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Core Temperature Measurement
Methods and Current Insights

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Abstract

Climatic injuries, including hypothermia, hyperthermia and heat stroke, are common in many sports activities. Body core temperature (T_c) measurement for the sportsperson can influence individual performance and may help to prevent injuries. Monitoring internal body T_c accurately requires invasive methods of measurement. The mercury thermometer, most commonly used to measure oral temperature (T_{oral}), has been almost exclusively the only instrument for measuring T_c since the 18th century. Rectal (T_{re}) and oesophageal temperatures (T_{oes}) have been the most preferred measurement sites employed in thermoregulatory investigations. However, these measurement sites (T_{re}, T_{oes}, T_{oral}), and the methods used to measure T_c at these sites, are not convenient. T_{oral} measurements are not always possible or accurate. T_{oes} is undesirable because of the difficulty of inserting the thermistor, irritation to nasal passages and general subject discomfort. T_{re} is not suitable under many circumstances as it is labour intensive and has a prolonged response time. However, T_{re} remains the most accurately available method for monitoring T_c in thermal illness that occurs during sports activities. In addition, T_{re} and T_{oes} require wire connections between the thermistor and the monitoring device. The purpose of this paper is to review the various existing methods of T_c measurements in order to focus on the breakthrough needed for a simple, noninvasive, universally used device for T_c measurement which is essential for preventing climatic injuries during sports events.

Complete and proper functioning of the body is dependent on maintaining a body core temperature (T_c) of between 36.5 to 38.5°C. Malfunctioning of the systems of the body occurs as the T_c increases or decreases from these values, the greater the variance, the greater the malfunction. T_c above 41.5°C or below 33.5°C causes a fast decline in the proper functioning of the body, which may result in injury and eventually death.[1] Two different mechanisms cause a rise in body T_c. The first is demonstrated by the malfunctioning of one or more of the internal systems of the body, accompanied by possible infection or contamination, resulting in fever. The second, of a totally different nature, is demonstrated by an upset of the delicate balance between the amount of heat absorbed from the environment, metabolic heat production, and the amount of heat emitted from the body, mainly by sweating. It should be noted that despite the differences in these two mechanisms and their different treatments, the result from both cases could be fatal.

Changes in the range of normal temperature have been known for years as a sign of illness.[2] Indeed, early treatment for infection and the fever resulting from it has been recorded in Deuteronomy 'The Lord shall smite thee with a consumption, with a fever, and with an inflammation . . . ' said God to Moses, threatening him to uphold the commandments.[3] High values of ambient temperature can influence the ability to regulate body temperature and cause a rise in body T_c. However, many diseases create a local infection, which is more difficult to document. A doctor from ancient times, Celsius, in 64 AD, described four characteristics of infection: fever (calour), rash (rubour), pain (dalour) and swelling (tumour). One hundred years later, Galen added a fifth characteristic – malfunction (functio lessa). These same cardinal symptoms guide medicine today and provide the basis for many clinical diagnoses. For example, in arthritis the criteria are emphasised – swelling of the joints, redness and fever become diagnostic tools for the extent of the illness. Ancient physicians were skilled in using their hands to estimate body temperature. The ability to measure temperature quantitatively was not known for a thousand years. Glassblowers from Florence in the 17th century created sophisticated instruments for measuring temperature. In some of these instruments they used a liquid containing beads of hollow glass which would float or sink depending on the temperature surrounding the instrument. This system was, of course, without merit or accuracy, and the measurement of the temperature was completely dependent on the location of the particles in the liquid and their density.

The first pioneer in the history of the thermometer was Galileo, who prepared a thermoscope from a glass tube with one end in liquid. In spite of the fact that the thermoscope was used as a simple instrument for measuring temperature, the tube was open to the air and the level of the liquid was therefore influenced by atmospheric pressure at the height above the ground where the thermoscope was placed. In 1702, Roemer understood and emphasised the importance of sealing the tube. In 1720, Fahrenheit suggested a scale to his thermometer, where the lowest point was 32 degrees (°F), determined by using salt with freezing water. The highest point, the point of boiling water, was 212 degrees (°F). The universal scale used today is the centigrade scale, which was suggested by Celsius in 1742. In fact, Celsius had determined the boiling point of water at 0 degrees and the freezing of ice at 100 degrees. However, in 1750 the Danish botanist Linnaeus inverted the scale so that the higher the heat, the greater the temperature.

Significant progress in the use of thermometers in medicine emerged from the scientific works of Professor Carl Wunderlich[4] of Leipzeig. His pioneering research in 1868, 'Fever in Disease', consisted of thousands of observations, including the first complete set of graphs representing different optimal temperatures for a wide range of diseases. He suggested the present design of the clinical thermometer, a narrow range instrument, usually ranging from 95 to 105°F, with a capillary kink in order to determine the type of material to be used in the thermometer at maximal temperature. He published around 40 reasons to prove the importance of measuring temperature. Wunderlich[4] was subjected to much criticism of his work, in particular from doctors whose manual clinical diagnoses were threatened. In time it was proven that this criticism was not justified, and he was able to continue his observations.

In 1877, Lehmann presented a method for measuring skin temperature (T_{sk}) using liquid crystal.[2] The method was based on changes in the colour of cholesteric esters in correlation with different body temperatures. The principle was presented by Lehmann, but was not used for over a century. At first, measurements were made by mixing black colours with crystals that were placed on the skin. By this method it was possible to observe the blocks of colour against the surface veins. As previously mentioned, any changes in colour correlated with changes in body temperature. This procedure was very inconvenient and limited in range. Removing the instrument with the correct temperature range was slow and uncomfortable for the patient. When the concept of microscopic encapsulation of chemicals was developed, more user-friendly instruments of this type were created. Improved contact areas were created as a result of using inflated airbags in order to increase contact with the skin. The surface of the sensor could, therefore, be spread on uneven and curved surfaces, with the blocks of colour representing the distribution of temperature. Colour changes occurred inside the airbag, which were seen through a clear picture window. The airbags were reusable, and a set of 6 to 8 ranges of temperature could be observed. This type of diagnostic system was reportedly used in pathological diagnoses for the breast and lower back, and suspicion of venous thrombosis. Nevertheless, this diagnostic system had its drawbacks, many of which were caused by contact with the skin, therefore presenting the T_{sk} rather than the T_c.

Surprisingly, the method we use for measuring T_c today has not been changed since the middle of the 18th century. Currently, the most popular instrument for measuring body T_c is the thermometer. The thermometer, as it is defined, relates to any instrument used for measuring temperature. The most popular thermometer is the mercury-based glass thermometer. However, because of limitations proposed over the past decade relating to the environment and the poisonous nature of mercury, its use in many countries has been declining in favour of the alcohol-based glass thermometer. In addition, digital and infra-red thermometers for the inner ear are becoming more popular. In spite of this, the mercury-based glass thermometer still remains the most popular medical instrument for measuring T_c.

The purpose of this paper is to review the different existing methods for T_c measurements in order to emphasise the need for a single, noninvasive, universally used device for T_c measurement. Such a device is essential for preventing climate-related injuries during sports events, and may be beneficial for athletes' performance.

1. The Thermometer

The requirements of the ideal thermometer are numerous.[5] Firstly, the accuracy level must be ±0.1°. In addition, the thermometer cannot be sensitive to outside influences such as changes in air temperature or irrelevant areas of the body such as limbs and skin. It must be stable from the point of accuracy and calibration. The size of the thermometer must be suitable for the area of use (e.g. mouth, oesophagus, rectum). An additional and important condition for its use is that the area where it is placed does not influence the accuracy of the thermometer.

Additional difficulties that may impair a true measurement include the sensor not being thermodynamically balanced with the measured medium, negligence or noncompliance in the method of measuring, (e.g. possible differences in the rectal measurement depending on the depth of insertion of the thermometer), local body heat fields and short measurement times that do not allow for reaching thermodynamic balance.[5]

2. Noninvasive Measurements

2.1 Oral

This method has the advantages of easy accessibility and the ability to change quickly with changes in body T_c. It is the most popular method for measuring body temperature and is used in most clinical experiments. However, since environmental influences might result with the head or face being cooler than the rest of the body, oral temperature (T_{oral}) registers lower than T_c. The method is problematic for small children and babies because of their behaviour. In adults it becomes problematic because of the possibility of error caused by cold or hot drinks being consumed, smoking before the measurement is taken or irregular breathing patterns. For athletes, rapid mouth breathing interferes with a correct measurement, and in cases of severe thermal illness, neurological compromise makes compliance difficult. In addition, there is the possibility of differences in temperature in different parts of the mouth cavity, where the preferred place is the sublingual pocket (i.e. under the tongue).

2.2 Axilla

Measuring fever at the axilla takes longer (necessary time for reaching equilibrium) in contrast to oral measurement. Studies found that measuring temperature in the axilla is less accurate compared with the rectum, mouth or tympanic membrane,[6] and that the measured temperature is generally much lower than T_c, particularly in athletes. Since this measurement can be inaccurate, it is not an advisable method to use in the clinic.

2.3 Tympanic Membrane

The tympanic membrane receives blood from the branches of the internal carotid artery that supply blood to the thermoregulatory centre in the hypothalamus of the brain. Therefore, the thermometer was developed to include this area. In addition, the ear canal is easily accessible for measuring temperature. However, many studies have demonstrated that this method of measurement is problematic, especially during physical effort in the heat, and can lead to errors in the measurements as a result of dirt, inaccurate placement and lack of skill of the measurer,[5-9] and thus does not provide an accurate reflection of T_c.

2.4 Body Surface

Measurement is taken by a thermistor attached to the skin. The measurement does not reflect the T_c temperature, but only the temperature of the skin. It is not reliable for measuring body T_c.

3. Invasive Measurements

3.1 Rectal

This location is considered the most practical and accurate for measuring body T_c. Generally, temperature readings here are higher than from other areas. In situations of shock, it is possible that the readings will be lower than actual core body temperature. The rectum is the most common site used in scientific research for heat exhaustion or stroke cases and diagnostic tests, especially in babies and small children. However, this measurement may have a prolonged response time compared with other techniques during rapid changes in T_c (e.g. oesophageal temperature).

3.2 Oesophagus

The oesophagus is preferred by many as the site to measure T_c [10] because of its deep body location close to the left ventricle, the aorta and to the blood flow to the hypothalamus. It is also preferred because of its rapid response. However, this site is undesirable in many settings because of the difficulty in inserting the thermistor, irritation to nasal passages, and general subject discomfort.[11] The measurement is considered less reliable than the pulmonary artery since the temperature is not the same for the length of the oesophagus and is also influenced by outside factors. This method is appropriate for research, but less so for clinical use.

3.3 Pulmonary Artery

This invasive measurement is done with the use of a catheter. The measurement is considered the most accurate since the artery brings blood directly from the core and its surroundings.[12]

3.4 Urinary Bladder

The reasoning behind measuring temperature in the bladder was the assumption that there was a link between the temperature of the urine and the temperature of the body. However, since this assumption proved inaccurate and was dependent on the rate of urination, the bladder became an unpopular choice.

4. Methods of Measurement

Digital electronic thermometers are used for measuring body T_c orally, or in the axilla. Popularity of digital electronic thermometers grew considerably when many countries put a ban on the use of mercury thermometers. The principle is based on a thermistor probe or thermocouple sensor that produces electronic signals that change with differences in temperature. The thermistors are constructed from heavy metals where the resistance of the metals decreases as the temperature rises and increases as the temperature decreases.[5] The degree of resistance is converted to temperature values. The base of the thermistor consists of metal alloys actually used as semiconductors. The alloy changes with the energetic state of the electrons so that only a small amount of thermal energy is needed to release some of the electrons and allow them to pass through a solid lattice in response to a given voltage.

Heat energy, even as a result of a small rise in temperature, is enough to release electrons, and in this way to increase conduction and reduce resistance. Because the number of available electrons increases exponentially with the temperature, the resistance decreases exponentially. According to the law of Ohm, the voltage (V) equals the product of the resistance (R) and the current (I) and is expressed as $V = I \bullet R$.

Knowing the constant current (I = constant) and merging the voltage enables us to calculate the resistance, which is affected by the temperature, thus making it possible to calculate the temperature. The thermocouple sensor[7,8] consists of two separate probes known as two point junctions. When the two junctions are at different temperatures, they produce a voltage proportional to the difference in temperatures: one of the junctions remains at a constant temperature whereby the second junction measures the body temperature through the wall of the probe. The difference in the voltage between the two points is converted to temperature.

The differences in the voltage are explained by the fact that in electronic conductors some of the electrons are free to move (as in gas). The difference in temperatures between the free points of a metal conductor will be expressed in higher energies at the hotter end, and diffusion towards the colder end. The charge, which is created from thermal diffusion of electrons, produces potential differences between the cold and hot ends. This voltage is proportional to the temperature differences.

Both types of digital sensors (thermistor and thermocouple sensors) have been found to be accurate, stable, and have a short response time to a change in temperature. They are also smaller compared with other probes. In both types of probes, two methods exist to display the temperature. Depending on the method of measurement, the time of measurement lasts from a number of seconds to a number of minutes according to the mode of operation. One method of operation is known as the steady-state mode, where the temperature value is displayed after the sensor has reached equilibrium. This measurement lasts a number of minutes. In the other mode, the predictive mode, the initial rate of temperature range is measured and in just a few seconds, a predicted value is displayed (in a true/temp curve). The second method is of course faster, but since it is based on prediction, its reliability is lower. In addition, in the prediction mode, the thermometer must be accurately placed at the measurement site and turned on with precision, since the calculation and prediction of the temperature begins with the primary contact with the body tissue.

4.1 Temperature Measurement by Infra-Red Waves

The most popular noninvasive method for measuring T_c is in the ear canal. With this method, which uses infra-red waves, it is possible to measure body temperature quickly and noninvasively by placing the probe inside the ear canal. This method is more convenient compared with other methods and is less influenced by thermal and environmental artifacts. There are two main locations for measuring temperature in the ear: the tympanic membrane and the ear canal. The tympanic membrane gets its blood supply from a section of the aorta that supplies blood to the thermoregulatory centre in the brain. Therefore, it is an important site for measuring body T_c. In addition, access to the ear canal is very convenient.

In the first method, a direct temperature measurement is obtained from the tympanic membrane and the surrounding tissues. The disadvantage of this method is the need for otoscopic manoeuvres required for accurate and true measurements. In the second method, the temperature in the ear canal is measured in order to determine T_c through usage of known algorithms. This method doesn't require any special manoeuvres and is simple and very convenient. However, since the temperature in the ear canal is lower than in the tympanic membrane because of heat emitted from the ear canal and its surroundings, a correction factor is added to reflect T_c. When the otoscope probe is placed in the patient's ear, the wave-guide, consisting of a cylinder with a highly polished interior surface, collects infra-red radiation from the direction in which it is aimed. Only the radiation emitted from tissue within its field of view strikes the transducer. This field of view depends on two factors: the viewing angle and the distance from the target surface. A typical reflective wave-guide with no refracting lens has a conical field of view of 45° around its axis. The radius of the field of view for such a wave-guide is equal to its distance from the target. Because infra-red thermometers determine the temperature of infra-red emission from a source rather than absorbing heat from the object and coming to thermal equilibrium with it, they typically display the temperature in less than 5 seconds.

In many studies, difficulties in achieving a true tympanic temperature have been recorded.[6-8] The wide viewing angle of these thermometers results in a field of view that is too large to measure temperature in the tympanic membrane alone. In fact, the probes from these devices will not always 'see' the membrane because of poor user technique or the anatomy of a particular ear canal. Research has shown that despite having the thermometer placed in the correct place, the temperature readings recorded from the tympanic membrane included averaging with the temperatures of the ear canal wall. As a result, generally, temperature readings were lower than the actual temperature of the tympanic membrane and T_c.[6-8] In order to compensate for these lower readings, there is an offset system included in the instrument. The system is calibrated from former information and shows computerised and updated temperature from other locations (e.g. oral, rectal, axilla). Other technology used to overcome the difficulties has involved scanning, where a series of measurements from the tympanic membrane are taken when the probe is in the ear. The maximal temperature that is measured is considered the temperature of the tympanic membrane.

The scientific literature has reported on the system of measuring temperature in the ear and the problems with the accuracy of this measurement.[5-9] For example, when the technique of the measurement by the medical staff is inconsistent, inaccurate measurements are recorded. The lack of standardisation stemming from the use of different types of thermometers causes a wide range of readings. Cerumen (earwax) build-up on the thermometer speculum causes an untrue measurement when a disposable probe is not used or the top is broken from improper use of the instrument. Additional factors that can cause a false result in the accuracy of the measurement include a temperature gradient between the interior and exterior parts of the ear canal, inadequate depth of insertion of the thermometer inside the ear canal, and external conditions such as environmental temperature.

In summary, following the complexity of the system and the many sources that can affect the measurement as a result of environmental factors and the anatomy of the ear, measuring temperature in the ear is not reliable for recording the presence of fever or the lack of it. In 1996, Hooker and Houston[9] summarised a study that dealt with comparing temperature measurement in the ear as opposed to the oral cavity in the emergency room:

Tympanic thermometers are convenient and well accepted and do not require contact with mucous membranes. However, most authors have shown that the tympanic thermometer is very insensitive to fever and current research indicates that its sensitivity is not as good as that of oral electronic thermometers in the detection of fever. On the basis of other reports and our own experience, we caution against reliance on these thermometers in screening for fever in emergency rooms.

5. Conclusion

In 1987, Brengelmann[12] concluded in his review that T_{oes} is the measurement of choice for T_c, and if it cannot be obtained, and if the head is not subject to thermal influences, then body T_{oral} should be the choice for T_c. However, the last century, and in particular the past two decades, signified a leap in the development and use of modern technology in the medical world. The invention of computerised tomography, magnetic resonance imaging and development of the polymerase chain reaction, created a tremendous upheaval in medical diagnostics.

However, during this amazing period of development and advancement in the medical world, with all its new methods and modern diagnostic instruments, we 'forgot' to develop a better method for measuring body temperature.

In spite of the development of the methods presented above, not one noninvasive method of measuring body T_c has been adopted. Measuring temperature with a mercury thermometer under the tongue still remains the most popular and accepted method in the world. In many instances, where it is not possible to measure temperature orally or when measurement of body T_c is needed, the measurement takes place in the rectum. Nonetheless, in an era in which interactions between new advancing technologies and medical science exist, the will to develop a simple, friendly, noninvasive and comfortable device especially for the benefit of athletes and medical staff appears more realistic than ever. It is surprising that the instrument has not yet been developed. For now, rectal temperature is considered the gold standard for temperature measurement for thermal illness in athletes.

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