenance. However, WM enhance thermal comfort and are valuable as part of a multimodal warming strategy.^{4,8} Advantages include silent operation and elimination of air circulation, reducing contamination concerns. Modern systems incorporate safety features to minimize the risk of thermal injury.

Intravenous Fluid Warmers (IVFW) target heat loss caused by the infusion of large volumes of unwarmed fluids or blood products. Each liter of room-temperature fluid can significantly lower core body temperature.^{8,11} IVFW systems use counter-current heat exchange to warm fluids to near-physiological temperatures before infusion. Their performance depends on flow rate, line length, and device capacity.¹¹ IVFW devices are particularly beneficial during major surgery, trauma resuscitation, and procedures involving high-volume fluid replacement. While they are not standalone warming solutions, IVFW systems play a crucial complementary role when combined with FAW and conductive warming methods to maintain perioperative normothermia.⁷⁻⁸

Validation Studies and Evidence of Effectiveness

This section synthesizes evidence from bench testing, randomized controlled trials (RCTs), systematic reviews, and clinical guidelines validating the performance and effectiveness of Forced-Air Warming (FAW), Warming Mattresses (WM), and Intravenous Fluid Warmers (IVFW) in preventing perioperative hypothermia.

Forced-Air Warming (FAW) is the most extensively validated modality. Bench studies confirm accurate heater performance, stable temperature delivery, and uniform airflow across blanket designs, supporting consistent clinical performance.^{4,9,12} Numerous RCTs demonstrate that FAW—particularly when used for pre-warming and intraoperative maintenance—significantly reduces the incidence and severity of perioperative hypothermia compared with passive insulation.^{10,13} Across a wide range of surgical populations, FAW is associated with higher intraoperative core temperatures, reduced post-operative shivering, and shorter post-anesthesia care unit stays.¹³ Head-to-head trials generally show FAW to be at least non-inferior, and often superior, to other active warming systems when applied appropriately.^{7,14} Systematic reviews and international guidelines endorse FAW as an evidence-based standard of care.^{7,15-16} Although concerns regarding operating room airflow disruption and contamination persist, current guideline assessments find insufficient clinical evidence linking FAW to increased surgical site infections when proper infection-control measures are followed.

Warming Mattresses (WM) provide conductive heating and are validated through bench testing for surface temperature uniformity and thermostat responsiveness. Clinical studies show that WM improve skin and peripheral temperatures and reduce heat loss compared with passive insulation.^{10,14} However, when used alone, they are generally less effective than whole-body FAW in maintaining core temperature, particularly during procedures with large exposed surgical fields. Evidence consistently supports WM as part of a multimodal warming strategy rather than a standalone solution. Advantages include silent operation and elimination of forced air, while limitations relate to restricted contact area and positional dependence.⁸⁻⁹ Recent design improvements have enhanced their performance in selected populations

Intravenous Fluid Warmers (IVFW) are validated for effective heat transfer across clinically relevant flow rates and are particularly important during large-volume fluid or blood administration.^{8,11} RCTs and systematic reviews demonstrate that IVFW reduce infusion-related heat loss and postoperative shivering, with greatest benefit in trauma and major surgery. However, IVFW are adjunctive devices and cannot fully counteract anesthesia-related heat redistribution alone.

Clinical Implementation of Active Warming Strategies

Selection of warming techniques should be based on patient risk factors, surgical duration, and expected fluid administration. Forced-air warming alone may be sufficient in short or low-risk procedures. Combined warming techniques should be considered in prolonged surgery, major procedures, or cases requiring large-volume infusion. Intravenous fluid warmers help prevent heat loss from cold infusions, while warming mattresses may be useful when forced-air warming is limited. In clinical practice, the choice of warming method should consider efficacy, safety, and cost-effectiveness.^{2,7}

Comparative Effectiveness and Multimodal Warming Strategies

Comparative analyses indicate that whole-body FAW ranks among the most effective single modalities, while multimodal strategies—combining pre-warming, intraoperative surface warming, and warmed fluids—consistently provide superior temperature control.^{7,14} Study heterogeneity and lack of standardized validation protocols remain limitations, underscoring the need for harmonized testing and continued safety surveillance.^{15,17-18}

Perioperative temperature management is most effective when warming devices are selected and combined according to their mechanisms of heat delivery, timing of use, and patient- and procedure-specific risk.^{9,19} Comparative evidence supports the use of both single-modality and multimodal strategies, with growing emphasis on early initiation and maximal body-surface coverage.^{7-8,16}

Single-modality effectiveness.

Across randomized controlled trials (RCTs) and meta-analyses, Forced-Air Warming (FAW) consistently demonstrates superior maintenance of intraoperative core temperature and lower rates of postoperative hypothermia compared with passive insulation.^{8,12,14} FAW rapidly restores peripheral heat content and mitigates redistribution hypothermia following anesthesia induction.^{7,8,13} Consequently, major guidelines recommend active warming, particularly FAW, for most adult surgical patients at risk. Conductive warming systems effectively increase skin temperature in contact areas but are generally less effective than whole-body FAW when used alone due to limited coverage.^{9,12} Newer underbody and large-surface conductive designs have improved performance in selected procedures. Intravenous Fluid Warmers (IVFW) effectively prevent infusion-related heat loss during large-volume or rapid fluid administration but do not address redistribution hypothermia and should be viewed as adjuncts rather than standalone solutions.^{8,11}

Variations within FAW. Blanket configuration influences effectiveness depending on surgical exposure and positioning. Upper- and lower-body FAW blankets provide comparable core-temperature maintenance when appropriately matched to the surgical field.⁹ Underbody FAW designs offer uniform surface coverage and are particularly advantageous when access to the torso or limbs is restricted.⁴ Recent trials suggest similar performance between underbody and overbody FAW when pre-warming and appropriate settings are used, emphasizing individualized blanket selection to maximize usable surface area without compromising sterility.

Comparative and network analyses.

Head-to-head and network meta-analyses consistently rank whole-body FAW and large-area warming systems among the most effective single modalities. Some newer resistive or circulating-water systems achieve comparable results under optimized conditions. Variability across studies largely reflects differences in pre-warming practices, device settings,

and temperature measurement methods.⁸⁻⁹ Overall, earlier initiation and greater surface coverage emerge as key determinants of effectiveness.

Evidence for multimodal strategies.

Combining interventions yields the most reliable thermal control. Pre-warming for 15–30 minutes before anesthesia significantly reduces redistribution hypothermia and, when combined with intraoperative FAW, results in higher core temperatures than intraoperative warming alone.^{7-8,13} Adding IVFW to surface warming provides further benefit in procedures involving significant fluid or blood administration, reducing both core temperature decline and postoperative shivering. Institutional bundled protocols incorporating pre-warming, intraoperative surface warming, warmed fluids when indicated, and routine temperature monitoring consistently improve normothermia at PACU arrival.

Tailoring and implementation.

Device selection should account for surgical exposure, anesthetic technique, patient risk factors, and positioning constraints. Elderly, low-BMI, or high-risk patients benefit most from multimodal approaches. Effective implementation requires timely initiation, continuous core-temperature monitoring, adherence to safety guidelines, and standardized institutional protocols. Although multimodal strategies incur higher upfront costs, evidence suggests downstream savings through reduced complications, shorter recovery times, and improved patient outcomes.^{2,8}

Safety, Limitations, and Device-Validation Challenges

Perioperative warming devices are effective but not without risk. Comprehensive validation must therefore address patient safety, infection concerns, practical limitations, and methodological challenges that complicate device comparison and generalizability. Understanding these issues is essential for safe implementation and evidence-based selection.

Patient safety risks. Thermal injury is the primary direct hazard associated with surface warming devices. Burns may occur due to malfunctioning thermostats, prolonged focal heat exposure, impaired thermoregulation, or occlusion of temperature sensors, particularly in patients with poor perfusion or neuropathy.^{17,20} Modern devices incorporate alarms and temperature cutoffs, yet careful monitoring remains essential, especially when warming beneath dressings or monitoring equipment. Intravenous fluid and blood warmers introduce additional risks: overheating may damage fluids or cause hemolysis, while inadequate warming fails to prevent heat loss. Regulatory guidance emphasizes the use of approved devices and adherence to manufacturer-specified flow rates and indications. Electrical and fire risks also exist, underscoring the importance of regular maintenance and biomedical engineering oversight.

Infection and airflow concerns. Forced-Air Warming (FAW) has generated debate regarding potential disruption of operating room airflow and theoretical contamination. While bench studies and observational reports raise concern, systematic reviews and guideline panels have not identified convincing clinical evidence linking FAW to increased surgical site infection rates. Current recommendations support continued FAW use alongside strict aseptic technique, appropriate blanket placement, and well-maintained ventilation systems, while encouraging ongoing surveillance.⁴

Practical limitations. The effectiveness of surface warming is constrained by surgical exposure requirements, as uncovered areas limit heat transfer. Device choice must align with patient positioning and operative access.^{4,9} Additionally, surface warming relies on adequate peripheral perfusion; hypovolemia, vasoconstriction, or low cardiac output may blunt central heat transfer, necessitating adjunctive measures such as pre-warming or warmed infusions. Operational factors—including preoperative time, staffing, costs, and disposable use—also influence feasibility and sustainability.

Validation challenges. Bench testing evaluates parameters such as heater accuracy and temperature stability under controlled conditions that may not reflect clinical realities. Furthermore, studies vary widely in temperature measurement sites, definitions of hypothermia, timing of assessment, and use of co-interventions, limiting comparability.^{9,18} Device-specific design differences further complicate interpretation. Regulatory approval pathways focus on safety and equivalence rather than comparative clinical effectiveness, making independent trials and post-market surveillance crucial.

Mitigation strategies and future directions.

Best practice includes strict adherence to manufacturer guidance, routine equipment maintenance, and standardized monitoring of core temperature.¹⁷ Multimodal, protocol-driven warming bundles reduce reliance on single devices and improve reliability.⁸ Future research should prioritize harmonized validation protocols linking bench performance to clinical endpoints, large pragmatic trials, robust surveillance systems, and consideration of environmental and cost-effectiveness impacts to guide sustainable perioperative warming strategies.

Practical Implementation and Cost-Effectiveness

This section translates evidence into operational guidance for perioperative teams and summarizes economic considerations when selecting and implementing active warming technologies.

A. Practical implementation

Preoperative screening and pre-warming.

All surgical patients should be risk stratified on arrival based on procedure type, expected duration, anticipated fluid or blood loss, baseline temperature, age, body mass index, and thermoregulatory impairment. Patients at moderate to high risk should be prioritized for active warming bundles.¹¹⁶ When feasible, pre-warming with forced-air or resistive systems for 15 - 30 minutes before induction increases peripheral heat content and attenuates redistribution hypothermia. Start and stop times should be documented.

Intraoperative device selection and timing.

Surface warming should be initiated at induction and continued intraoperatively until normothermia is achieved.¹⁶ Forced-air warming (FAW) remains the preferred backbone strategy due to its strong evidence base.¹⁵ Blanket configuration (upper, lower, or underbody) should maximize covered surface area without interfering with the sterile field.⁴ Intravenous fluid and blood warmers should be added when large or rapid infusions are anticipated, and conductive or underbody systems may be used when FAW access is limited.^{7,11} Multimodal strategies (pre-warming + FAW + IV fluid warming) are consistently most effective. Device temperatures and flow rates must follow manufacturer recommendations.¹⁷

Temperature monitoring and recovery.

Core temperature should be monitored using reliable sites (e.g., esophageal, nasopharyngeal, or bladder) and recorded at baseline and regular intraoperative intervals.¹⁷ Protocols should specify escalation thresholds (e.g., <36°C). Active warming should continue into the post-anesthesia care unit until the patient maintains normothermia and is comfortable, with clear handover documentation.

Safety, infection control, and training.

Routine device maintenance, alarm recognition, and proper use of disposables reduce thermal and electrical risks.²⁰ Current evidence does not mandate discontinuation of FAW for infection concerns; appropriate device use, intact disposables, and ongoing surgical site infection surveillance are recommended. Staff competency training and integration of warming steps into perioperative checklists improve compliance and outcomes.

B. Cost-effectiveness and procurement

Costs and savings. Direct costs include capital equipment, disposables, and maintenance, while operational costs relate to staff time and energy use. These are often offset by indirect savings from reduced transfusions, fewer wound complications, shorter recovery times, and decreased length of stay.^{2-3,8}

Economic evidence and procurement.

Economic models consistently show FAW—often combined with warmed fluids—to be cost-effective for intermediate and major surgeries. The magnitude of benefit depends on baseline hypothermia rates, case mix, and staffing costs. Institutions are encouraged to perform local cost modeling and align procurement with surgical volume, transfusion risk, and sustainability considerations, favoring bundled and protocolized warming strategies to maximize clinical and economic benefit.^{7,15,18}

Future Perspectives

Advances in perioperative thermal management have reduced the incidence of inadvertent hypothermia, yet important opportunities remain to improve effectiveness, safety, personalization, sustainability, and evidence standards. Future progress will require coordinated innovation across technology, research, regulation, and health systems.

Smart, closed-loop warming system represent a key technological frontier.

Unlike current open-loop devices, closed-loop platforms could automatically adjust heat delivery using continuous core-temperature feedback. Integration with reliable monitoring and adaptive control algorithms may enable tighter temperature control, reduce thermal overshoot, and trigger alerts when heat transfer is insufficient.^{9,17} Future research should focus on validating controller safety, robustness across patient populations, and superiority for clinically meaningful outcomes.

Personalization and predictive analytics offer opportunities to tailor warming strategies to individual risk. Predictive models incorporating patient characteristics, procedural factors, and intraoperative trends could guide the timing of pre-warming, device selection, and temperature targets. Machine-learning approaches using large perioperative datasets may optimize resource allocation and improve outcomes, particularly where pre-warming capacity is limited.^{2,8}

Device miniaturization and novel modalities

are expanding warming options beyond the operating room. Wearable or low-profile systems may enhance preoperative, postoperative, and transport warming, while hybrid resistive–convective technologies could improve responsiveness and coverage. Validation must emphasize comfort, mobility, and safety alongside efficacy.⁹

Standardized validation protocols remain a critical gap. Harmonized bench tests linked to core clinical outcomes—such as defined temperature thresholds, shivering, transfusion needs, and infection rates—would improve device comparison and procurement decisions.^{3,15,18} Consensus reporting standards detailing device models, settings, and measurement methods are essential.

Regulatory pathways and post-market surveillance should increasingly emphasize real-world performance. Comparative effectiveness studies, clinical registries, and transparent reporting of device testing and adverse events will strengthen safety oversight and guide practice.⁹

Sustainability considerations are increasingly important. Development of reusable or recyclable components, energy-efficient heaters, and life-cycle–informed procurement can reduce environmental and financial burdens without compromising patient safety.^{2,20}

Implementation science and equity must accompany technological advances. Pragmatic, multicenter trials of warming bundles, embedded economic evaluations, and context-specific adaptations are needed to ensure effective uptake across diverse healthcare settings, including low-resource environments.^{2,7,16}

Conclusion

Perioperative hypothermia remains a common and clinically important problem, contributing to increased morbidity, delayed recovery, and patient discomfort. Evidence from bench testing, randomized

controlled trials, and systematic reviews consistently shows that active warming technologies—particularly Forced-Air Warming (FAW), warming mattresses, and intravenous fluid warmers (IVFW)—are effective in maintaining perioperative normothermia when appropriately applied. Each modality acts through a distinct mechanism, and understanding these principles enables clinicians to tailor warming strategies to surgical type, patient physiology, and intraoperative risk.

Comparative evidence highlights that multimodal approaches, combining pre-warming, intraoperative surface warming, and warmed fluid administration,

provide the most reliable protection against hypothermia, especially in high-risk patients and major procedures. Successful implementation requires attention to timing, monitoring, staff training, and safety protocols, while economic analyses suggest that structured warming bundles are cost-effective by reducing complications and recovery time.

Future advances in smart, personalized warming systems and standardized validation frameworks are expected to further enhance safety, effectiveness, and patient-centered perioperative care.

Table 1 Comparative Overview of Perioperative Warming Modalities

Dimension	Forced-Air Warming (FAW)	Warming Mattresses (Conductive Systems)	Intravenous Fluid Warmers (IVFW)
Primary mechanism	Convective heat transfer via warmed airflow through disposable blankets	Conductive heat transfer via direct contact with a heated surface	Internal heat delivery via warmed intravenous fluids
Bench validation	Demonstrates precise outlet temperature control, stable airflow distribution, and rapid thermal responsiveness	Provides stable and controlled surface temperatures when continuous contact is maintained	Performance varies across devices; modern systems maintain target temperatures even at high flow rates
Effect on core temperature	High effectiveness; most effective single modality for maintaining normothermia	Low–moderate; primarily improves peripheral temperature rather than core temperature	Moderate; particularly effective during large-volume or rapid infusions
Impact on surgical site infection (SSI)	Some trials report reduced SSI rates ⁷	No direct effect on SSI	No direct effect on SSI
Role in multimodal warming	Core component and primary warming modality	Adjunctive modality, particularly in prolonged or high heat-loss procedures	Essential adjunct in cases involving major fluid administration

Dimension	Forced-Air Warming (FAW)	Warming Mattresses (Conductive Systems)	Intravenous Fluid Warmers (IVFW)
Guideline recommendations	Recommended as first-line active warming by NICE ² and endorsed by Cochrane reviews	Recommended only as part of combined strategies, not as sole warming method	Recommended in conjunction with FAW when large-volume fluid or blood administration is anticipated
Safety profile	No evidence of increased SSI risk when used appropriately; well-established safety record	Risk of pressure injury or thermal burns if improperly positioned or monitored	Depends on accurate temperature sensors; risk of overheating if malfunction occurs
Key limitations	May interfere with surgical access in some operative fields; requires disposable blankets	Reduced effectiveness when contact is interrupted; limited use in surgeries requiring special positioning	Does not address cutaneous or evaporative heat loss
Suitability by surgical type	Applicable to most surgical procedures and anesthesia techniques	Limited in procedures requiring non-supine positioning	Best suited for trauma, major surgery, and massive transfusion scenarios
Effect on redistribution hypothermia	Highly effective, especially with prewarming	Limited	No direct effect
Cost-effectiveness	High; associated with reduced SSI, bleeding, and faster recovery	Cost-effective as an adjunct, not as standalone therapy	Cost-effective in high-risk patients requiring substantial fluid replacement
Role in Enhanced Recovery After Surgery (ERAS) protocols	Primary equipment of ERAS in perioperative temperature management	Supportive role in high-risk or prolonged procedures	Recommended adjunct to FAW in multimodal ERAS strategies

*Data summarized from randomized controlled trials, systematic reviews, and international guidelines.^{3,6-7,13-15}

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