Heat and temperature

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Key points
Heat and temperature are inter-related but not the same.
Temperature is measured in Kelvin one of seven base SI units.
Temperature can be measured by electrical and non-electrical means.
Hypothermia is detrimental to patients in numerous ways.
Understanding temperature measurement is relatively simple and easy to apply to patient management.

Physical principles

The concept of temperature is as fundamental a physical concept as the three fundamental quantities of mechanics—mass, length, and time. Temperature is a measure of the average translational kinetic energy associated with the disordered motion of atoms and molecules. Temperature is the property of a system, which determines whether or not heat is transferred to or from an object. In a qualitative manner, temperature can be described as the determination of the object’s sensation of warmth or coldness. When a calibrated thermometer is put in thermal contact with a system and reaches thermal equilibrium, then there exists a quantitative measure of the temperature of the system.

Heat refers to the state of energy an object has in relation to the kinetic energy of its molecules or atoms. For example, an iceberg has a low temperature but contains a lot of heat as it has a large number of molecules. Heat will transfer down a temperature gradient from a warm object to a cooler object. Heat energy is therefore measured in the usual unit of energy, the Joule (J). The rate of heat flow is measured in J s⁻¹ or Watts (W). An object does not possess ‘heat’; it has internal energy that can be increased by transferring energy from a higher temperature object, i.e. heating.

Heat and temperature are major components of the classic three laws of thermodynamics.

(i) First law of thermodynamics: Energy can be neither created nor destroyed, it can only be converted from one form into another.
(ii) Second law of thermodynamics: Energy will disperse from a concentrated form to a dilute form if it is not hindered from doing so. For example, a hot pan will cool if removed from heat.
(iii) Third law of thermodynamics: The entropy of an object at absolute zero is zero, i.e. if an object is cooled down to −273°K, it would cease to have any kinetic energy within its molecules.

Because it logically precedes the first and second laws of thermodynamics, the zeroth law of thermodynamics was previously taken for granted but is a necessary for the preceding laws. It states: if two systems are at the same time in thermal equilibrium with a third system, they are in thermal equilibrium with each other. The zeroth law allows temperature to be defined; the ‘triple point’ is the only point at which all three states can exist at the same temperature and pressure.

Another law that relates temperature and its transmission is the Stefan–Boltzmann law. This refers to the concept of a black body, i.e. an ideal object that emits an equal amount of infrared energy as that given to it; so the hotter an object gets the more energy it emits as infrared energy. The total emissive power (E) is proportional to the fourth power of the body’s absolute temperature (T):

\[ E = e\sigma T^4 \]

where \( \sigma \) is Stefan’s constant, \( 5.67 \times 10^{-8} \) W m⁻² K⁻⁴, \( A \) the area, and \( e \) the emissive efficiency, which is close to 1 for a blackened surface and very small for a well-silvered one. Note that for a hot body in surroundings of temperature \( T_0 \), the net energy loss per second will be: \( e\sigma A(T^4 - T_0^4) \).

In general, the energy in a gas molecule is directly proportional to the absolute temperature. As the temperature increases, the kinetic energy per molecule increases. This concept links temperature, energy, and the ideal gas equation. Boltzmann demonstrated that the average kinetic energy of the molecules of a gas was directly comparable with the measured pressure. From the Gay–Lussac law, it is known that pressure is directly proportional to temperature and therefore the kinetic energy of the molecules is related directly to the temperature of the gas.

Three temperature scales are recognized, those of: Centigrade (Celsius), Fahrenheit, and Kelvin, which is the SI unit for temperature.
Fahrenheit

Fahrenheit (1714) used the mercury thermometer to develop this temperature scale. The zero point was set using a mixture of sodium chloride and ice. According to this scale, water boiled at 212°F, ice melted at 32°F, and body temperature was assumed to be 100°F.

Centigrade

Anders Celsius developed the first precise scale in 1742. He used ‘degree’ as the unit of temperature. All of his standards for comparison to make his markings (on his scale) were based on the properties of water: 100°C for the boiling point and 0°C for the melting point of ice.

Kelvin (absolute temperature scale)

This temperature scale was designed by Lord Kelvin (William Thompson, 1824 – 1907), a British inventor and scientist. Kelvin is a temperature scale that is designed so that zero Kelvin is defined as absolute zero (at absolute zero, all actual temperatures are above absolute zero) and the size of one unit is the same as the size of 1°C. The triple point is the temperature and pressure at which the solid, liquid, and gas phase of a substance exist in equilibrium. The Kelvin is defined as being a unit of absolute temperature equal to 1/273.16 of the absolute temperature of the triple point of water (273.16 K at 611.2 Pa). This scale uses the absolute zero, −273.16°C. The boiling point of water according to this scale is 373 K. The Kelvin is the SI unit of temperature.

Relationship between heat and temperature

The interrelationship between heat and temperature is intrinsically associated with the change in state from solid to liquid to gas and there are several important concepts related to this.

The first concept is that of latent heat; this refers to the energy (or heat) required to change the state of a substance without changing its temperature. To understand this concept, see Figure 1. If a were, for example, a block of ice, as you added heat to the system the temperature of the ice would rise. However, at a certain point B, the temperature of the ice would remain constant as all the energy being given to the system is used to break the crystalline bonds of ice to produce water molecules in a less bound state thereby creating a liquid, i.e. water. Further energy given to the system causes a further rise in temperature until reaching 100°C. At this point, the temperature reaches a plateau as all the energy is being used to break the bonds between water molecules to form a gas, i.e. steam. It can be seen from the graph that much more energy is required to convert a liquid to a gas than a solid to a liquid (i.e. comparing length D to B).

Two terms therefore arise from these concepts.

(i) Latent heat of fusion (or crystallization): The energy given out or taken in when a substance changes state from solid to liquid or from liquid to solid with no temperature change in the system. This process is reversible, i.e. when converting from liquid to solid, energy is released from the system.

(ii) Latent heat of vaporization: This is the energy given out or taken in when a substance changes state from liquid to gas or from gas to liquid with no temperature change in the system. Similarly, this is a reversible process as noted above.

Also related to the above is the specific latent heat of vaporization or fusion. This refers to the energy required to change the temperature of a unit mass, usually a kilogram of a substance by 1°C at a specified temperature. The amount of energy required is higher at lower temperatures and lower at higher temperatures. A body at a higher temperature already has a lot of energy and will therefore require less to reach a latent heat point.

A special circumstance arises with gas systems. If a gas is compressed (work carried out upon it), it will usually lead to an increase in the energy (i.e. heat) of its molecules. If done slowly enough, the temperature rise expected with increased heat does not occur as the energy is lost to the surroundings; this is an isothermal change. If the gas is compressed suddenly, there is not enough time for the heat to be lost to the surroundings and the energy is held within the system and the temperature can rise suddenly. The converse is true, i.e. a gas allowed to expand rapidly will cool. As the decreased pressure leads to loss of energy of molecules with reduced heat, these are known as adiabatic changes. A clinical example of this concept is seen in the cryoprobe where rapid expansion of CO₂ leads to cooling.

Clinical application

These physical principles are important in that heat in patients, and subsequently their temperature, has a bearing on their anaesthetic management and their postoperative recovery. Several studies have shown that hypothermic patients (i.e. core temperature <36°C) have potentially severe physiological disturbances. A temperature of 36°C is the standard being used by the National Institute of Clinical Excellence guidance, below which is termed inadvertent...
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perioperative hypothermia. Patients undergoing anaesthesia have their physical and behavioural responses to cold abolished.

**Mechanisms of heat loss**

Loss of heat is from five main mechanisms: radiation, convection, conduction, evaporation, and respiration.

**Radiation (40%)**

Heat can also be transferred without the presence of a medium. This occurs by the process of radiation. Thermal radiation is a form of electromagnetic radiation similar to light. It travels in straight lines, can be reflected, and its intensity obeys the inverse square law. A silica prism, demonstrating that it has a longer wavelength than visible light, can refract it (it is therefore often known as infrared radiation). The amount of radiation emitted by a body depends on its temperature and the quality (e.g. colour) of its surface (Stefan–Boltzmann law). The wavelength of the brightest part of the emission spectrum decreases with increasing temperature.

**Conduction (5%)**

Conduction of heat occurs between two objects in direct contact where a temperature gradient exists between them. The formula for heat conduction is given by:

$$ Q = hA(Thot - Tcold) $$

where $A$ is the area of the body and $\Delta T$ the temperature difference between body and fluid. However, $h$ depends on many factors, e.g. shape and orientation of surface, density, viscosity, specific heat, and thermal conductivity of fluid, and whether fluid flow is laminar or turbulent. For a given body and fluid, Newton’s law of cooling applies, i.e. rate of heat loss is proportional to the temperature difference ($\Delta T$), provided $\Delta T$ is small and forced convection applies.

**Evaporation (15%)**

Evaporation refers to latent heat losses, i.e. when a liquid converts to a gas, it needs to gain energy to do so and this energy in the form of heat is taken from the patient.

**Respiration (10%)**

Respiration is a form of evaporative heat loss.

**Heat loss during anaesthesia**

Both general and regional anaesthesia have been shown to reduce core body temperatures with losses of 0.5–1°C within the first hour due to redistribution of heat from the core to the periphery, and a further loss of 0.3°C h$^{-1}$ thereafter. It should be noted that a 1000 ml bag of fluid at room temperature could reduce body temperature by 0.5°C. Volatile anaesthetic agents lower the thermoregulatory threshold so that the body’s thermoregulatory mechanisms are not triggered until lower temperatures. Metabolic production of heat is greatly depressed during anaesthesia.

There are three phases occurring during hypothermia.

(i) **Redistribution**: This occurs within the first hour or so and is due to movement of heat from core to periphery as a result of vasodilatation.

(ii) **Linear phase**: During this phase, heat loss exceeds heat production; most surgery does not extend beyond this phase. Losses are due to radiation, convection, conduction, evaporation, and respiratory losses.

(iii) **Plateau phase**: Once temperature falls below the thermoregulatory threshold, peripheral vasoconstriction increases to limit the heat loss from the core compartment. Patients with autonomic neuropathy or regional blocks do not exhibit this response.

Hypothermic patients have a reduced cardiac output and are prone to ventricular arrhythmias below 30°C. Blood viscosity increases and haematocrit will rise. This combined with a left shift of the haemoglobin–oxygen dissociation curve can cause ischaemic changes in myocardial tissue due to reduced oxygen delivery. However, global oxygen demand will fall along with carbon dioxide production. Other systems are affected resulting in confusion, reduced urine output, and increased blood glucose and potassium. Postoperative shivering can increase oxygen consumption 10-fold thereby exacerbating myocardial ischaemia. The cold patient is also at risk of coagulopathy. Wound infection rates can also be shown to be increased markedly in patients who are hypothermic after operation. Pharmacodynamics of drugs is also altered. The volatile agents have increased potency and therefore decreased MAC. Neuromuscular blocking agents will have longer effect due to reduced metabolism. Global fall in metabolic rates will reduce the rate of drug metabolism.
Temperature measurement

The above consequences mean that the measurement of temperature in the operative patient is important and steps to reduce heat losses are an important aspect of anaesthetic practice. A thermometer is an instrument that measures the temperature of a system in a quantitative way. The easiest way to do this is to find a substance that has a property that changes linearly with its temperature. Measurement of temperature can be divided into non-electrical and electrical techniques. Non-electrical techniques rely on the physical properties of substances.

Non-electrical techniques

The expansion of mercury in a linear manner led to the introduction of the mercury thermometer. Mercury-in-glass thermometers have a slow response time and are now considered neither safe nor convenient to use. Mercury freezes at −38.7°C and boils at 357°C, whereas alcohol freezes at −117°C and boils at 78.5°C. Therefore, alcohol and mercury are more suited to low and high reading thermometers, respectively.

Bimetallic strips, where two dissimilar metals with different coefficients of expansion, are bonded together and their relative movements cause bending of a coil attached to a pointer are found in theatre temperature gauges. Alongside these, may be found bourdon gauges where a hollow tube extends when the gas inside it expands and a pointer or sensor indicates temperature.

Electrical techniques

Electrical means of measuring temperature rely on four principal devices: the resistance thermometer, thermistor, thermocouple, and infrared tympanic thermometer.

Resistance thermometer

The basic principle of this technique is that a metal wire’s resistance to current increases linearly with temperature. The most commonly used metal is platinum and the wire is incorporated in a Wheatstone bridge circuit to give very accurate measurement of temperature. These are often seen in the flow sensors of ventilators. (The movement of gases cools the wire and allows measurement of flow.) A Wheatstone bridge is a very sensitive device used in many transducers.

Thermistor

The thermistor is a metal oxide semiconductor. As thermistors change temperature, there is an exponential decline in resistance. However, in commercial applications where a narrow range is required, the output is often linearized by the device. They are very accurate with 0.1 – 0.2°C increments possible. They are advantageous in that thermistors can be made very small and are durable, unless subjected to severe changes in temperature.

Thermocouple

Thermocouples are based on the fact that junctions of two different metals produce a small voltage or current change in response to temperature. This is commonly known as the Seebeck effect. The junctions in clinical temperature measurement are usually copper and constantan (copper with 40% nickel). This combination will produce a voltage change of 40 mV per °C. These devices are highly accurate and available in very small sizes.

Infrared tympanic thermometer

This is a device which measures radiant infrared (an application of the Boltzmann constant), commonly from the ear drum, which is detected by a thermopile (a collection of thermocouples). This signal is then converted within around 5 s into a temperature reading which is very accurate for core temperature.

Other methods

Other physical and electrical methods of measuring temperature are available (e.g. liquid crystal thermometer) but are not commonly used in anaesthetic practice.

Further reading


Please see multiple choice questions 22–24