BMC Surgery

REVIEW Open Access

Strategies for perioperative hypothermia management: advances in warming techniques and clinical implications: a narrative review

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Abstract
Perioperative hypothermia is a frequent clinical complication resulting from the cold environment of the operating room and prolonged skin exposure, leading to adverse outcomes and increased healthcare burdens. To address this issue, this narrative review discusses in detail the currently common warming strategies for perioperative hypothermia .Forced air warming (FAW) systems are widely recognized as the most effective intervention for maintaining core body temperature. Additionally, alternative technologies, such as circulating-water mattresses, carbon-fiber resistive heating systems, self-regulated heated air garments, self-heating blankets, and chemical heat packs, offer diverse advantages and disadvantages. Passive warming methods, including thermal reflective blankets and cotton blankets, provide a cost-effective solution, albeit with reduced efficacy compared to active warming measures. Recent advancements have focused on improving both active and passive warming approaches to balance effectiveness and cost-efficiency. While FAW remains the gold standard, other systems offer specific benefits, such as improved portability and reduced costs, making them suitable for use in diverse clinical scenarios. Effective perioperative temperature management reduces hypothermia-related complications, decreases healthcare expenditures, and provides substantial social and organizational benefits. Thus, selecting the most appropriate warming intervention in clinical practice requires a tailored approach, considering both patient-specific needs and resource availability.

Keywords Perioperative Hypothermia, Thermal management active, Passive warming, Forced air warming, Surgical complications

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In physiological conditions, human body temperature remains relatively stable to facilitate the proper functioning of biological processes, primarily regulated by the thermoregulatory system [1]. This system comprises temperature receptors (central and peripheral thermoreceptors), the thermoregulatory center, efferent pathways, effectors, and mechanisms for behavioral regulation. Temperature receptors are distributed throughout the skin, liver, skeletal muscle, hypothalamus, and other regions of the central nervous system, allowing for precise detection of body temperature [2]. When temperature fluctuations occur, these receptors become activated, generating electrical signals and increasing the frequency of action potentials in the corresponding afferent nerve fibers, which are subsequently transmitted through spinal pathways to the thermoregulatory center [3]. The thermoregulatory center, primarily located in the spinal cord and brain—particularly within the hypothalamus—receives and processes these signals and initiates appropriate responses via the efferent system.

Under physiological conditions, the thermoregulatory center integrates inputs from both peripheral and central thermoreceptors, coordinating with other neural centers to regulate body temperature through three primary mechanisms: (1) regulating skin vasoconstriction or vasodilation, as well as sweat gland activity via the sympathetic nervous system to influence heat dissipation, while modulating brown adipose tissue metabolism to regulate heat production; (2) adjusting behavioral thermoregulation through activation of the somatic nervous system, involving modifications in skeletal muscle activity and tone to influence thermogenesis; and (3) regulating the secretion of thyroid hormones, adrenaline, noradrenaline, and growth hormone to modulate metabolic activity, thereby affecting heat production [4, 5]. Efferent pathways and effectors encompass both autonomic and behavioral defense mechanisms. Major autonomic responses to cold exposure include vasoconstriction of small arteries in the extremities, reducing skin blood flow to minimize heat loss, along with shivering. In infants, non-shivering thermogenesis in brown adipose tissue serves as the primary mechanism for heat production [6]. Behavioral defenses, such as adjusting clothing, moving actively in a cold environment, and seeking a warm and dry shelter, are among the most effective thermoregulatory mechanisms, supporting autonomic regulation to maintain core temperature near the physiological set point [7].

It is generally accepted that a thermoregulatory set point is located in the preoptic area/anterior hypothalamus, with central temperature-sensitive neurons maintaining this set point at approximately 36.5–37.5 °C [8]. When deviations from this set point occur, the feedback system (thermoreceptors) transmits signals of deviation to the central system (preoptic hypothalamus), which then performs comprehensive analysis and activates effectors to restore the core temperature to the set point. During surgical procedures, a core temperature below 36 °C is defined as perioperative hypothermia, a frequent clinical occurrence associated with delayed drug metabolism, extended hospital stays, coagulopathy, increased risk of infection, and an elevated incidence of cardiovascular complications, which collectively heighten medical risks [9–12]. Consequently, maintaining normothermia during the perioperative period has gained substantial clinical attention. Various warming strategies have been developed to address this issue, encompassing both pharmacological approaches and physical interventions. Among these, perioperative amino acid infusion has proven effective in maintaining body temperature, while magnesium shows promise in reducing the incidence of postoperative shivering [13, 14]. Although heating anesthetic machine/ventilator gases or humidifier gases shows promise as an approach for preventing perioperative hypothermia, research specifically evaluating its effectiveness in hypothermia prevention remains limited and insufficiently directed. In this narrative review, we focus on physical interventions and therefore provide only a brief overview of the pharmacological aspects.

Core temperature and monitoring site

In daily life, multiple factors, including circadian rhythms, gender, age, menstrual cycle, muscle activity, and mental state, can lead to physiological fluctuations in body temperature. However, under normal physiological conditions, the temperature of core regions of the human body, such as the head and deep structures of the trunk, remains relatively stable and is tightly regulated by the central thermoregulatory system. Fluctuations in core temperature are generally minimal, usually within fractions of a degree during the day, with slightly greater variations occurring at night [15]. Peripheral tissues, including the skin, subcutaneous tissue, muscles, and extremities, are more susceptible to environmental temperature changes and thermoregulatory responses, particularly the skin and distal limbs, which exhibit greater temperature variability. Notably, skin temperature is closely associated with local blood flow, and therefore any factor affecting vasoconstriction or vasodilation can alter skin temperature. This makes skin temperature a potential indicator of vascular function, which can be useful for diagnosing peripheral vascular disease. Typically, peripheral temperature is 2–4 °C lower than core temperature [16]. As a result, healthcare professionals usually monitor core temperature to assess a patient's physiological status.

During the perioperative period, the majority of surgical patients experience varying degrees of hypothermia, with an incidence ranging from 4 to 90% [17, 18], primarily due to anesthetic-induced inhibition of thermoregulatory functions, combined with prolonged exposure of large areas of skin to the low-temperature environment of the operating room [19, 20]. A nationwide study investigated the incidence of unintentional intraoperative hypothermia in patients undergoing general anesthesia, along with its associated risk factors and clinical outcomes. The overall incidence of intraoperative hypothermia was 44.3%, with cumulative incidences of 17.8%, 36.2%, 42.5%, and 44.1% at 1, 2, 3, and 4 h after anesthesia induction, respectively [21]. Studies have demonstrated that patients are more prone to developing hypothermia when the operating room temperature is below 21 °C [22]. Under general or regional anesthesia, changes in core temperature follow a characteristic three-phase curve: the initial (redistribution) phase involves a rapid decrease in core temperature; during the second (linear) phase, the rate of decline slows; and finally, in the stable phase, core temperature remains relatively constant [10]. Clinically, core temperature is regulated by balancing heat production and heat loss. Heat is produced through the metabolism of macronutrients in tissue cells and the utilization of ATP. The major heat-producing organs include the viscera—particularly the liver, which is the most metabolically active organ at rest—and skeletal muscles, which are responsible for the majority of heat production during physical activity [23]. Heat loss occurs predominantly via conduction, convection, radiation, and evaporation [24, 25]. Total body heat is reflected in the mean body temperature, calculated as: mean body temperature $= 0.87 \times$ core temperature $+ 0.13 \times$ skin temperature [26].

Accurate monitoring of core temperature and proper measurement technique are essential for clinical interpretation. Several scientific anesthesia societies and patient associations recommend the monitoring and control of core temperature during procedures performed under general or neuraxis anesthesia with a duration of more than 30 min or during surgical intervention lasting over one hour [27]. Pulmonary artery temperature is considered the gold standard for assessing core temperature but is often challenging to obtain. Consequently, rectal, oral, and axillary temperatures are frequently used as surrogate measures [28]. Rectal temperature is an approximation of core temperature but can be influenced by lower limb temperature and is inconvenient to measure. The agreement between axillary and rectal temperature measurements is relatively low [29]. As a result, axillary temperature is actually a highly variable and unstable measurement from deep body temperature. Axillary temperature requires the removal of sweat prior to measurement to avoid inaccurate readings. Anatomical sites with good blood perfusion, such as the distal third of the esophagus, the tympanic membrane, and the nasopharynx, are most suitable for core temperature measurement. Proper placement of an esophageal temperature probe, ideally within the lower third of the esophagus, is critical for accuracy, as it closely approximates the temperature of blood within the right atrium [30]. Tympanic membrane temperature is a good reflection of hypothalamic temperature and can be measured using a thermocouple-equipped tympanic probe or infrared thermometry, although factors such as cerumen buildup or difficulty in inserting the probe may compromise accuracy [31]. Tympanometry may seem simple, but to obtain accurate results the user needs appropriate training and expertise. The difficulty is that nearly all clinical infrared aural canal thermometers are intentionally too large to even fit more than a few millimeters into the aural canal and therefore do not "see" the tympanic membrane. As normally used, that is directed into the aural canal, infrared aural canal "tympanic membrane" systems essentially measure skin temperature and therefore poorly estimate core temperature [32].

The zero-heat-flux thermometer, a non-invasive method introduced by Fox and Solman in 1970, estimates tissue temperature by achieving a temperature gradient-free state through the use of two thermometers and an insulating layer, controlling heater temperature to maintain a consistent reading [33]. Theoretically, the temperature of subcutaneous tissue can represent core temperature; however, deviations may occur due to convective blood flow effects. Nonetheless, the forehead is considered a suitable site for zero-heat-flux thermometer use [33]. To accurately monitor changes in patient temperature during surgery, body temperature should be measured continuously or intermittently (at least every 15 min), and monitoring should continue in the post-anesthesia care unit (PACU) to ensure timely warming interventions if temperature falls below 36 °C.

Forced air warming devices

Early intraoperative warming during anesthesia induction is commonly implemented using Forced Air Warming (FAW) devices, often in combination with warmed intravenous fluids, to mitigate the risk of intraoperative hypothermia [34]. The use of FAW to prevent perioperative hypothermia can be traced back to 1847, when von Bibra & Harnass first documented its use in Erlangen, Germany, one year after Thomas Green Morton conducted the first general anesthesia in Boston [35]. Currently, various FAW devices are available commercially, generally consisting of a power unit and a blanket that transfers heated air directly to the patient's body surface, thereby reducing radiative heat loss and warming the patient via convection [36, 37]. The transfer of heat from an air medium to the body is less efficient than the transfer of heat from water of the same temperature, which constitutes the main disadvantage of the FAW system. The efficacy of FAW systems is largely contingent on the design of the blanket, with an optimal blanket characterized by a minimal temperature differential across its surface. For larger (full-body) blankets, high airflow from the power unit is particularly crucial, whereas smaller blankets (e.g., upper body and pediatric blankets) require lower airflow rates [35].

Full-body blankets are generally employed for preoperative and postoperative warming, whereas upper body blankets are typically selected intraoperatively due to their cost-effectiveness. However, depending on the nature of the surgical procedure, localized warming may be necessary. Recently, lower body blankets have been developed to provide effective intraoperative warming in cases where upper body blankets are challenging to use, such as during cardiac or pediatric surgeries. Studies have demonstrated that the use of lower body blankets for forced air warming 60 min after anesthesia induction during abdominal surgery significantly increases core temperature, outperforming upper body blankets and passive insulation (average differences in core temperature increase were 0.19 °C and 0.5 °C, respectively). At 120 min post-induction, the warming effect of lower body blankets continued to exceed that of upper body blankets and passive insulation (average differences in core temperature increase were 0.13 °C and 1.13 °C, respectively) [38]. Furthermore, lower body blankets proved more effective in preventing postoperative shivering compared to passive insulation, making them an effective intervention for regulating core temperature and preventing shivering in abdominal surgery patients within the first two hours following anesthesia induction. Additionally, the study highlighted that circulating water mattresses were the least effective warming intervention for abdominal surgeries [38].

In an average adult patient (70 kg, 170 cm) body surface area is 1.82 m^2 and contact area with a underbody forced-air warming blanket is about 1.08 m^2 while it is about 0.35 m^2 with an upper body forced-air warming blanket [37]. Lower body blankets cover a larger surface area compared to upper body blankets, although improper placement or the weight of the blanket may limit its efficacy, and uncovered upper body regions may increase radiative heat loss. Nevertheless, both blanket types are effective in preventing intraoperative hypothermia, with specific choices dependent on the type of surgery and the patient's condition [37]. While FAW systems are widely recognized as effective for perioperative hypothermia prevention, certain limitations have been identified. A 2015 study found that 20 min of preoperative forced air warming did not entirely prevent intraoperative hypothermia or shivering but significantly reduced the severity of hypothermia. In the pre-warmed group, no patients developed moderate or severe hypothermia, whereas in the control group, 21% and 13% of patients experienced moderate and severe hypothermia, respectively [39]. These findings suggest that FAW systems should be combined with additional measures to achieve optimal outcomes in reducing perioperative hypothermia risk [27]. A 2019 study demonstrated that pre-warming for 15 to 30 min before transurethral resection of the prostate (TUR) under spinal anesthesia effectively prevented postoperative hypothermia compared to patients who did not receive pre-warming. Patients who received 15 to 30 min of pre-warming experienced shorter recovery times, while pre-warming for 45 min offered no additional benefits [40].

Regarding safety, some studies have raised concerns that FAW systems may serve as a source of microbial contamination during surgery if non-perforated blankets are used. Approximately 40% of warmers tested positive for pathogens such as Staphylococcus aureus, Klebsiella, and Cryptococcus. However, when perforated blankets, as recommended, were used, no microbial contamination was detected in the airflow, with microorganisms primarily colonizing the interior tubing and filter surfaces of the warmer [41]. Subsequent studies indicated that while FAW systems may increase the bacterial load in the operating room air, there is no evidence to suggest an increased risk of hospital-acquired infections. On the contrary, the benefits of FAW systems in preventing severe intraoperative hypothermia far outweigh potential infection risks, and their effectiveness has been well documented [42, 43].

FAW systems also offer significant advantages from an economic standpoint. Cost analyses indicate that the total expenditure for utilizing FAW systems is $11,849.96, compared to $14,095.13 when no warming equipment is employed, resulting in cost savings of approximately 16% per patient ($2,245.17). Similarly, cost-effectiveness analyses demonstrate that FAW systems can achieve superior therapeutic outcomes while reducing overall treatment costs [44, 45]. Budget impact analyses further reveal that increasing the usage rate of FAW devices can reduce direct medical costs by 7.61–13.20% [44]. In addition to these cost benefits, FAW systems provide important social and organizational advantages. By reducing hospital stay durations related to adverse events resulting from perioperative hypothermia, FAW systems lower productivity losses, specifically decreasing social costs by 30.77% (from $645.22 to $447.08). FAW systems also reduce the average hospital stay from 8.45 days to 5.85 days (a reduction of 14.75–25.60%) compared to patients without warming equipment [44], thereby improving bed utilization and accessibility to healthcare services. Moreover, FAW systems reduce postoperative infection rates and cardiovascular complications, ultimately improving patient outcomes [46–48]. In conclusion, the appropriate use of FAW systems not only reduces social and medical costs, shortens hospital stays, and improves patient prognosis but also effectively maintains body temperature and prevents hypothermia-related complications [44].

Self-regulated heated air garment

In the ongoing pursuit of enhanced thermal management, researchers have developed the self-regulated heated air garment, a device similar in function to the forced air warming system that aids in maintaining surgical patients' body temperature. This disposable garment is connected to a portable heating unit capable of generating up to 1000 BTU per hour. Patients can use a handheld controller to regulate both temperature and airflow, within a range extending from ambient room temperature to 43 °C to ensure better comfort during the pre-anaesthetic and post-operative awakening transit phases. The garment can be utilized to provide thermal support during the preoperative, intraoperative, and postoperative periods, thereby enhancing thermal comfort, reducing postoperative pain, and decreasing opioid consumption [49]. Postoperative pain is often linked to preoperative anxiety, and thermal comfort is a critical determinant of patient well-being. Sufficient warmth has been shown to enhance patient satisfaction. Early studies indicated that patients who received preoperative warming with a forced air heating blanket reported positive experiences regarding warmth and comfort, along with reduced anxiety levels [50]. The self-regulated heated air garment, which can be used continuously throughout the surgical process, is easy to operate and has been demonstrated to effectively improve thermal comfort, alleviate preoperative anxiety, and consequently reduce postoperative pain.

Infusion fluid warming

Infusion fluid warming is a commonly employed intraoperative intervention, often combined with other strategies to elevate patient body temperature, reduce anesthesia recovery time, and enhance thermal comfort. Unfortunately, we did not find definitive reports on infusion temperatures, rates, and durations, which we believe may be due to inconsistencies in the heating ranges of different infusions. For example, heating at 43 °C and up to 46 °C does not produce clinically significant elevated plasma hemoglobin levels [51]. but this temperature range does not necessarily apply to other fluids. In specific procedures, such as liposuction, patients are exposed to low-temperature infusion or irrigation fluids in a cold operating room, along with prolonged exposure to a low-temperature environment, thereby increasing the risk of intraoperative hypothermia [52]. In such situations, warming infusion fluids is typically adopted by healthcare providers. While prolonged pre-warming prior to anesthesia induction can mitigate the risk of hypothermia, it may also interfere with surgical workflow. In contrast, short-term pre-warming during anesthesia induction, combined with warmed intravenous infusion, is more efficient and conserves both time and space [53].

A 2013 study involving 60 patients, divided into a control group and an experimental group, examined the effectiveness of warmed intravenous fluids. The experimental group received warmed intravenous fluids during surgery, whereas the control group relied solely on passive insulation. The results indicated that 22 patients (73.4%) in each group had temperatures below 36 °C at the conclusion of surgery, with no significant difference in hypothermia incidence between the groups ($p=1.0000$). These findings suggested that the use of warmed intravenous fluids alone was insufficient to prevent intraoperative hypothermia, with key factors being the patient's temperature upon entering the operating room and the ambient temperature, rather than the administration of cold infusion fluids [54]. Although pre-warming during anesthesia induction did not significantly reduce hypothermia incidence, it did enhance patient thermal comfort and slowed the rate and extent of temperature decline.

In contrast, a 2015 study reported that the use of warmed intravenous fluids during surgery increased core temperature by approximately 0.4–0.7 °C compared to room-temperature fluids, a difference that was validated at multiple intraoperative time points. By the end of surgery or in the recovery room, core temperatures in the warmed fluids group were approximately 0.6 °C higher than those in the room-temperature fluids group. Although modest, this difference was sufficient to alleviate mild hypothermia and reduce the risk of postoperative shivering, representing moderate-quality evidence [55]. Discrepancies between the findings of the two studies may be attributed to insufficient pre-warming time in the earlier study and the vasodilation effect induced by anesthesia induction, leading to heat redistribution from the core to peripheral tissues, thereby diminishing the efficacy of the intervention [56]. Consequently, clinicians should select appropriate warming devices based on the type of surgery and patient characteristics, and rigorously adhere to intervention guidelines to ensure surgical safety, enhance patient comfort, and reduce operative risks.

Circulating-water mattress

The circulating-water mattress (CWM) is a warming device utilized to prevent perioperative hypothermia by maintaining patient temperature via a pad connected to an electric heating unit that circulates warm water. The primary advantage of CWM lies in its ability to effectively sustain core body temperature. However, a notable disadvantage is the requirement for sterile materials to prevent contamination, which subsequently increases nursing costs. Studies have demonstrated that patients using a circulating-water system require fewer transfusions during surgery, and that CWM is more effective in mitigating intraoperative bleeding and reducing transfusion requirements compared to electric heating blankets. Hypothermia-induced peripheral vasoconstriction can exacerbate intraoperative bleeding and increase the need for transfusions, whereas CWM effectively prevents perioperative hypothermia through the maintenance of core temperature.

Furthermore, when compared to forced air warming (FAW), CWM has demonstrated superior performance in maintaining body temperature, reducing intraoperative bleeding, and minimizing transfusion needs, and may also outperform electric heating blankets in preventing surgical site infections and associated complications [57, 58]. However, CWMs are not without risk. One study reported a case of second-degree burns sustained on the back and chest of a patient during endoscopic surgery due to the use of a circulating-water device, with gradual improvement observed in subsequent days. Although the specific device in question was not a CWM, its similarity to CWM raises concerns about potential risks [59].

In terms of cost, CWM is relatively expensive, requiring sterile materials, with a price range of approximately \$2000 to \$3000 [60]. Despite the high cost, researchers advocate for circulating-water systems as an effective active surface warming method that significantly enhances perioperative outcomes, suggesting that clinicians consider their use as a standard care measure for adult surgical patients [61].

Carbon-fiber resistive heating system

The carbon-fiber resistive heating system represents a novel intraoperative warming technology utilizing carbon fiber, powered by a 15 V DC power supply, which is capable of independently heating multiple regions, thus providing broader body surface coverage during almost any type of surgery. Given that heat loss is proportional to the exposed surface area, the carbon-fiber resistive heating system effectively minimizes temperature loss. Unlike forced air warming (FAW), this system requires no disposable components, making it a more cost-effective solution in clinical settings. The carbon fiber heating pads are covered with washable layers, equipped with antibacterial coatings, and are impermeable, allowing disinfection through simple wiping. In major abdominal surgeries, the carbon-fiber resistive heating system has demonstrated equivalent efficacy to FAW in maintaining core temperature, while offering greater cost-efficiency and convenience [62]. In another study comparing resistive heating and FAW, no significant differences were observed between the two systems in terms of intraoperative and 48-hour postoperative bleeding volume, fluid infusion, thermal comfort, or risk of shivering [63].

The resistive heating system offers several distinct advantages, including the use of low-voltage DC power, which ensures enhanced safety without interference with other electronic devices in the operating room. In the event of system puncture by a sharp object, current continues to flow through adjacent conductive fabric, thereby maintaining functionality. Additionally, resistive heating systems are reusable, thereby incurring lower operating costs compared to FAW, which requires the use of disposable components. In conclusion, the resistive heating system—with its flexible heating coverage, high safety profile, and reduced operating costs—constitutes a promising approach to maintaining intraoperative body temperature [64]. In clinical practice, healthcare providers should consider both the efficacy and cost implications of different warming systems. Selecting cost-effective interventions, particularly when performance differences are negligible, can alleviate the financial burden on healthcare systems and patients. The reusable nature of the resistive heating system, in particular, significantly reduces economic pressures on hospitals. While FAW may be more effective in preventing postoperative hypothermia compared to resistive heating, the carbon-fiber resistive heating system remains an attractive option given its economic advantages and accessibility.

Self-heating blanket

The self-heating blanket is composed of 12 heating pads containing iron powder, which, upon exposure to air, undergoes an exothermic oxidation reaction, generating heat and reaching an average temperature of 40 °C within 30 min, with a maximum temperature not exceeding 43 °C. This heat is sustained for up to 10 h. Compared to forced air warming (FAW) blankets, the self-heating blanket provides continuous warming during pre-warming and patient transport without interruption, thus enhancing patient comfort during transfer [43]. Both the self-heating blanket (SW) and FAW effectively increased patients' mean body temperature during pre-warming; however, the incidence of intraoperative hypothermia was higher in the SW group (61%) compared to the FAW group (49%). FAW set at 43 °C was effective in raising the body temperature of hypothermic patients. Despite no statistically significant difference in core temperature maintenance between the two systems, most patients and nursing staff found both blankets convenient to use [65].

Additional studies have indicated that at 120- and 180-minutes following induction of general anesthesia, the self-heating blanket demonstrated greater efficacy than FAW in maintaining core temperature. Sensitivity analysis further showed that the self-heating blanket outperformed FAW in maintaining core temperature between 60- and 90-minutes post-anesthesia induction [66]. Another study suggested that utilizing the self-heating blanket could reduce the risk of unintentional intraoperative hypothermia by 79%, with an incidence rate of hypothermia in the self-heating blanket group at 13%, compared to 43% in the control group [67].

Since the self-heating blanket does not require an external power source, it is portable and suitable for a wide range of settings, including emergency situations where power supply may be limited. This characteristic makes it particularly favored, whereas FAW devices require an external power source and may generate noise, which can negatively impact patient comfort [68]. Moreover, laminar airflow disturbances caused by FAW equipment may increase the risk of hospital-acquired infections, particularly in orthopedic surgeries, whereas self-heating blankets are devoid of such concerns [69, 70]. The cost of a self-heating blanket is approximately $13.27, compared to $8.53 for an FAW blanket, although FAW requires an additional heating unit and power supply. While FAW performs better in mitigating sweating-related discomfort, the portability and overall cost-effectiveness of the self-heating blanket make it a popular choice for maintaining intraoperative temperature [65].

Chemical heat packs

Chemical heat packs are small, portable heating devices akin to self-heating blankets but are more compact and easier to transport. When manually compressed, an internal compartment is ruptured, initiating a chemical reaction that generates heat, reaching temperatures of approximately 54.5 °C (130 °F). Typically, heat packs are wrapped in towels and placed on specific areas of the patient's body, such as the head, back, or armpit, facilitating direct contact with the skin and thereby elevating skin temperature via conduction. Studies have demonstrated that the use of chemical heat packs can increase the body temperature of trauma patients by an average of 0.8 °C (1.36 °F) during transport, underscoring their effectiveness in trauma patient care [71]. Each chemical heat pack is priced at approximately $0.54, making them a cost-effective option suitable for large-scale application, with significant clinical utility.

Passive warming interventions

When active warming measures are unavailable, passive interventions can be employed to maintain patient temperature. Passive warming involves the use of cotton blankets and thermal reflective blankets, which reduce the area of skin exposed to a cold environment, thereby minimizing convective and radiative heat loss. Protective garments, blankets, and hats made from thermal reflective materials have been demonstrated to be effective in maintaining body temperature during surgery [72]. Thermal reflective devices are widely used in preoperative and emergency settings; these products often consist of multilayer aluminum and non-woven fabric, effectively preserving body temperature by preventing radiative and convective heat loss [73]. Studies have shown that thermal reflective blankets can effectively increase peripheral temperature and significantly reduce the core-peripheral temperature gradient, thereby enhancing peripheral tissue heat content [74]. When compared to forced air warming (FAW), thermal reflective blankets exhibit similar efficacy in maintaining body temperature, with no significant differences in cost. Tongue temperature during surgery was consistently maintained above 36 °C in both groups, with no significant differences in environmental conditions, fluid infusion, or blood loss [75].

However, passive warming is generally less effective than active warming in preventing hypothermia. Studies have found that even 60 min of preoperative passive warming did not effectively prevent hypothermia, largely due to core-to-peripheral temperature redistribution. Active warming methods such as FAW and carbon-fiber resistive heating have demonstrated greater efficacy in mitigating hypothermia [76]. Although passive warming measures help to maintain body temperature during the perioperative period, they do not completely prevent a drop in body temperature during surgery because they do not have the ability to heat. Nonetheless, passive warming measures are highly cost-effective. For instance, thermal reflective surgical caps cost $1.54 each, compared to $9.75 for FAW, resulting in a cost saving of approximately $8.21 per unit for healthcare institutions. These data suggest that passive warming is an economical and effective option, particularly when active warming is not feasible. Thermal reflective devices, in particular, can serve as simple and effective warming measures, especially for elderly patients and those undergoing regional anesthesia [73].

Conclusion

Perioperative hypothermia is a prevalent clinical issue, primarily resulting from the cold environment of the operating room and prolonged skin exposure, which can lead to multiple complications and adverse outcomes, significantly impacting surgical results. To mitigate this problem, healthcare providers have implemented various interventions, among which forced air warming (FAW) systems have been demonstrated to be highly effective in maintaining core temperature and are currently regarded

Table 1 Comparison of intraoperative warming techniques: benefits, limitations, and applications

Classification	Intervention	Effectiveness	Risks	Cost	quality-price ratio	Overall
Active insulation	Forced Air Warming Devices	★★★★★	★★☆☆☆	★★★☆☆	★★★★★	★★★★★
	Self-Regulated Heated Air Garment	★★★★☆	★★☆☆☆	★★★☆☆	★★★☆☆	★★★☆☆
	Infusion Fluid Warming	★★★★☆	★☆☆☆☆	★☆☆☆☆	★★★★☆	★★★★☆
	Circulating-Water Mattress	★★★☆☆	★★★★☆	★★★★★	★☆☆☆☆	★☆☆☆☆
	Carbon-Fiber Resistive Heating System	★★★★☆	★☆☆☆☆	★★☆☆☆	★★★★☆	★★★★☆
	Self-Heating Blanket	★★★☆☆	★☆☆☆☆	★★★☆☆	★★☆☆☆	★★★☆☆
	Chemical Heat Packs	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★★★☆☆	★★★☆☆
Passive insulation	Thermal reflective blankets	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★★★☆☆	★★★☆☆

Notes:

★~★★★★★represents five levels: low, relatively low, medium, relatively high and high

Note: Due to variations in item costs across countries, with differing reference amounts and currencies, and the difficulty in obtaining specific cost data, a five-star rating system is used here to provide an approximate estimate for comparative purposes

as the optimal intervention. With advancements in technology, numerous warming devices have been developed, each with distinct advantages and limitations, necessitating tailored selection based on specific clinical circumstances. In addition to active warming methods, passive warming measures, such as blankets, thermal reflective caps, and chemical heat packs, offer a viable alternative. These approaches utilize the patient's endogenous heat without reliance on mechanical devices or external energy sources. Although the resultant temperature increases are less pronounced compared to active warming techniques, passive warming presents significant cost advantages, making it suitable for large-scale implementation. Overall, various interventions aimed at addressing perioperative hypothermia have been shown to reduce complication rates, decrease healthcare expenditures, and yield significant social and organizational benefits. Selecting the most effective and cost-efficient intervention in clinical practice requires careful consideration of each patient's unique circumstances to ensure optimal outcomes.

Acknowledgements
None.

Author contributions
J.N., W.J.T. L.X.H. and S.Y. conceived the study and collected the data. participated in drafting the initial draft. All authors read and approved the final version of the manuscript.

Funding
The study was funded by the Cuiying Scientific and Technological Innovation Program of Lanzhou University Second Hospital (CY2022-HL-B06) and Scientific Research Project for the Health Industry of Gansu Province (GSWSKY-2024-150).

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics statement
Not application.

Conflict of interest
No potential conflict of interest relevant to this article was reported.

Received: 1 November 2024 / Accepted: 16 December 2024
Published online: 30 December 2024

References

1. Nakamura K. Central circuitries for body temperature regulation and fever. Am J Physiol Regul Integr Comp Physiol. 2011;301(5):R1207–28.
2. Xu X, Rioux TP, Castellani MP. Three dimensional models of human thermoregulation: a review. J Therm Biol. 2023;112:103491.
3. Satinoff E. Neural organization and evolution of thermal regulation in mammals. Science. 1978;201(4350):16–22.
4. De Witte J, Sessler DI. Perioperative shivering: physiology and pharmacology. Anesthesiology. 2002;96(2):467–84.
5. Hales JR, Jessen C, Fawcett AA, King RB. Skin AVA and capillary dilatation and constriction induced by local skin heating. Pflugers Arch. 1985;404(3):203–7.
6. Tews D, Wabitsch M. Brown Adipose tissue in children and its metabolic function. Horm Res Paediatr. 2022;95(2):104–11.
7. Schlader ZJ, Simmons SE, Stannard SR, Mündel T. The independent roles of temperature and thermal perception in the control of human thermoregulatory behavior. Physiol Behav. 2011;103(2):217–24.
8. Sessler DI. Temperature monitoring and perioperative thermoregulation. Anesthesiology. 2008;109(2):318–38.
9. Rauch S, Miller C, Bräuer A, Wallner B, Bock M, Paal P. Perioperative Hypothermia-A Narrative Review. Int J Environ Res Public Health. 2021;18(16):8749.
10. Sessler DI. Complications and treatment of mild hypothermia. Anesthesiology. 2001;95(2):531–43.
11. Wang J, Fang P, Sun G, Li M. Effect of active forced air warming during the first hour after anesthesia induction and intraoperation avoids hypothermia in elderly patients. BMC Anesthesiol. 2022;22(1):40.
12. Hart SR, Bordes B, Hart J, Corsino D, Harmon D. Unintended perioperative hypothermia. Ochsner J. 2011 Fall;11(3):259 – 70.
13. Aoki Y, Aoshima Y, Atsumi K, et al. Perioperative amino acid infusion for preventing hypothermia and improving clinical outcomes during surgery under General Anesthesia: a systematic review and Meta-analysis. Anesth Analg. 2017;125(3):793–802.
14. Kawakami H, Nakajima D, Mihara T, Sato H, Goto T. Effectiveness of Magnesium in preventing shivering in Surgical patients: a systematic review and Meta-analysis. Anesth Analg. 2019;129(3):689–700.
15. Sessler DI. Perioperative Thermoregulation and heat balance. Lancet. 2016;387(10038):2655–64.
16. Ruetzler K, Kurz A. Consequences of perioperative hypothermia. Handb Clin Neurol. 2018;157:687–97.
17. Sun Z, Honar H, Sessler DI, et al. Intraoperative core temperature patterns, transfusion requirement, and hospital duration in patients warmed with forced air. Anesthesiology. 2015;122(2):276–85.

18. Ribeiro E, Ferreira RC, Montanari FL, Botelho MTSL, Correia MDL, Duran ECM. Conceptual and operational definition of the components of the nursing diagnosis hypothermia (00006) in the perioperative period. Rev Bras Enferm. 2021;74(2):e20190684.
19. Scott EM, Buckland R. A systematic review of intraoperative warming to prevent postoperative complications. AORN J 2006,83,1090–113.
20. Kurz A. Thermal care in the perioperative period. Best Pract Res Clin Anaesthesiol. 2008;22(1):39–62.
21. Yi J, Lei Y, Xu S, et al. Intraoperative hypothermia and its clinical outcomes in patients undergoing general anesthesia: national study in China. PLoS ONE. 2017;12(6):e0177221.
22. Giuliano KK, Hendricks J. Inadvertent Perioperative Hypothermia: current nursing knowledge. AORN J. 2017;105(5):453–63.
23. González-Alonso J, Quistorff B, Krustrup P, Bangsbo J, Saltin B. Heat production in human skeletal muscle at the onset of intense dynamic exercise. J Physiol. 2000;524(Pt 2):603–15.
24. Lynch S, Dixon J, Leary D. Reducing the risk of unplanned perioperative hypothermia. AORN J. 2010;92(5):553–62.
25. Collins S, Budds M, Raines C, Hooper V. Risk factors for Perioperative Hypothermia: A literature review. J Perianesth Nurs. 2019;34(2):338–46.
26. Brück K, Zeisberger E. Adaptive changes in thermoregulation and their neuropharmacological basis. Pharmacol Ther. 1987;35:163–215.
27. Recio-Pérez J, Miró Murillo M, Martin Mesa M, et al. Effect of Prewarming on Perioperative Hypothermia in patients undergoing Loco-Regional or General Anesthesia: a Randomized Clinical Trial. Med (Kaunas). 2023;59(12):2082.
28. Bock M, Hohlfeld U, von Engeln K, Meier PA, Motsch J, Tasman AJ. The accuracy of a new infrared ear thermometer in patients undergoing cardiac surgery. Can J Anaesth. 2005;52(10):1083–7.
29. Craig JV, Lancaster GA, Williamson PR, Smyth RL. Temperature measured at the axilla compared with rectum in children and young people: systematic review. BMJ. 2000;320(7243):1174–8.
30. Pasquier M, Paal P, Kosinski S, Brown D, Podsiadlo P, Darocha T. Esophageal temperature measurement. N Engl J Med. 2020;383(16):e93.
31. Sessler DI. Perioperative Temp Monit Anesthesiology. 2021;134(1):111–8.
32. Imamura M, Matsukawa T, Ozaki M, Sessler DI, Nishiyama T, Kumazawa T. The accuracy and precision of four infrared aural canal thermometers during cardiac surgery. Acta Anaesthesiol Scand. 1998;42(10):1222–6.
33. Boisson M, Alaux A, Kerforne T, et al. Intra-operative cutaneous temperature monitoring with zero-heat-flux technique (3 M SpotOn) in comparison with oesophageal and arterial temperature: a prospective observational study. Eur J Anaesthesiol. 2018;35(11):825–30.
34. Hynson JM, Sessler DI, Moayeri A, McGuire J, Schroeder M. The effects of preinduction warming on temperature and blood pressure during propofol/nitrous oxide anesthesia. Anesthesiology. 1993;79(2):219–. – 28, discussion 21A-22A.
35. Bräuer A, Quintel M. Forced-air warming: technology, physical background and practical aspects. Curr Opin Anaesthesiol. 2009;22(6):769–74.
36. Hynson JM, Sessler DI. Intraoperative warming therapies: a comparison of three devices. J Clin Anesth. 1992;4(3):1949.
37. Alparslan V, Kus A, Hosten T, Ertargin M, Ozdamar D, Toker K, Solak M. Comparison of forced-air warming systems in prevention of intraoperative hypothermia. J Clin Monit Comput. 2018;32(2):343–9.
38. Chen YC, Cherng YG, Romadlon DS, et al. Comparative effects of warming systems applied to different parts of the body on hypothermia in adults undergoing abdominal surgery: a systematic review and network meta-analysis of randomized controlled trials. J Clin Anesth. 2023;89:111190.
39. Jo YY, Chang YJ, Kim YB, Lee S, Kwak HJ. Effect of Preoperative forced-air warming on Hypothermia in Elderly patients undergoing Transurethral Resection of the prostate. Urol J. 2015;12(5):2366–70.
40. Becerra Á, Valencia L, Ferrando C, Villar J, Rodríguez-Pérez A. Prospective observational study of the effectiveness of prewarming on perioperative hypothermia in surgical patients submitted to spinal anesthesia. Sci Rep. 2019;9(1):16477.
41. Avidan MS, Jones N, Ing R, Khoosal M, Lundgren C, Morrell DF. Convection warmers–not just hot air. Anaesthesia. 1997;52(11):1073–6.
42. Huang JK, Shah EF, Vinodkumar N, Hegarty MA, Greatorex RA. The Bair Hugger patient warming system in prolonged vascular surgery: an infection risk? Crit Care. 2003;7(3):R13–6.
43. Moretti B, Larocca AM, Napoli C, et al. Active warming systems to maintain perioperative normothermia in hip replacement surgery: a therapeutic aid or a vector of infection? J Hosp Infect. 2009;73(1):58–63.
44. Zucconi G, Marchello AM, Demarco C, Fortina E, Milano L. Health Technology Assessment for the Prevention of Peri-operative Hypothermia: evaluation of the correct use of Forced-Air Warming Systems in an Italian hospital. Int J Environ Res Public Health. 2022;20(1):133.
45. Monzani R, Barbera G, Restelli U, Galeone C, Petrini F. Protocol implementation for normothermia in surgery settings in Italy: Budget-Impact analysis. Risk Manag Healthc Policy. 2020;13:2347–56.
46. Kurz A, Sessler DI, Lenhardt R. Perioperative normothermia to reduce the incidence of surgical-wound infection and shorten hospitalization. Study of wound infection and temperature group. N Engl J Med. 1996;334(19):1209–15.
47. Bezerra ASM, Santos VB, Lopes CT, de Barros ALBL. Effect of nurse-initiated forced-air warming blanket on the reduction of hypothermia complications following coronary artery bypass grafting: a randomized clinical trial. Eur J Cardiovasc Nurs. 2021;20(5):445–53.
48. Frank SM, Fleisher LA, Breslow MJ, et al. Perioperative maintenance of normothermia reduces the incidence of morbid cardiac events. A randomized clinical trial. JAMA. 1997;277(14):1127–34.
49. Benson EE, McMillan DE, Ong B. The effects of active warming on patient temperature and pain after total knee arthroplasty. Am J Nurs. 2012;112(5):26–33.
50. Fossum S, Hays J, Henson MM. A comparison study on the effects of prewarming patients in the outpatient surgery setting. J Perianesth Nurs. 2001;16(3):187–94.
51. Poder TG, Nonkani WG, Tsakeu Leponkouo É. Blood warming and hemolysis: a systematic review with Meta-analysis. Transfus Med Rev. 2015;29(3):172–80.
52. Zhang M, Wang L, Tan L, et al. Effects of Heated Infiltration Solutions and forced-air heating blankets on intraoperative hypothermia during liposuction: a Factorial Randomized Controlled Trial. Aesthetic Plast Surg. 2024;48(10):1956–63.
53. He HC, Yu BJ, Mai SY et al. Effects of three different Heating devices on patients undergoing surgery: a Network Meta-Analysis. J Perianesth Nurs. 2024: S1089-9472(23)01105-X.
54. De Mattia AL, Barbosa MH, de Freitas Filho JP, Rocha Ade M, Pereira NH. Warmed intravenous infusion for controlling intraoperative hypothermia. Rev Lat Am Enfermagem. 2013;21(3):803–10.
55. Campbell G, Alderson P, Smith AF, Warttig S. Warming of intravenous and irrigation fluids for preventing inadvertent perioperative hypothermia. Cochrane Database Syst Rev. 2015;2015(4):CD009891.
56. Oh YJ, Jun IJ. The effect of brief warming during induction of General Anesthesia and warmed intravenous fluid on intraoperative hypothermia in patients undergoing urologic surgery. Med (Kaunas). 2024;60(5):747.
57. Hasegawa K, Negishi C, Nakagawa F, Ozaki M. Core temperatures during major abdominal surgery in patients warmed with new circulating-water garment, forced-air warming, or carbon-fiber resistive-heating system. J Anesth. 2012;26(2):168–73.
58. Matsuzaki Y, Matsukawa T, Ohki K, Yamamoto Y, Nakamura M, Oshibuchi T. Warming by resistive heating maintains perioperative normothermia as well as forced air heating. Br J Anaesth. 2003;90(5):689–91.
59. Gali B, Findlay JY, Plevak DJ. Skin injury with the use of a water warming device. Anesthesiology. 2003;98(6):1509–10.
60. Perez-Protto S, Sessler DI, Reynolds LF, Bakri MH, Mascha E, Cywinski J, Parker B, Argalious M. Circulating-water garment or the combination of a circulating-water mattress and forced-air cover to maintain core temperature during major upper-abdominal surgery. Br J Anaesth. 2010;105(4):466–70.
61. Nieh HC, Su SF. Meta-analysis: effectiveness of forced-air warming for prevention of perioperative hypothermia in surgical patients. J Adv Nurs. 2016;72(10):2294–314.
62. Negishi C, Hasegawa K, Mukai S, Nakagawa F, Ozaki M, Sessler DI. Resistive-heating and forced-air warming are comparably effective. Anesth Analg. 2003;96(6):1683–7.
63. Madrid E, Urrútia G, Roqué i Figuls M, Pardo-Hernandez H, et al. Active body surface warming systems for preventing complications caused by inadvertent perioperative hypothermia in adults. Cochrane Database Syst Rev. 2016;4(4):CD009016.
64. Zhang Z, Inman C, Waters D, Dee P. Effectiveness of application of carbon-fibre polymer-fabric resistive heating compared with forced-air warming to prevent unintentional intraoperative hypothermia in patients undergoing elective abdominal operations: a systematic review and meta-analysis of randomised controlled trials. J Clin Nurs. 2020;29(23–24):4429–39.
65. Lauronen SL, Kalliovalkama J, Aho A, Mäkinen MT, Huhtala H, Yli-Hankala AM, Kalliomäki ML. Self-warming blanket versus forced-air warming blanket

during total knee arthroplasty under spinal anaesthesia: a randomised non-inferiority trial. Acta Anaesthesiol Scand. 2023;67(8):1102–9.
66. Al-Dardery NM, Abdelwahab OA, El-Samahy M, Seif AM, Mouffokes A, Khaity A. Self-warming blankets versus active warming by forced-air devices for preventing hypothermia: a systematic review and meta-analysis. Med (Baltim). 2023;102(18):e33579.
67. Rosenkilde C, Vamosi M, Lauridsen JT, Hasfeldt D. Efficacy of prewarming with a self-warming blanket for the Prevention of Unintended Perioperative Hypothermia in patients undergoing hip or knee arthroplasty. J Perianesth Nurs. 2017;32(5):419–28.
68. Thapa HP, Kerton AJ, Peyton PJ. Comparison of the EasyWarm® self-heating blanket with the Cocoon forced-air warming blanket in preventing intraoperative hypothermia. Anaesth Intensive Care. 2019;47(2):169–74.
69. Avidan MS, Jones N, Ing R, et al. Convection warmers – not just hot air. Anaesthesia. 1997;52:1073–6.
70. Kellam MD, Dieckmann LS, Austin PN. Forced-air warming devices and the risk of surgical site infections. AORN J. 2013;98:354–66.
71. Watts DD, Roche M, Tricarico R, et al. The utility of traditional prehospital interventions in maintaining thermostasis. Prehosp Emerg Care. 1999;3(2):115–22.
72. Hooper VD, Chard R, Clifford T, et al. ASPAN's evidence-based clinical practice guideline for the promotion of perioperative normothermia. J Perianesth Nurs. 2009;24(5):271–87.
73. Williams AK. Benefits of Passive warming on Surgical patients undergoing Regional Anesthetic procedures. J Perianesth Nurs. 2018;33(6):928–34.
74. Koenen M, Passey M, Rolfe M. Keeping them Warm-A Randomized Controlled Trial of two Passive Perioperative warming methods. J Perianesth Nurs. 2017;32(3):188–98.
75. Tjoakarfa C, David V, Ko A, Hau R. Reflective blankets are as effective as Forced Air Warmers in maintaining patient Normothermia during hip and knee arthroplasty surgery. J Arthroplasty. 2017;32(2):624–7.
76. Yoo JH, Ok SY, Kim SH, et al. Efficacy of active forced air warming during induction of anesthesia to prevent inadvertent perioperative hypothermia in intraoperative warming patients: comparison with passive warming, a randomized controlled trial. Med (Baltim). 2021;100(12):e25235.

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