

Heat Production and Loss

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DEFINITIONS	
Heat:	Heat is a form of energy that can be transferred from one (a hotter) object to another (a colder) object, the energy being in the form of the kinetic energy of the molecules of the object.
Temperature:	Temperature is the thermal state of an object which determines whether it will give heat to another object or receive heat from it. Heat is transferred from the object at the higher temperature to the object at the lower temperature.
Calorie:	The SI (Système International d'Unités) unit of heat is the same as that of energy, namely the Joule (J). The calorie is used here where 1 calorie = 4.186 J. Calorie spelt with a capital 'C' represents 1000 calories when it is used in dietary nutrition.
Celsius/centigrade:	The temperature scale is the Celsius (°C) (after Anders Celsius), or centigrade scale, because under standard conditions water freezes at 0°C and boils at 100°C.
Conduction:	Conduction is heat transfer through a solid medium. Conduction is the process whereby heat energy is transmitted through a substance by the transfer of the energy of motion of the molecules to adjacent molecules. Metals are good conductors of heat but gases are poor conductors. The air surrounding a person provides protection from heat loss through conduction.
Convection:	Convection is the heat transfer through a fluid medium such as air or water. This occurs because the warmer molecules move within the fluid, i.e. float to the top when warm or sink to the bottom when cool. The air layer next to the surface of the body is warmed by conduction and as it is heated it expands, becomes less dense and so rises. The resulting convection current carries heat away from the body.
Radiation:	All objects absorb, reflect or emit electromagnetic energy (radiation) over a spectrum of wavelengths. Such energy includes light waves and heat as infrared waves. The radiation emitted carries energy away from the object and causes it to cool down. If this energy is absorbed by another object, that object will become hotter. Thus radiation can transfer heat energy between two objects which are not in contact.
Latent heat of vaporization:	The amount of heat required to increase the energy of a fluid to change its state from liquid to vapour without any temperature change is called the latent heat of vaporisation.
Evaporation:	Evaporative heat loss is due to the loss of latent heat of vaporisation of moisture or other solutions applied to the skin's surface. The loss of heat by this route is dependent on the total area of skin exposed to the atmosphere.
Critical temperature:	Neutral temperature is the ambient temperature that results in minimal oxygen consumption. Critical temperature is the ambient temperature below which an unclothed, unanesthetised individual cannot maintain a normal core temperature. The lower limit of the thermoregulatory range (critical temperature) is 1°C for an adult, but is 23°C for the full term infant and 28°C for the premature infant. The thermoregulatory range of the neonate is narrower than that of the adult and the operating rooms must be kept at least 23°C for neonates. Note that the thermoregulatory zone is different to the thermoneutral zone – the temperatures between which we do not have to actively regulate our body temperature.

HEAT PRODUCTION AND LOSS

Humans are homeothermic as they actively maintain their core body temperature within a narrow range, usually 36.5-37.3°C. When core body temperature changes outside this range of 0.5-0.8°C, various

thermoregulatory mechanisms are activated to bring the temperature back to normal. Anesthesia disrupts many aspects of thermoregulation, leading to perioperative hypothermia, which in turn can lead to several complications. Often, measurement of temperature is

Summary

Under general anesthesia the body cannot compensate for hypothermia because anesthetics inhibit central thermoregulation by interfering with hypothalamic function.

Anesthetic-induced vasodilatation causes redistribution of heat from the warm central compartment to cooler peripheral tissues.

Even mild core hypothermia can be detrimental and lead to patient harm. It is therefore important to monitor core temperature during general anesthesia and take active measures to conserve heat. Induced hypothermia has proved to be protective during times of cerebral or cardiac ischemia as metabolic oxygen requirement is lowered by systemic cooling. Hyperthermia during sepsis, hyperthyroidism, malignant hyperthermia, and drug or transfusion reactions if not recognized and treated promptly can lead to life-threatening physiological disturbances.

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Table 1. Neutral and critical temperatures

	Neutral Temperature °C	Critical Temperature °C
Preterm neonate	34	28
Term neonate	32	23
Adult	28	1

neglected during and after anesthesia. By understanding the physiology of thermoregulation and the impact of anesthesia on this process, one can use simple steps to maintain normal body temperature in the perioperative period and thereby prevent adverse patient outcomes.

PHYSIOLOGY

The brain uses negative feedback mechanisms to maintain body temperature within a narrow range, which ensures that chemical reactions at a cellular level can occur optimally. Body temperature increases with metabolic activity – it is lowest during sleep, higher during the day, with oral temperatures between 36.5 and 37.3°C in the morning in normal adults. In menstruating women, body temperature can increase up to 1°C at ovulation due to the effect of luteinizing hormones.

In order to understand the impact of anesthetics on the process of thermoregulation and how different parts of the body have different temperatures, it is useful to construct a two-compartment model of the human body. Imagine that the body is divided into a central core compartment surrounded by a peripheral compartment (Figure 1). The core is made up by major thoracic and abdominal organs and the brain, holds two-thirds of the body heat content, and is maintained within a narrow temperature range (36.6 to 37.4°C). The periphery is by the limbs and skin and subcutaneous tissue, and contains about one-third of the body heat content. The temperature of the periphery varies widely from 0°C up to 40°C depending on the environment, but is usually 30-32°C. This 5-7°C difference between core and peripheral body temperature is maintained by vasoconstriction in the blood vessels leading to the peripheral tissues.

Heat production

Heat is produced as a by-product of normal metabolic activity. In a body at rest, the basal metabolic rate (BMR) is about 40kcal.m⁻².h⁻¹, which is about 1700kcal.day⁻¹ in an adult man weighing 70 kg. Roughly two-thirds of the energy available from the metabolism of glucose, amino acids, or fat is dispersed as heat; the rest is stored as chemical energy in the form of ATP (adenosine triphosphate). Metabolism of fat releases almost twice the energy (9.3cal.g⁻¹) when compared to that of glucose and amino acids (4.1cal.g⁻¹).

Heat production can be increased by voluntary muscle activity (exercise), involuntary muscle activity (shivering), or non-shivering thermogenesis. Heat production can be increased up to six-fold while shivering, and up to 20-fold at maximum intensity of exercise.

In brown adipose tissue, when all the energy of metabolism is dispersed as heat without storing any in ATP, it is called non-shivering thermogenesis. In neonates without significant muscle mass, non-shivering thermogenesis is an important method of heat production.

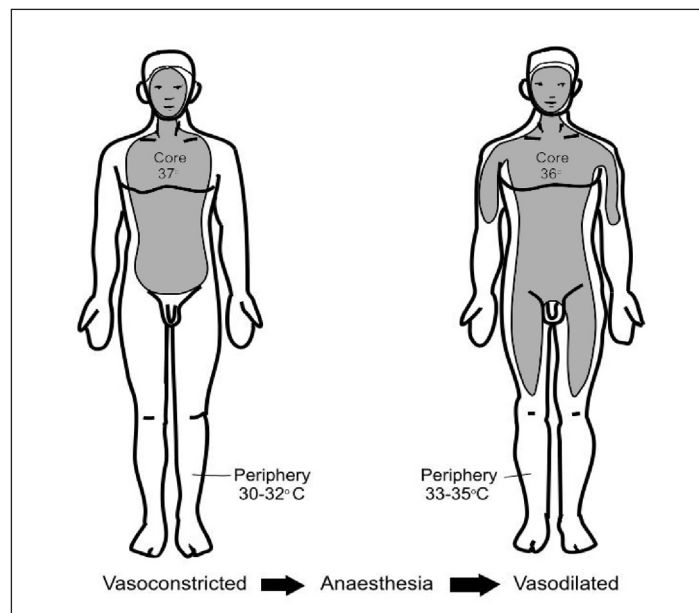


Figure 1. The effects of anaesthesia on heat balance. The human body consists of two compartments in this model. At baseline, the central core is considerably warmer than the periphery. By inhibiting tonic vasoconstriction, both general and regional anesthesia decrease core temperature by redistribution of heat from the central core to the peripheral thermal compartment. This mechanism explains the decrease in core temperature of 1°C in the first 30-60 minutes following induction of anesthesia. As the periphery is now warmer, further heat loss occurs as the gradient between the skin and surroundings is greater

(Modified with permission from Doherty M and Buggy D. Thermoregulation. In: Hemmings & Hopkins, ed. Foundations of Anesthesia, 2nd Edition, Philadelphia: Elsevier; 2006: 809-826)

Brown adipose tissue has an abundant vascular supply and sympathetic innervation. Non-shivering thermogenesis is inhibited by sympathetic blockade and by inhalational agents.

Metabolic rate is higher in children, and metabolic activity is increased by hormones such as thyroxine and growth hormone. Under normal conditions, body heat is preserved by tonic peripheral vasoconstriction.

Heat loss

Heat loss occurs by conduction, convection, and radiation of heat from the body to the surrounding area, and by evaporation of sweat.

Heat loss by conduction occurs by direct contact of the body with an object of lower temperature and contributes to only 1-2% of heat loss.

A layer of air normally trapped next to the skin contributes to insulation. Clothing increases this insulating layer and prevents heat loss to the environment. Convective heat loss occurs when the layer of air next to the skin moves and carries heat away from the body. In an operating room with forced airflow, convection can account for 25% of the heat loss or more. The amount of heat lost by convection depends on the surface area of the body that is exposed and the amount of airflow. As a reminder, at the same temperature, windy days feel cooler than calm days.

Heat loss by evaporation is increased in the operating room from the evaporation of skin-preparation solutions and in major surgeries with open abdominal cavities. Evaporative heat loss is more significant in premature neonates because of their increased skin permeability.

Radiation is transfer of heat by infrared waves from the body to cooler objects (not in physical contact with the body) in the surrounding area, and constitutes the major method of heat loss to the environment. Almost 60% of heat loss can occur via radiation. The amount of heat loss depends on the fourth power of the temperature difference between the objects. If the operating room temperature is decreased by 2°C, heat loss will be increased by a factor of 16 (2⁴).

Normal respiration accounts for a small amount of the total heat loss, typically 10%. Eight per cent of this loss occurs through increasing the humidity of the inspired air to 100%, and 2% is due to warming the air. Under anesthesia the inspired gases are usually dry and heat is lost in both humidifying the air and in warming dry air. Heat loss through this route can be avoided by humidifying inspired gases and is reduced when low fresh gas flows are used in an anesthetic circle system with soda lime, instead of high flows through a non rebreathing system. Loss of heat through this route becomes important when high fresh gas flows are used, especially in small children.

A patient under anesthesia in an operating room loses or gains body heat via some combination of conduction, convection, radiation, or evaporation. The major mechanism of heat loss or gain varies with time and depends upon the phase of the anesthetic, set temperature and humidity of the operating room, air-conditioning and net air-flow or air-exchange in the operating room, whether or not the patient is draped with impervious (plastic or paper) drapes or pervious (linen) drapes, the total surface area of the body exposed and whether or not major body cavities (thorax or abdomen) are open and institution of active methods of patient cooling or warming.

Physiological Control

The main site of thermoregulation is the hypothalamus, which receives information from temperature sensitive nerve endings throughout the body. The sense organs for temperature are the unsheathed nerve endings in the skin and subcutaneous tissue that respond to temperatures above or below core temperature by changing the rate at which they send impulses to the central nervous system. Cold receptors – neurons that respond to temperatures from 10 to 36°C – are present in a large number in the peripheral compartment when compared to warm receptors that respond to 30 to 45°C. The sensation of heat or cold produced by a temperature change gradually fades because the neurons are subject to adaptation between 20 and 40°C. The skin provides about 20% of the total thermal input to the central nervous system, while thermally sensitive cells throughout the body provide the rest of the input. The input from various sites is integrated in the anterior hypothalamus.

The posterior hypothalamus compares the aggregate thermal input with the set point temperature and initiates appropriate responses when necessary. The temperature at which a response is triggered is termed the threshold temperature. The threshold temperature may change with gender, exercise, food intake, and during infection, and may be altered with certain drugs. The threshold for vasoconstriction

is 36.5°C and 36.0°C for shivering. General anesthesia lowers this threshold by 2-3°C. The inter-threshold range is the range of core temperatures at which no thermoregulatory response is triggered. This range is normally 0.2-0.5°C, but general anesthesia can increase this range to 5.0°C (Figure 2).

Changes in temperature beyond the inter-threshold range initiate efferent responses that increase heat production (shivering or non-shivering thermogenesis), or decrease heat loss (vasoconstriction) in response to cold; or increase heat loss (sweating and vasodilatation) in response to warmth. When core temperature decreases, initially muscle tone is increased, and then shivering occurs. Shivering is an involuntary skeletal muscle activity that occurs once the cold core temperature threshold is reached (36.0°C). Sustained shivering can double heat production. Shivering after anesthesia is distressing for the patient and can increase pain by involuntary movement of muscles splinting the surgical site. Even though oxygen consumption is increased by shivering, it does not cause hypoxemia. In fact, hypoxemia inhibits shivering. Pethidine, in a dose of 0.3mg.kg⁻¹ IV, stops postanesthetic shivering. However, the patient must be actively warmed to raise core temperature and treat this hypothermia, or to prevent hypothermia from occurring in the first place.

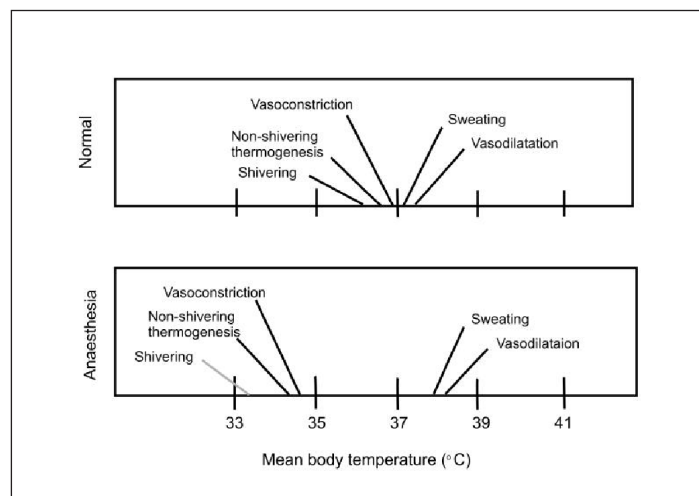


Figure 2. Threshold temperature for initiation of thermoregulatory effector responses. For each response the threshold is indicated by the intersection with the x-axis. (A) Normal: note the temperature range within which no autonomic effector is activated is about 0.5°C; (B) Anaesthesia: the threshold temperature for activation of cold responses (vasoconstriction and shivering) is shifted to the left, and for warm responses (vasodilation and sweating) is shifted to the right. The temperature range within which no thermoregulatory effector is activated is increased up to 5°C

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MEASUREMENT OF TEMPERATURE

Body temperature can be measured at various sites, including the skin at the axilla (over the axillary artery), tympanic membrane, oral cavity, nasopharynx, distal esophagus, rectum, or urinary bladder and in the pulmonary artery. Core temperature can be measured in the nasopharynx or lower esophagus. An oesophageal stethoscope with

a thermistor positioned to hear both the heart sounds and breath sounds is ideal. Rectal and bladder temperatures can be erroneous as measures of core temperature since those organs are not sufficiently well-perfused to reflect changes in core heat content. Recently temporal artery thermometers have become available to measure temperature over the forehead. These may be more consistent when compared to devices that measure tympanic membrane temperatures as measured through the external auditory canal.

EFFECTS OF ANESTHESIA

General anesthesia typically leads to core hypothermia which occurs in three phases. In the first hour following induction of anesthesia, there is a rapid reduction of 1.0-1.5°C in the core temperature due to redistribution of heat from the core to the periphery because of anesthetic-induced vasodilatation. As basal metabolic rate is reduced by 20-40% during anesthesia, heat loss could exceed heat production in the next 2-3 hours and lead to continued gradual reduction in core temperature. In the third phase when patients become sufficiently hypothermic and vasoconstriction occurs at the lower temperature threshold, heat loss and heat production are matched. This is the plateau phase. The pattern of hypothermia during spinal or epidural anesthesia is similar to that of general anesthesia for the first two phases. As vasoconstriction is blocked due to the regional anesthetic, the plateau phase may not occur and serious hypothermia could occur (Figure 3).

CONSEQUENCES OF HYPOTHERMIA

Hypothermia has adverse effects on patient outcome, including an increased incidence of myocardial ischemia and cardiac morbidity,

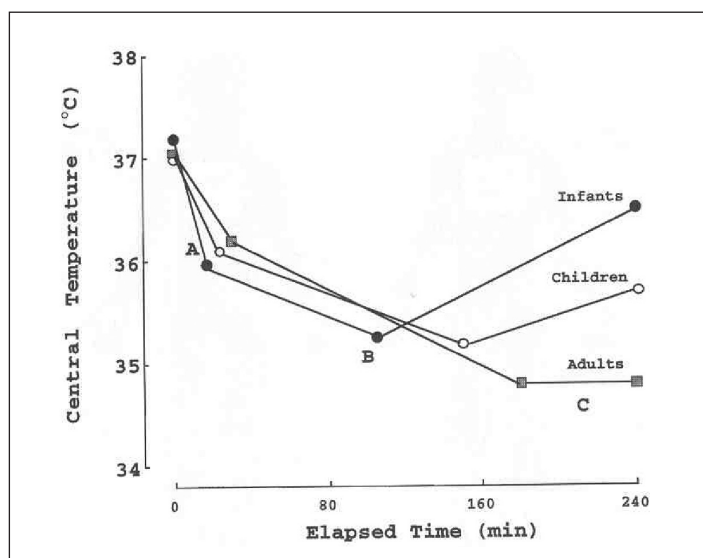


Figure 3. This represents the typical pattern of heat loss during anesthesia, which occurs in three phases for infants (closed circles), children (open circles), and adults (squares). (A) Redistribution of heat from the core to the periphery following induction of anesthesia; (B) Heat loss to the environment, (C) Steady state and rewarming

(Modified with permission from Bissonnette & Ryan. Temperature Regulation. In: Cote, Todres, Goudsouzian, Ryan, eds. A Practice of Anesthesia for Infants and Children, 3rd Edition, Philadelphia: Elsevier; 2001: 610-636).

arrhythmias, interference with coagulation, increased blood loss, and postoperative shivering. Mild hypothermia has an increased risk of postoperative sepsis, surgical wound infection, prolonged postanesthetic recovery, and prolonged hospitalization.

In patients with core hypothermia with a temperature of 34.5-35.9°C, increased plasma catecholamine concentrations lead to hypertension, myocardial irritability, and can induce myocardial ischemia and arrhythmias. Inadequate hemostasis due to impaired platelet function, and suboptimal clotting factor activation as a result of hypothermia can lead to increased blood loss and increased blood transfusion requirement.

Hypothermia can induce vasoconstriction in the skin and subcutaneous tissues leading to a lower tissue oxygen tension, setting up conditions for poor wound healing and wound infection. Mild hypothermia directly impairs immune function, including B cell-mediated antibody production and nonspecific oxidative bacterial killing by neutrophils.

Hypothermia slows drug metabolism. The duration of action of vecuronium is more than doubled in patients with a core temperature less than 35°C. Solubility of inhaled anesthetic agents increases in hypothermia with a decrease in MAC of 5% for every one degree decrease in core temperature. Hypothermia increases plasma concentrations of propofol by thirty percent with a three degree decrease, and fentanyl by five per cent per one degree decrease in core temperature. This can lead to delayed awakening from anesthesia in patients who are hypothermic, thereby increasing the length of their stay in the recovery room.

PREVENTION AND TREATMENT OF HYPOTHERMIA

Remember that prior to surgery patients are unclothed and relatively less insulated. They maintain their core temperature by active peripheral vasoconstriction. Induction of anesthesia causes general vasodilatation and transfers heat from the core to the periphery, unmasking this heat deficit. By actively warming the peripheral tissue in the preoperative period by exposing the patient to radiant heat or using a forced-air convective warmer over one hour, the peripheral compartment can be warmed and the transfer of heat from core to

Consequences of hypothermia

1. Shivering in the recovery room
2. Cardiac morbidity
3. Poor wound healing
 - a. Reduced tissue oxygen tension
 - b. Immunosuppression
4. Delayed emergence due to slowing of drug metabolism
 - a. Prolongation of neuromuscular blockade
 - b. Delayed emergence
 - i. Prolonged elimination of inhaled agents
 - ii. Increased plasma concentration of propofol and fentanyl

periphery that occurs upon induction of anesthesia can be avoided. However, rapid warming can lead to sweating.

Insulating the patient using one layer of an insulator (linen blanket) reduces heat loss by 30%, as it traps a layer of air between it and the skin; however, more passive insulation (additional blankets) is of little benefit. Once heat has been distributed from the central core to the periphery after induction of anesthesia, the core may be rewarmed by actively rewarming the periphery and creating a peripheral to core heat transfer. An electrically powered air heater and fan can be used to warm the patient's peripheral compartment by blowing warm air into a disposable patient cover placed directly over the patient's skin. The amount of heat transferred depends on the extent of body surface covered using these covers. It is crucial to remember not to rewarm ischemic tissues until blood flow is first restored (any limb under a tourniquet).

Intravenous fluid at room temperature can reduce core temperature unless actively warmed. One liter of IV fluid can reduce core temperature by approximately 0.25°C. One unit of refrigerated red blood cells at 4°C can reduce core temperature by 0.25°C. Fluid warming is, therefore, essential when large amounts of fluid are to be administered. Active fluid warming will prevent hypothermia

Prevention and treatment of hypothermia

1. *Preoperative period*
 - a. Warm environment with ambient temperature above the critical temperature
 - b. Insulated patient with at least one layer of insulation
2. *Intraoperative period*
 - a. Warm Operating Room
 - b. Insulated patient
 - c. Forced air warming as soon as possible
 - d. Circulating water mattress under the patient when feasible
 - e. Heating lamps in neonates
 - f. Warmed IV fluids when large volume of fluids are used
 - g. Warmed blood using in line warmers
 - h. Cardiopulmonary bypass warming
 - i. Field irrigation with warmed fluids
 - i. Wound wash outs with large volumes of fluids
 - ii. Peritoneal or pleural cavity irrigation
 - iii. Bladder irrigation cystoscopy
3. *Postoperative period*
 - a. Forced air warming
 - b. Circulating water mattress in the ICU
 - c. Pethidine (0.3 mg.kg⁻¹ intravenous or intramuscular) for active shivering.

but not actually warm the patient unless large amounts of blood are transfused rapidly.

As less than 10% of metabolic heat loss occurs via the respiratory tract, airway humidification contributes very little to actively warming the patient.

SPECIAL CONSIDERATIONS

Neonates and infants

Infants, especially neonates and preterm babies, are at very high risk for perioperative hypothermia. This is because of their increased surface area to volume ratio, thin skin with minimal insulating fat, and less effective efferent responses to cold temperatures. Infants under the age of 3 months cannot shiver. Non-shivering thermogenesis, the major mechanism of heat production, increases the metabolic rate and oxygen consumption and may strain the cardiopulmonary system, especially in a sick child, or one with cyanotic congenital heart disease. The critical temperature, the temperature at which an unclothed infant does not lose heat to the environment, is higher in infants than in adults. The ambient temperature must be raised to 24°C or above, and the infant should be wrapped and transported in an incubator. At induction and during emergence, infants should be placed on a heating blanket or under an overhead radiant heater. During surgery, use of forced air heating, warmed IV fluids, and warmed humidified gases will decrease heat loss.

Cardiopulmonary bypass

During cardiac surgery, mild deliberate hypothermia to 34°C is used for myocardial, cerebral, and spinal cord protection. Brain metabolism is reduced by 50% at 28°C. Recently, patients are also being cooled actively for 24 to 48 hours after the return of spontaneous circulation following cardiac arrest in an attempt to prevent cerebral injury.

Hyperthermia

During bacteremia, pyrogens released by bacteria can lead to cytokine (interleukin, IL-1) release. This can lead to a change in the set-point in the hypothalamus, leading to heat conservation (vasoconstriction) and heat production (shivering) producing a fever. Septic patients present with fever, which may persist during anesthesia, especially if the infected tissue is handled during surgery. In inadequately prepared or undiagnosed hyperthyroid patients, thyroid storm may rarely cause hyperthermia. In these patients, despite an adequate anesthetic, tachycardia, hypertension, and hyperthermia (temperature >38°C) are suggestive of thyrotoxicosis.

Malignant hyperthermia (MH) is a rare congenital genetic disorder in which a life-threatening reaction can occur from certain general anesthetic agents. While tachycardia, hypertension, muscle rigidity, and bronchospasm all occur, temperature elevation is a late sign in MH.

In warm climates, in operating rooms without air conditioning, some patients, especially children, and those with pre-existing fever could become hyperthermic when covered with impervious drapes when undergoing long procedures. In this setting, active cooling by either infusion of cold IV fluid and/or blowing ambient air over the extremities may be necessary to keep them normothermic.

Treatment of hyperthermia

1. *Preoperative period*
 - a. Acetaminophen oral or rectal
2. *Intraoperative period*
 - a. Cold water soaked sponges placed over major vessels in the neck, groin and axilla (over the axillary, femoral and carotid artery)
 - b. Active cooling of the operating room
 - c. Forced air cooling using cooling devices that blow cooler air into jackets or blankets placed on the patients skin (torso and/or extremities)
 - d. Circulating water mattress placed over or under the patient for cooling
 - e. Cooled IV fluids
 - f. Cardiopulmonary bypass assisted cooling
 - g. Field irrigation with cold fluids
 - i. Gastric mucosa using cooled saline instilled via a naso-gastric tube
 - ii. Peritoneal or pleural cavity irrigation
 - iii. Bladder irrigation using a three-way urinary catheter
3. *Postoperative period*
 - a. Forced air cooling
 - b. Circulating water mattress in the ICU

SUMMARY

Physiological thermoregulation is a multilevel control system. The initial response to cold begins with vasoconstriction, followed by shivering. Anesthesia decreases the threshold temperature at which these responses occur, facilitates transfer of heat from the core to the periphery by abolishing the tonic vasoconstriction, and decreases heat production by decreasing metabolic activity.

Mild perioperative hypothermia is associated with poor patient outcomes, including increased wound infection and increased length of stay in the hospital. In cooler climates actively warming the patient prior to induction of anesthesia prevents the occurrence of hypothermia. Anesthetists, by playing an active role in maintaining patient normothermia in the perioperative phase, can play an important role in ensuring a positive outcome for the patient.

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