Diagnosis, prevention and treatment of accidental and perioperative hypothermia

Abstract: Accidental hypothermia and its variant, perioperative hypothermia, is a rather common clinical phenomenon in patients. This is surprising because the negative effects on clinical outcomes are well described and effective patient-warming devices are available today. The aim of this paper is to describe the physiologic background of accidental and perioperative hypothermia, the clinical relevance and existing prophylaxis and treatment options. Patient warming techniques will be discussed in detail. Remaining technical and clinical challenges and the need for further research will be addressed. We will present existing guidelines and standards and analyse the impact of accidental and perioperative hypothermia on cost effectiveness.

Keywords: body core temperature; normothermia; patient warming devices; thermoregulation.

Introduction

Despite strong evidence that unintended hypothermia is detrimental to patient outcomes [30, 70, 103] and effective patient warming systems being widely available [9, 47, 67] accidental hypothermia is still a common phenomenon in many patients and, obviously, open questions remain. On September 29th and 30th, 2011, a closed workshop “Detection, Prevention and Treatment of Accidental Hypothermia” was organized by the Section Patient Monitoring (Fachausschuss Methodik der Patientenüberwachung) of the German Society for Biomedical Engineering (Deutsche Gesellschaft für Biomedizinische Technik; DGBMT) of the Association for Electrical, Electronic and Information Technologies (VDE). Experts from academia, hospitals, product development and industry (see Acknowledgements) discussed established facts, open questions, needs for research and development and technical and economic restrictions, as well as regulations and standards.

The aim of this paper is to present the results of the workshop in the context of results from scientific studies and publications.

Physiology of thermoregulation

Because humans – as all mammals – belong to the warm-blooded or homoeothermic species, humans are in need of a near constant core body temperature. In cases where the core temperature differs significantly from habitual, all physiologic functions deteriorate. Under normal conditions, the core temperature will be kept constant at approximately 37°C by a closed-loop system – the thermoregulatory system. The thermoregulatory system consists of an afferent (sensing), a central regulatory component (located in the hypothalamus) and an efferent (response) component [101]. Heat and cold receptors can be found widely distributed throughout the body in the skin, deep abdominal and thoracic tissue, the spinal cord and in several regions of the brain. A typical thermoregulatory response can be characterized by a threshold, a gain, that controls the degree of response and the maximum response intensity [104]. The thermoregulatory system is normally able to keep the core temperature constant within 0.2°C of a targeted value. The precision is similar in both sexes, but declines in the elderly [77]. The efferent response system has an autonomic and a behavioural part. Behaviour is the more potent reaction; by changing clothes or moving to a warmer or colder environment, it allows humans to live and work in such extreme environments as the arctic or the tropics. The most effective autonomic efferent response is the regulation of cutaneous evaporation (sweating) and the cutaneous vasomotoric response (vasoconstriction/vasodilatation). Shivering increases thermogenesis by unintentional muscular activity.
and may increase the metabolic rate by double to threefold [56]. Non-shivering thermogenesis is important mainly for the thermoregulation of neonates [25]. The uncoupling protein 1 (UCP 1) in brown adipose tissue (BAT) allows the direct conversion from substrates into heat by bypassing the adenosine triphosphate (ATP) synthase. In the last decades, it was doubted that non-shivering thermogenesis has a significant contribution to the thermoregulation of adults [19]. Recently, several authors reported sites of BAT in adults using positron emission tomography (PET-CT) [90, 126]. One study showed that these BAT-sites were activated after exposure to a cold environment [125]. However, the contribution of non-shivering thermogenesis to the thermoregulation of adults remains unclear.

If the core temperature cannot be maintained within the normal range, the reason can be either extreme external conditions, which cannot be compensated for, or a dysfunction of the hypothalamic control loop, as well as a combination of both mechanisms.

There is unfortunately no consistent definition for the different stages of hypothermia. A commonly used definition (e.g., [39, 105]) distinguishes between mild hypothermia (32 °C/33 °C – 36 °C), moderate hypothermia (29 °C/30 °C – 32 °C/33 °C) and deep hypothermia (<29 °C/30 °C). Table 1 displays the known effects of hypothermia.

We believe it makes sense to differentiate further between perioperative and other forms of accidental hypothermia. In accordance with the aim of this paper, we will focus primarily on the reasons for, the consequences of and the treatment of accidental and perioperative hypothermia. An extensive discussion of mild therapeutic hypothermia is beyond the scope of this paper.

Accidental hypothermia

Accidental hypothermia is a consequence of exposure to a cold environment that cannot be compensated. Several factors account for a failed compensation. There are certain patient groups at higher risk. Children have a higher body mass specific surface area compared to adults, and thus their heat loss is much higher. Substance-dependent persons may be at special risk because of lower vasoconstriction and shivering thresholds (e.g., opioids effects) and higher heat loss (vasodilatation caused by alcohol or drugs) and a risky lifestyle (homelessness, inadequate clothing, etc.).

Elderly and critically ill persons bear a higher risk for accidental hypothermia because of disturbed thermoregulation. Finally, all persons suffering extreme exposures (e.g., water, snow) or less extreme exposures for a prolonged time – possibly in conjunction with severe trauma – bear a very high risk for accidental hypothermia. Prolonged exposure – at the trauma site and during repeated examinations and transport – is also a reason why significant numbers of emergency patients develop hypothermia. At admission to an emergency room, Mommsen et al. reported recently an incidence of 36.8% for hypothermia in multiple trauma patients [86]. However, hypothermia was defined rather conservatively as a core temperature <35°C within 2 h of admission. A threshold of <36°C would have increased the number of hypothermic admissions significantly. In these patients, the waiting time at the emergency site, the transport time in the possibly insufficiently warmed ambulance, recurrent examinations and diagnostic procedures cumulate to a relatively long exposure time. This, together with the infusion of large amounts of unwarmed fluids, contributes to a consequently high risk for hypothermia.

Perioperative hypothermia

Hypothermia is an accidental but surprisingly frequent perioperative complication. While waiting for and during surgery, patients are limited in their ability to regulate body temperature through behaviour. Most patients wear only a light hospital gown and generally cannot leave the holding area or induction room for a warmer environment if feeling cold. An undressed adult patient needs an ambient temperature of approximately 28 °C to maintain his thermal steady state (thermoneutrality) [38]. A typical operating room (OR) temperature will be kept markedly

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Classification</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>32/33–36°C</td>
<td>Mild hypothermia</td>
<td>Shivering, impairment of plasmatic and cellular coagulation, impairment of immune response</td>
</tr>
<tr>
<td>29/30–32/33°C</td>
<td>Moderate hypothermia</td>
<td>Reduction of metabolism, respiratory depression, depressed consciousness</td>
</tr>
<tr>
<td>27–30°C</td>
<td>Deep hypothermia</td>
<td>Failure of thermoregulation, ventricular fibrillation</td>
</tr>
</tbody>
</table>

Table 1 Classification of body core temperatures and consequences. Adapted from Silbernagel et al. [111]. *Thresholds vary in the literature.
Incidence of perioperative hypothermia

Without active perioperative warming, the majority of surgical patients will become at least slightly hypothermic (core temperature < 36°C) [4]. Torossian et al. reported a survey on thermomanagement in 316 European hospitals that on a certain day during 8083 surgical procedures, only in 19% of the patients was body temperature monitored, and only 38% were actively warmed [118]. Several authors found high incidences of hypothermia (< 36°C) ranging from 41% to more than 60% in postoperative surgical patients on arrival in the intensive care unit (ICU) [1, 58, 59, 93].

Effects of mild perioperative hypothermia

The effects of mild hypothermia have been extensively reported and cover a broad range of complications. The incidence of wound infections triples, hospital stay is prolonged by 20% [70], blood-loss and transfusion rates increase [97, 103] and the risk for cardiac complications [28, 30] quadruples. The metabolism of the majority of drugs is reduced, including typical anaesthetics such as propofol [75] and muscle relaxants such as vecuronium [40] and atracurium [75]. Consequently, mild perioperative hypothermia lengthens postoperative recovery – even when temperature is not a criterion for transfer [74]. Shivering occurs postoperatively in 40% of unwarmed patients [56] and is correlated with adrenergic activation [29] and discomfort [69, 100].

Protective effects of mild, moderate and deep hypothermia

Some selected patient groups undoubtedly benefit from hypothermia. In cardiothoracic surgery, several operations will be performed in therapeutic hypothermia. The degree of hypothermia depends on the disease, the type of surgery and the preoperative state of the patient. If circulatory arrest is intended during difficult surgical procedures, the patients will be cooled to as low as 18°C [102]. It has been shown that in patients with successful resuscitation following cardiac arrest, mild therapeutic hypothermia improved neurological outcome and decreased mortality [50]. Consequently, therapeutic protective hypothermia in comatose post-cardiac arrest patients is recommended in both the American and European resuscitation guidelines [34, 112].
Although some patients may benefit from hypothermia, the focus of this paper is diagnosis, prevention and treatment of accidental or unintentional perioperative hypothermia.

**Maintaining normothermia**

In contrast to other physiologic parameters, such as blood pressure or blood oxygen saturation, the deleterious effects of mild hypothermia are not obvious. The paramedic, the emergency physician or the anaesthetist who allows the patient to develop mild hypothermia will in most cases not recognize the correlation, e.g., to the wound infection, until several days later. Therefore, two important points must be taken into account to avoid and treat accidental and perioperative hypothermia.

1. If significant change of core temperature are suspected or anticipated, measure core temperature, and
2. Consider the application of an adequate, patient- and situation-appropriate patient warming system [15].

**Measuring core temperature**

Measuring a patient’s core temperature sounds trivial, but involves several issues worth consideration. The gold standard for core temperature measurements remains the measurement of the temperature of the blood in the pulmonary artery with a Swan-Ganz catheter. Because this invasive method is only available in very selected patient collectives, other less invasive methods must be used. Unfortunately, the precision decreases, usually with the degree of invasiveness. In Table 2, we present established methods of temperature measurements. All methods have their own advantages and disadvantages. For a detailed discussion of the characteristics of each method, we would like to refer to a recently published review on temperature measurement [129] by our group – the Section Patient Monitoring of the DGBMT.

Generally speaking, it is much more important to measure temperature at all. The choice of methods, depending on availability of methods, the situation and the intended procedures.

**External warming methods**

**Insulation**

Because the skin is the primary source of heat loss, insulation is a relatively effective, passive external warming method. As an easily available technique, exposure time of the uncovered skin should be reduced as much as possible. A single layer of a typical cotton hospital blanket reduces heat loss by 30%. The addition of more layers or the use of warmed blankets does not, unfortunately, increase the benefit proportionally [106]. Reflective insulation materials are not more efficient compared to standard drapes [4, 6, 13, 17, 92, 108]. The recent improvements made in clothing for outdoor activities indicate that technological advances in drapes and blankets for hospital use must be possible [15].

<table>
<thead>
<tr>
<th>Location</th>
<th>Accuracy</th>
<th>Response</th>
<th>Invasiveness</th>
<th>Issues/Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulmonary artery</td>
<td>Gold standard</td>
<td>Fast</td>
<td>High</td>
<td>Temperature measurement secondary to hemodynamic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>monitoring, Puncture-related complications</td>
</tr>
<tr>
<td>Oesophagus</td>
<td>Good</td>
<td>Fast</td>
<td>Medium</td>
<td>Perforation, irritation, interference with breathing</td>
</tr>
<tr>
<td>Urinary Bladder</td>
<td>Good</td>
<td>Fast</td>
<td>High</td>
<td>Precision dependent on urinary flow</td>
</tr>
<tr>
<td>Rectum</td>
<td>Medium</td>
<td>Slow</td>
<td>Medium</td>
<td>Perforation, irritation</td>
</tr>
<tr>
<td>Nasopharynx</td>
<td>Good</td>
<td>Fast</td>
<td>Medium</td>
<td>Irritation, bleeding, dislocation</td>
</tr>
<tr>
<td>Gastrointestinal pill</td>
<td>Good</td>
<td>Medium/slow</td>
<td>Low</td>
<td>Rarely available</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hard to swallow, No standard location</td>
</tr>
<tr>
<td>Tympanic (contact)</td>
<td>Good</td>
<td>Fast</td>
<td>Medium</td>
<td>Irritation, perforation, dislocation</td>
</tr>
<tr>
<td>Tympanic (non-contact)</td>
<td>Low</td>
<td>Fast</td>
<td>Low</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Oral cavity</td>
<td>Medium</td>
<td>Fast</td>
<td>Low</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Axilla</td>
<td>Low</td>
<td>Slow</td>
<td>Low</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Forehead</td>
<td>Good</td>
<td>Slow</td>
<td>Low</td>
<td>Slow</td>
</tr>
<tr>
<td>Inner canthus of the eye</td>
<td>Low</td>
<td>Fast</td>
<td>Low</td>
<td>Accuracy</td>
</tr>
</tbody>
</table>

*Table 2 Locations for temperature measurements. Adapted from Wartzek et al. [129].*
Elevated ambient temperatures

Theoretically, a high room temperature is able to prevent hypothermia sufficiently. Per 1 °C higher ambient temperature, heat loss will be reduced by 10%. To maintain normothermia with the ambient room temperature as sole method, more than 26 °C would be necessary [26]. In a hospital setting, this is uncomfortable, especially for fully dressed surgeons, and therefore will only be acceptable in special settings. For example, elevated ambient temperatures up to 32 °C are used on a regular base in pediatric surgery and at specialized burns units. However, even a modestly higher OR temperature contributes to thermomanagement.

Infrared radiation

Patient warming with infrared radiators is an effective, active external method of preventing hypothermia. Infrared radiation can be subdivided into three smaller spectral bands (IR-A, IR-B and IR-C). From IR-A to IR-C, the wavelength increases but the energy decreases. IR-A permeates deep into the human cutis, with approximately 35% absorption in the epidermis, 48% in the corium and 17% within the subcutis [21]. In contrast, IR-C will be absorbed completely into the non-perfused epidermis, which results in lower efficacy and a higher risk of burns [16], whereas IR-B can be characterized as “in-between.” If an IR-A radiator is equipped with a water filter, only deeper tissue layers will be warmed efficiently with reduced risk of burns in superficial skin layers [60].

The perioperative use of IR radiant heating is possible [72, 119], but currently its use is not very common because the available area for radiant warming (and therefore the efficacy) is usually limited and the radiant heat is inconvenient for the OR staff.

In conclusion, an application for radiant heating is always given if patients are exposed for a longer time without covering. This makes it a valuable technique for pre- and post-operative warming in paediatrics and in the emergency department.

Forced-air warming

Forced-air or convective warming is presumably the most common approach of perioperative patient warming. It has been proven to be highly effective [33, 107], safe, non-invasive, easy to use and superior to several other systems [9, 47, 67, 116]. An advantage is nearly immediate achievement of the working temperature of the device [52]. The functional principle of forced-air warming is that a ventilator blows warmed air via a tube in specially designed blankets. These blankets are available in several different types, e.g., full body, upper, lower- and under-body, to be adapted to different situations. Forced-air blankets are either single use or reusable after laundering with disinfection, so certain costs do occur in every case. The efficacy of forced-air warming is determined by the blower strength and the temperature gradient between the blanket and the skin area available for warming [11]. Because forced-air warming is so easy to apply, it bears a special risk. If the blower is used without the designated blanket, e.g., by putting the tube under the patient’s duvet, it can cause severe burns (“hosing”) [85, 122]. Other intrinsic limitations of forced-air warming are the potentially disturbing noise of the fan and the increased temperature in proximity to the device [10]. Further concerns exist about bacterial contamination of the forced-air system [110]. A possible transfer of microbial pathogens with the airstream into the surgical field has been described [2]; however, several studies have challenged the clinical relevance of these findings and found no difference in bacterial dispersion with or without forced-air warming [5, 46, 120].

Conductive warming – under-body mattresses

Patient-warming with warming mattresses is a long established active, conductive warming principle. Warming mattresses use different functional principles. Nevertheless, whether the mattress works with warmed circulating water or direct electrical heating within the mattress, the efficacy of heating mattresses is relatively low [47, 67, 88, 105]. The heat transfer from the mattress to the skin and, consequently, to the core starts only if the mattress is warmer than 37°C. Unfortunately, the heat loss via the patient’s back intraoperatively is very low [14], and therefore the change in heat balance remains small [47]. Warming mattresses are always an option if other more effective methods are not applicable. Examples include the neuro-angiographic lab, where the sterile area reaches from the thigh to the head, and therefore only a small area remains for potentially applying forced-air warming, for example, or during off-pump coronary artery bypass surgery (OPCAB).

Conductive warming – over-body blankets

In contrast to warming mattresses, warming with heating blankets, which lie on the patient’s body, is much more
effective. The heat transfer depends mainly on the contact area between blanket and skin, and it is not important if the blanket heats with circulating water [14, 36, 54], with resistive carbon fibres [35, 64, 91] or polymers [10, 63]. In all areas, without direct contact between blanket and skin, only radiation contributes to warming. However, if the available area for conductive warming is large enough, it is a valuable alternative to the perioperative quasi-standard forced-air warming. It is potentially more cost-effective (no single-use blankets or laundry costs), quieter and does not increase ambient temperature significantly.

**Humidified and/or warmed inspired air**

Humidifying and/or warming inspired air can be considered a hypothermia protection method rather than a warming method. Neither active nor passive (heat and moist exchange filter; HME) climatisation of the inspired air transfer a relevant amount of heat [7, 16, 47]. Nevertheless, HME filters offer further cross-infection prophylaxis, and consequently the use of HME filters is today the standard of care during mechanical ventilation.

**Warm water immersion**

In the treatment of severe large-area burns, maintaining normothermia is a challenge because evaporation and exposure of large wounds cause massive heat loss. As discussed earlier, high room temperatures (>30°C) are very often used for these patients. Several burn centres immerse the patient in large tubs containing warm water for cleaning and debridement procedures. As a secondary effect, immersion is an efficient hypothermia protection but demands complex logistics and challenges the anaesthesiological team.

**Prewarming**

Prewarming is an effective external method that alleviates the maintenance of perioperative normothermia [48, 57]. Prewarming reduces the temperature gradient between periphery and core, and therefore the heat redistribution after induction of anaesthesia is reduced. Prewarming can be achieved through several methods, such as convective or conductive warming or with infrared radiators. The patient must be transferred early to the holding area or the anaesthesia induction room, where the prewarming is applied. The optimal duration of prewarming is between 30 min and 1 h [109]. However, Horn et al. showed recently that shorter prewarming times (10 min) are also comparably effective [45]. Heat loss between prewarming and induction of anaesthesia must be avoided. The challenge (and limitation) of prewarming is to apply the prewarming protocol correctly in the daily hospital routine. Reliable OR scheduling and good cooperation between all parties involved is necessary. In many hospitals this cannot be assured, and therefore prewarming is a very effective but, unfortunately, rarely used method.

**Internal warming methods**

**Warmed infusions**

Administration of warmed infusions using fluid warmers is an active, internal warming method. The mean body temperature of adults decreases by approximately 0.25°C if only one pack of cooled (4°C) erythrocyte concentrate or 1000 ml of crystalloids (room temperature) is infused [105]. This heat loss can be effectively prevented if warmed fluids are given. A limitation is that patient warming, in addition to compensating for the heat loss caused by fluid infusion, is not feasible. The reason is that both the maximum fluid temperature and the maximum amount of fluids are limited. Because the method is only effective if larger amounts of fluids are given (>500 ml), special fluid-warmers with high capacity heaters and high flow-rates are beneficial in patients with expected needs for large amounts of fluids (e.g., trauma or major abdominal/thoracic surgery). Additional warming with an alternative patient warming principle, e.g., convective or resistive warming devices, is necessary.

**Warming with intravascular warming catheters**

Warming with catheter-based intravascular warming systems is an effective, internally active method. It requires central venous access (femoral, jugular or subclavian vein) for a special warming catheter. These catheters usually have heat exchange balloons at the tip that are perfused by warmed fluids. The advantage of this method is that, after installation, the patient’s body temperature will be regulated automatically. These systems can be used for patient warming or cooling. The induction of therapeutic hypothermia, for example, for the inclusion
of post-cardiac-arrest patients into a hypothermia proto-
col, is easily performed. It is also possible to define the
rewarming or cooling rate to avoid too rapid temperature
changes.

However, the puncture of a central vein with a large-
bore catheter is invasive and, considering the high price
of a catheter (approx. €900), these warming methods are
reserved for special indications.

**Extracorporeal warming**

**Extracorporeal warming without haemodynamic support**

Several extracorporeal warming methods are available. Even small hospitals can warm hypothermic patients with
haemodialysis or continuous veno-venous haemofiltra-
tion [18, 114, 123]. This method is rapidly initiated and
offers the possibility to correct electrolyte disturbances
and treat renal failure. A drawback is that it requires anti-
coagulation and stable haemodynamics. A typical indica-
tion for rewarming with haemofiltration or dialysis is an
intoxicated and hypothermic patient. If the toxin can be
dialysed, simultaneous rewarming of the patient is pos-
sible [71].

An alternative method is continuous arterio-venous
rewarming [31, 32]. This method has several limitations. It
is very invasive (large-bore arterial cannula) and the extra-
corporeal blood flow, which determines the rewarming
rate, is not easy to adjust because the flow is dependent
on the patient’s blood pressure. Arterio-venous rewarm-
ing causes a significant left-right shunt that cannot easily
be compensated by the hypothermic organism (bradycar-
dia, reduced inotropia) [12].

**Extracorporeal warming with haemodynamic support**

The most effective and the most invasive warming method
for patients with severe hypothermia is the cardiopulmo-
nary bypass (CPB) [66, 76, 98, 99, 113]. The advantage of CPB
is that the hypothermia itself and the haemodynamic con-
sequences of deep hypothermia can be treated simultane-
ously. In the initial phase of deep hypothermia with cardiac
arrest, CPB replaces the function of the heart and lungs
completely and sufficiently rewarms the patient. Later, after
partial rewarming and return of spontaneous circulation
(ROSC), the CPB flow can be reduced stepwise according to
the actual cardiac function. Several tertiary hospitals, which
regularly receive patients with hypothermic cardiac arrest
(e.g., avalanche casualties in the alpine regions) introduced
treatment protocols with very fast installation of CPB (e.g.,
femoro-femoral CPB) with promising results [127, 128].

Extracorporeal membrane oxygenation (ECMO) is
another option for the treatment of deep accidental hypo-
thermia [37, 117]. In general, ECMO systems use two differ-
ent techniques: veno-venous and veno-arterial ECMO. Both
systems have in common that the patient’s blood will be
drained from a central vein (e.g., femoral access to the vena
cava inferior) and extracorporeal gas exchange will be per-
formed. In veno-venous ECMO, the oxygenated blood will
be pumped back into a central vein; in veno-arterial ECMO,
blood will be pumped into the arterial system. In contrast to
veno-venous ECMO, veno-arterial ECMO offers the possibil-
ity of hemodynamic support and is, therefore, suitable for
earlier phases of resuscitation. The place for veno-venous
ECMO is the phase after initial stabilisation if pulmonary
failure requires extracorporeal gas exchange [24, 34].

Both CPB and ECMO are maximally invasive tech-
niques that require permanent anticoagulation. They are
restricted to specialized medical centres with experienced
surgeons, anaesthetists and perfusionists. For success-
ful treatment of severe hypothermia with extracorporeal
techniques, correct patient selection and efficient treat-
ment protocols with 24-h availability for immediate initia-
tion of CPB or ECMO are necessary.

A variety of techniques for thermal protection/rewarm-
ing and the measurement of body core temperatures is avail-
able on the market today (Table 3). From a technical point
of view, it seems that all requirements for successful treat-
ment of hypothermia are met. In the following section of this
paper, we will concentrate on existing regulations and stand-
ards and the cost effectiveness of preventing hypothermia.

**Regulations, standards and guidelines**

Several organisations have published guidelines on perioperative thermo-management. In the following, we
describe the situation in the United States and in Europe.

**United States**

Several American institutions and organisations recom-
mend the maintenance of perioperative normothermia
to reduce surgical site infections (SSI). For example, the
Institute for Healthcare Improvement (IHI; www.IHI.org) recommends the use of forced-air warming perioperatively
to maintain normothermia [81]. The Center for Disease
Control (CDC; www.CDC.gov) published “Guideline for the Prevention of Surgical Site Infection,” [82] which states that excellent surgical techniques are believed to reduce SSI. Among the techniques included was the prevention of hypothermia.

The American Society of Anesthesiologists (ASA) states in “Quality Incentives in Anesthesiology”: “We propose that achievement of an immediate postoperative temperature >36 °C is an important, beneficial and realistic goal for patients undergoing general anaesthesia lasting more than 60 min.” [94]. In 2009, the American Society of PeriAnesthesia Nurses (ASPAN) published an evidence-based clinical practice guideline for the promotion of perioperative normothermia.

**United Kingdom**

The National Collaborating Centre for Women’s and Children’s Health published a guideline on SSI [115] that recommends inter alia the implementation of the National Institute for Health and Clinical Excellence (NICE) guideline “Inadvertent perioperative hypothermia“ [53].

**Germany**

To the authors’ knowledge, no clinical guideline or standard on accidental or perioperative hypothermia has been published in Germany to date. However, the latest version of the “German Law to Secure Protection against Infections” (“Infektionsschutzgesetz”; IfSG) states that the director of a hospital has to assure that all necessary measures – in compliance with scientific knowledge – have been taken to avoid nosocomial infections. Compliance with scientific knowledge can be assumed if the hospital follows the Recommendations of the Hospital Hygiene and Infection Prevention Committee of the Robert Koch Institute (RKI) [96]. These recommendations include a statement that perioperative normothermia must be maintained in all patients, with the exception of patients who would profit from protective hypothermia. Ultimately, this means that if SSI occurs and the patient was hypothermic at the end of surgery, it must be proven by the healthcare providers that all possible efforts to maintain normothermia had been undertaken. Currently, the importance of this new legal situation seems not to be widely known.

### Table 3 Patient warming methods.

<table>
<thead>
<tr>
<th>Category</th>
<th>Options</th>
<th>Invasiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive external</td>
<td>- Unwarmed blankets</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>- Humidified inspired air</td>
<td>Low</td>
</tr>
<tr>
<td>Active external</td>
<td>- Forced-air warming</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>- Conductive warming</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>- Warm-water immersion</td>
<td>(High)</td>
</tr>
<tr>
<td></td>
<td>- Infrared emitters</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>- Elevated ambient temperature</td>
<td>Low</td>
</tr>
<tr>
<td>Active internal</td>
<td>- Warmed and humidified inspired air</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>- Warmed infusions</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>- Intravascular warming catheters</td>
<td>High</td>
</tr>
<tr>
<td>Extracorporeal</td>
<td>- Haemodialysis/haemofiltration (CVVH)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>- Veno-venous rewarming</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>- Arterio-venous rewarming</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>- Extra corporal membrane oxygenation (ECMO)</td>
<td>Very high</td>
</tr>
<tr>
<td></td>
<td>- Cardiopulmonary bypass</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Categories adapted from Kempainen and Brunette [62].

**Cost-effectiveness**

In health care today, emphasis is often on improving cost effectiveness [51, 130]. This theme is constantly reiterated in all discussions about health care expenditures.

In non-medical industries, the scope of cost-effectiveness is most often very clear. It is typically only analysed from the perspective of the investor, which in most cases is also the company benefiting from this investment.

In health care, there may be many different perspectives to assess cost-effectiveness. Also, the investor and
beneficiary may not always be identical. Therefore, the perspective needs to be defined before engaging in a ROI analysis. Different perspectives in health care may include the following:

- The individual care provider, e.g., the general practitioner;
- The care delivery organization (CDO), e.g., hospital;
- A health management organization (HMO);
- An entire health care system, i.e., the public purse;
- The employer of the patient;
- The individual patient.

Two examples may illustrate these different perspectives. In the first scenario, a radiology practice privately invests in a new magnetic resonance imaging (MRI) device. This new device will allow additional MRI studies and increasing the number of studies will increase the revenue of the radiology practice. In a fee-for-service environment, this may yield a significant return on investment for the respective radiology practice, and thus be cost-effective. However, the payer or health care system will incur additional expenses.

In the second scenario, a newly developed clinical pathway system significantly shortens the length of stay after laparoscopic cholecystectomy. In a case base, capital or DRG environment, this may be very cost-effective for the respective hospital and cost-neutral for the payer. If the reimbursement is done on a per diem basis, only the payer may benefit, while the hospital runs into significant financial losses. Here, we look at cost-effectiveness from two perspectives: that of the CDO and that of the entire healthcare system, always assuming that the interventions discussed provide benefit for the patient.

One of the leading goals is to reduce the cost per service item. A service item could be a specific medical procedure, e.g., a minimally invasive procedure, one specific disease episode, the complete treatment for one DRG or even the entire health coverage for a population. In principle, there are three approaches to reduce costs:

- Reduction of resource consumption, i.e., the direct cost for an individual service item. This could, for example, be achieved by a medical device that has lower operating costs.
- Increase of the number of procedures performed with the same resource, i.e., reduction of the fixed cost per service. An example could be extended operating hours for expensive imaging equipment. Of course, this reduction of fixed costs should always be calculated against the absolutely increased direct costs.
- Reduction of complications for the delivered service item. This approach to reduce cost is highly specific for health care. Typically, complications are excessively expensive, as they require additional treatment, increase the length of stay and may result in compensation for malpractice. Therefore, even a small reduction in the complication rate may have a significant effect on the cost-effectiveness of a health care operation. It can even be said that with the currently poor quality standards in health care improvements in the quality of care will typically lead to better cost effectiveness [3, 23, 55].

The latter is the most important approach with respect to the prevention and treatment of accidental hypothermia.

Known complications of perioperative hypothermia that increase treatment costs include increased number of SSI [70], increased transfusions [97], prolonged hospital [70] and post-anaesthetic recovery room [8] stays and an increased number of cardiac events [30]. According to Melling et al. [84], patient warming has a number needed to treat (NNT) of 10 to 15 patients for the prevention of surgical wound infection.

Another calculation of the cost-benefit ratio of patient-warming to avoid perioperative hypothermia for patients in the United Kingdom can be found in the NHS Costing report [89] of the NICE guideline “Inadvertent Perioperative Hypothermia” [53]. The baseline risk of the consequences of inadvertent perioperative hypothermia, as well as the related relative risk for each consequence and the costs (per consequence and cost-saving per inadvertent perioperative hypothermia patient), together with a QALY calculation, are shown in Table 4 and the calculated net benefit per hypothermic patient is given in Table 5. Both are based on the cost-effectiveness analysis of the NICE guideline (CG65) “Inadvertent perioperative hypothermia.”

For the United Kingdom, Coello et al. calculated that SSIs might, depending on the site of infection, increase length of stay from 3.3 to 21 days, causing up to an additional £6103 of costs [22]. Further savings are possible if cardiac events and transfusion needs are considered.

For the US, Mahoney et al. calculated in a meta-analysis with outcomes and costs the average cost per hypothermic patient to be between $2412 and $6839 [80].

The US governmental health insurance program Medicare recognizes the importance of normothermia through an initiative, the Surgical Care Improvement Project (SCIP) Infection 10 quality measure, which mandates documentation of either active perioperative warming or normothermia. Anaesthesiologists who participate in
the Physician Quality Reporting Initiative 2011 earn a 2% bonus payment that will be subsequently converted to a 2% malus in 2016 if reporting is not done [20].

In conclusion, thermomanagement can be cost-efficient, but the patients at risk must be identified correctly and the appropriate patient warming strategies selected. In high-risk patients, even an elaborate warming technique may be cost-efficient [42]. Bonus and/or malus systems of health insurance companies could help to establish adequate patient thermomanagement as a standard of care.

Limitations and problems

Medical limitations and problems

Maintaining normothermia and treating hypothermia is still a challenge and an unsolved problem to this day. The task for the coming years is to establish a “Culture of Normothermia” in preclinical and clinical settings. The negative effects of hypothermia are well known, and we have efficient warming methods that need only to be applied. However, there are situations in which we are still not able to warm patients efficiently.

Preclinical problems

Emergency and especially trauma patients present high risks for accidental hypothermia [41, 114]. Therefore, emergency medical staff must be sensitized to the risks of accidental hypothermia and also to the increased survival chances in hypothermic cardiac arrests. Direct transportation (with advance notification) to a dedicated tertiary hospital with the possibility of immediate CPB installation can save lives.

With the exception of warm summer days, the typical emergency patient in moderate climate zones presents already with beginning hypothermia to the emergency

<table>
<thead>
<tr>
<th>Consequence of IPH</th>
<th>Baseline risk</th>
<th>Relative risk (95% CI)</th>
<th>Cost of consequence</th>
<th>QALYs loss</th>
<th>Cost saving per IPH patient</th>
<th>QALY gain</th>
<th>Net benefit gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgical wound infection (minor surgery)</td>
<td>3.0%</td>
<td>4.0 (1.6–10.2)</td>
<td>£950.00</td>
<td>0.07</td>
<td>£86.00</td>
<td>0.006</td>
<td>£211.00</td>
</tr>
<tr>
<td>Surgical wound infection (intermediate, major surgery)</td>
<td>3.0%</td>
<td>4.2 (1.6–10.2)</td>
<td>£3858.00</td>
<td>0.07</td>
<td>£347.00</td>
<td>0.008</td>
<td>£473.00</td>
</tr>
<tr>
<td>Blood transfusion (intermediate and major surgery)</td>
<td>12.0%</td>
<td>1.2 (0.9–1.6)</td>
<td>£244.00</td>
<td></td>
<td>£5.00</td>
<td></td>
<td>£5.00</td>
</tr>
<tr>
<td>Blood transfusion (minor surgery)</td>
<td>0.0%</td>
<td>1.2 (0.1–1.6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morbid cardiac event (age group 20 years)</td>
<td>0.0%</td>
<td>2.2 (1.1–4.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morbid cardiac event (age group 50 years)</td>
<td>2.4%</td>
<td>2.2 (1.1–4.7)</td>
<td>£2048.00</td>
<td>3.54</td>
<td>£59.00</td>
<td>0.055</td>
<td>£1165.00</td>
</tr>
<tr>
<td>Morbid cardiac event (age group 70 years)</td>
<td>4.5%</td>
<td>2.2 (1.1–4.7)</td>
<td>£2341.00</td>
<td>1.93</td>
<td>£111.00</td>
<td>0.057</td>
<td>£1249.00</td>
</tr>
<tr>
<td>Mechanical ventilation</td>
<td>0.3%</td>
<td>1.6 (1.0–2.6)</td>
<td>£1144.00</td>
<td></td>
<td>£2.00</td>
<td></td>
<td>£2.00</td>
</tr>
<tr>
<td>Pressure ulcer (intermediate and major)</td>
<td>1.8%</td>
<td>1.9 (0.9–4.1)</td>
<td>£1064.00</td>
<td></td>
<td>£17.00</td>
<td></td>
<td>£17.00</td>
</tr>
<tr>
<td>Total hospital length of stay in days (minor surgery)</td>
<td>0.25</td>
<td>+19%</td>
<td>£275.00</td>
<td></td>
<td>£13.00</td>
<td></td>
<td>£13.00</td>
</tr>
<tr>
<td>Total hospital length of stay in days (intermediate surgery)</td>
<td>1</td>
<td>+19%</td>
<td>£275.00</td>
<td></td>
<td>£51.00</td>
<td></td>
<td>£51.00</td>
</tr>
<tr>
<td>Total hospital length of stay in days (major surgery)</td>
<td>4</td>
<td>+19%</td>
<td>£275.00</td>
<td></td>
<td>£204.00</td>
<td></td>
<td>£204.00</td>
</tr>
</tbody>
</table>

Table 4 Health economic model for inadvertent perioperative hypothermia (IPH) based on NICE clinical guidelines 2008 [89].

Table 5 Resultant variation in the net benefit per hypothermic case prevented by age and magnitude of surgery. Mean values across 1000 samples generated by the probabilistic sensitivity analysis and 95% confidence interval [89].
team. Therefore, efficient rewarming methods should be available. But today preclinical patient warming is mainly restricted to insulation and elevated ambient temperatures in the ambulance car. From a technical point of view, conductive (forced-air) or resistive warming during the transportation is possible. A practical application could be a (vacuum) mattress with an integrated heating system. However, as far as we know, there are only a few conventional warming mattress systems on the market today.

As many trends in trauma management originate from military medicine, more applications exist for active and passive patient warming for military casualty evacuations.

Clinical problems

In a clinical setting, hypothermia can be treated successfully in the majority of patients with the rewarming systems available today. However, in some areas, unmet needs can still be identified.

The MR-suite is an area in which both patient warming and core temperature monitoring is impossible today. Some MR-compatible patient monitors offer temperature monitoring with a fiberoptic probe. Unfortunately – to our knowledge – these temperature probes are only for measurements at less accurate measurement sites such as the armpit.

Few data exist about the temperature course during MR imaging. The magnetic field itself is theoretically able to heat a human body. Machata et al. showed that, in their setting using 1.5 and 3 Tesla scanners, the core temperature of infants and small children under deep sedation increased significantly [78]. In praxi, the effect may depend on several difficult to estimate factors, e.g., general anaesthesia or not, the type of MRI-device (air-stream within the gantry), the environmental temperature, clothing or blankets, etc. Therefore, in the future, continuous core temperature monitoring and rewarming should be possible for anaesthetized patients during MR-imaging.

Another patient group that is at special risk for developing hypothermia comprises patients undergoing major trauma or abdominal or vascular surgery. Low preoperative core temperature, high fluid or blood product demands, prolonged surgical time and large uncovered areas contribute to the development of hypothermia. In some of these cases, it is very difficult or nearly impossible to maintain normothermia with conventional methods like convective or resistive warming and warmed i. v. fluids. This situation aggravates if – as in vascular surgery – it is contraindicated to warm unperfused areas (e.g., the lower body during aortic clamping). In these cases, more invasive warming methods can be considered. Because the majority of these patients will get a central venous access anyway, central venous warming catheters are an option.

Need for further research

Technical aspects

In contrast to other biomedical areas, thermomanagement is a paradox situation where a broad variety of methods of all degrees of efficacy and invasiveness already exist. The main focus of further research in this field should be concentrated on improvement of already available applications. In general, systems should be less complex, more flexible and interoperable.

A technical factor that may hinder physicians in determining a body temperature target is difficulty measuring core temperature accurately. Good measurement sites for precise temperature measurements are very often inaccessible depending on the type of surgery. An urgent requirement for the future is the development of precise non-invasive core temperature measurements. We discussed these topics in detail in our 2011 position paper on temperature management [129].

Existing technologies should be improved in a way that the “no patient-warming areas” of today’s hospitals (MRI, patient transports, etc.) can be eliminated. Today, during MRI under general anaesthesia, neither core temperature measurements nor rewarming of patients is a standard of care in the majority of patients. MRI-compatible patient-warming devices are not available today. Continuous measuring of a patient’s core temperature remains a technical challenge. The routine integration of fiberoptical temperature probes for core temperature measurements into MR-compatible patient monitors is needed. An alternative future option is that the MRI system itself is theoretically able to measure temperatures. The method (MR-thermometry) is used routinely for the temperature monitoring of the area of interest during high-intensity focussed ultrasound (HIFU) treatments [43]. However, today, only relative temperature changes can be measured with insufficient precision (> ±1°C). An improved MR-thermometry for core temperature monitoring would be of interest.

Consequently, patient warming should be possible in the future. MR-compatible thermomanagement systems could be, for example, integrated into the cushion of the MRI patient support (“table”), or it should be possible to adjust the temperature of the airstream within the scanner bore according to patient needs (cooling/warming).
Thermomanagement systems in the future may be more user-friendly and should offer decision-making assistance. A closed-loop thermomanagement system would be desirable. The heating unit should have an interface to receive the actual core temperature of the patient and regulate the heating power according to the intended temperature goal. Integration into already existing patient monitoring systems would be an option. In the next years, anaesthesia patient data management systems will continue to replace the classical anaesthesia chart. Because these computerized systems store demographic (sex, age, weight, height) and clinical data (type of surgery/anaesthesia) of a case, the risk for hypothermia could be calculated a priori using a simulation program. This would support the physician in choosing the appropriate warming techniques. A few such simulation programs already exist (e.g., for preterm newborns, adults, fire fighters) [27, 121], and first validation studies have been finished with promising results [61, 65, 124]. Today, the barrier for installation of an extracorporeal patient warming system (e.g., intravascular warming catheters) is relatively high because it is a highly invasive technique. An effective central-venous warming catheter with a large bore lumen for rapid infusions could lead to new indications, e.g., first line i. v. access with additional warming options for trauma victims with expected demand for mass transfusion in the emergency room. Today, unfortunately, all available systems miss a large, high-flow lumen for massive transfusions.

Finally, it may be suggested that thermal insulation materials for emergencies and surgical draping could be improved to protect against hypothermia. Better insulation or even self-heating fabrics – as already available for military evacuations – would be highly desirable.

**Medical aspects**

As mentioned earlier, the main problem for the successful treatment of hypothermia is a lack of awareness of the healthcare providers. One reason may be that results from maintaining normothermia are not immediately apparent. Further efforts to establish a “culture of normothermia” in hospitals have to be intensified. A model may be the successful campaigns on hand hygiene in Europe of the last years [79].

The few available guidelines are more general recommendations and non-specific. For the future, evidence-based clinical practice guidelines would be helpful. These guidelines should offer guidance for the appropriate selection of patients, rewarming strategies and treatment goals (who, how and how much warming). Remaining concerns, e.g., costs, hygiene or burns, that may hinder the initiation of patient warming should be addressed by evidence-based facts.

Another problem is the inconsistent definitions for hypothermia, which make the setting of treatment goals and the comparison of studies (e.g., with meta-analyses) difficult. This leads again to the question of which temperature measurement methods and sites are the most adequate. Future guidelines should include clear recommendations for the preferred methods in specific situations.

**Conclusion**

The reasons for and consequences of accidental or perioperative hypothermia are well understood today. A multitude of warming devices with varying invasiveness and efficacy are commercially available. Surprisingly, unintentional hypothermia is still a common problem in healthcare today.

We strongly suggest that every emergency and anaesthetized patient’s core temperature be monitored and documented. If the measurement shows that the patient is in danger of becoming hypothermic, an adequate rewarming strategy should be applied early. Prewarming should be considered if the OR management structures allow for it. Furthermore, clinical areas in which precise core temperature measurements (e.g., MRI) or rewarming are not available (MRI, ambulance cars, helicopters…) should be unacceptable in future. In the future, every patient should be entitled to efficient thermomanagement and normothermia.

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