Biomedical Sensors: Temperature Sensor Technology

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"...the clinical thermometer ranks in importance with the stethoscope. A doctor without his thermometer is like a sailor without his compass"
Family Physician, 1882

Celsius thermometer (attached to a barometer) made by J.G. Hasselström, Stockholm, late 18th century

1. Introduction

Human body temperature is of vital importance to the well being of the person and therefore it is routinely monitored to indicate the state of the person's health. Despite the fact that temperature measurement in humans seems so simple, a wide variety of devices are available to record a temperature from skin, oral or rectal mucosa or the tympanic membrane. The choice of clinical thermometers for health professionals and parents has never been so complicated.

This chapter makes an attempt to provide an overview of temperature sensing technologies in medicine. The introductory sections give a brief and general description of temperature and its effect on the human body. A synoptic historical review on the evolution of the thermometer including the clinical thermometer is given in section 3. Section 4 describes the main sensors/transducers used in the development of clinical thermometers, such as thermocouples, thermistors, Resistance Temperature Detectors (RTDs), semiconductor temperature sensors, liquid crystal temperature sensors, and infra-red radiation sensors. These thermometers have been designed and developed for application in various parts of the body such as the rectum, the mouth, the axilla, the esophagus, the bladder, the ear, the temporal artery, the skin, and this will be the content of section 5. It will be almost impossible for this chapter to cover every possible application and evaluation study relating to different thermometers; however an effort is made in section 6 to provide an integrative review of studies comparing selected invasive and non-invasive temperature measurement methods.

2. Temperature

In the literature one can find many definitions of temperature. Here are some samples:

1. "Temperature is the degree of 'hotness' of a body: more precisely it is the potential for heat transfer. In our everyday lives, we are aware of different temperatures through the sensation of touch, but how hot or cold something feels is subjective. We can say that the kettle is hotter than the ice-cream, but not by how much. Measurement, on the other hand, must be objective and a thermometer is used." ***National Physical Laboratory,*** ***Teddington, Middlesex, UK***

2. "Temperature can be defined in macroscopic terms, using concepts of thermodynamics, as an intrinsic property of matter that quantifies the ability of one body to transfer thermal energy (heat) to another body." Temperature can also be defined on a microscopic scale as proportional to the random kinetic energy of an assemblage of molecules or atoms." ***"Industrial Temperature Measurement" T.W Kerlin and R.L. Shepard, The Instrument Society of America, Research Triangle Park, NC, 1982 (ISBN 0-87664-622-4)***

3. **"**Temperature is a measure of how fast the atoms and molecules of a substance are moving. In a qualitative manner, we can describe the temperature of an object as that which determines the sensation of warmth or coldness felt from contact with it. It is easy to demonstrate that when two objects of the same material are in thermal contact, the object with the higher temperature cools while the cooler object becomes warmer until a point is reached after which no more change occurs, and to our senses, they feel the same. When the thermal changes have stopped, we say that the two objects or systems are in *thermal equilibrium*. We can then define the temperature of the system by saying that the temperature is that quantity which is the same for both systems when they are in thermal equilibrium. If we experiment further with more than two systems, we find that many systems can be brought into thermal equilibrium with each other; thermal equilibrium does not depend on the kind of object used. Put more precisely, *if two systems are separately in thermal equilibrium with a third, then they must also be in thermal equilibrium with each other*, and they all have the same temperature regardless of the kind of systems they are. The statement in italics, called the *zeroth law of thermodynamics* may be restated as follows:

If three or more systems are in thermal contact with each other and all in equilibrium together, then any two taken separately are in equilibrium with one another. **(Quote from T. J. Quinn's monograph *Temperature*)**

Now one of the three systems could be an instrument calibrated to measure the temperature - i.e. a thermometer. When a calibrated thermometer is put in thermal contact with a system and reaches thermal equilibrium, we then have a quantitative measure of the temperature of the system. For example, a mercury-in-glass clinical thermometer is put under the tongue of a patient and allowed to reach thermal equilibrium in the patient's mouth - we then see by how much the silvery mercury has expanded in the stem and read the scale of the thermometer to find the patient's temperature.
Quinn, T. J. Temperature 1990 Academic Press ISBN 0-12-569681-7

2.1 Body temperature

The human body regulates temperature by keeping a tight balance between heat production and heat loss. For example when the body is too hot, the blood vessels in the skin expand (dilate) to carry the excess heat to the skin's surface. When the body is too cold, the blood vessels narrow (contract or vasoconstrict) so that blood flow to the skin is reduced to conserve body heat. In both cases the body employs various mechanisms to regulate the body temperature (i.e. the body sweats, and as the sweat evaporates helps to cool the body). Also, shivering causes the muscles to contract involuntary which helps to generate more heat. Under normal conditions, these mechanisms keep the body temperature within a narrow, safe range.

Humans regulate heat generation and preservation to maintain internal body temperature or core temperature. Temperature regulation is controlled by the hypothalamus (in the brain), which is often called the body’s thermostat. Normal core temperature varies between 36.5 and 37.5 °Celsius (°C), which is 97.7 to 99.5 °Fahrenheit (°F). Fever occurs (in adults) when the oral temperature is above 100 °F(37.8 °C) or a rectal or ear temperature is above 101 °F(38.3 °C). For children fever occurs when rectal temperature is 100.4 °F (38 °C) or higher (Mackowiak et al, 1992; Herzog et al, 1993).

An abnormally low (hypothermia) or high (hyperthermia) body temperature can be serious and even life-threatening. Low body temperature may occur from cold exposure, shock, alcohol or drug use, or certain metabolic disorders, such as diabetes or hypothyroidism. A low body temperature may also be present with an infection, particularly in newborns, older adults, or people who are frail. At high body temperatures, heatstroke occurs and the body fails to regulate its own temperature (body temperature continues to rise). Symptoms of heatstroke include mental changes (such as confusion, delirium, or unconsciousness) and skin that is red, hot, and dry, even under the armpits (Marieb, 1992).

Body temperature can be measured in many locations of the body such as mouth, ear, armpit, rectum, forehead, bladder, skin, esophagus, etc. Such temperature measuring techniques will be discussed in more detail in the following sections.

3. What is a Thermometer?

The word thermometer is derived from two smaller word fragments: *thermo* from the Greek for heat and *meter* from Greek, meaning to measure. Thermometers measure temperature, and this is possible by using materials that change in some way when they are either heated or cooled. For example in a mercury or alcohol thermometer the liquid expands as it is heated and contracts when it is cooled, therefore the length of the liquid column is longer or shorter depending on the temperature (http://en.wikipedia.org/wiki/Thermometer).

A thermometer is a device that provides measures of the temperature of a system in a quantitative manner and the easiest way to do this is to find a material having a property that change in a regular way with its temperature. The most direct 'regular' way is a linear one:

$$t(x) = ax + b$$

where t is the temperature of the substance and changes as the property x of the substance changes. The constants a and b depend on the substance used and may be evaluated by specifying two temperature points on the scale, such as 32° for the freezing point of water and 212° for its boiling point.

For example, the element mercury is liquid in the temperature range of -38.9°C to 356.7°C (the Celsius °C scale will be discussed later). As a liquid, mercury expands as it gets warmer its expansion is linear and can be accurately calibrated.

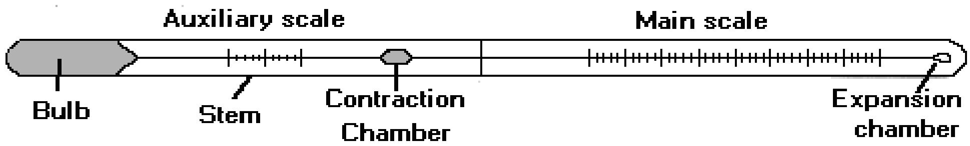


Figure 3.1: Mercury-in-glass thermometer

The mercury-in-glass thermometer illustrated in Figure 3.1 contains a bulb filled with mercury that is allowed to expand into a capillary. Its expansion is calibrated on the glass scale. Modern thermometers are calibrated in standard temperature units such as Fahrenheit or Celsius.

3.1 The development of thermometers and temperature scales

In this section a general historical review of the development of the thermometer will be given with special references to the evolution of the clinical thermometer. *The historical highlights in the development of thermometers and their scales given in this section are mostly based on "Temperature" by TJ Quinn and "Heat" by JM Cork and a recent historical review of clinical thermometers by JMS Pearce.*

Of the many tools and instruments regarded as essential to the clinical examination, none has had such widespread application as the clinical thermometer. In the time of Hippocrates, only the hand was used to detect the heat or cold of the human body, although fever and chills were known as signs of morbid processes. In Alexandrine medicine, the pulse was observed as an index of disease, superseding the crude assessment of temperature. In the middle Ages, the four humors were assigned the qualities of hot, cold, dry and moist, and thus fever again acquired importance (Pearce, 2002).

The first attempt at standardization of temperature scales took place approximately in 170 AD when Galen in his medical reports, suggested a standard "neutral" temperature made up of equal quantities of boiling water and ice. Four degrees of heat and four degrees of cold were on either side of this temperature (http://www.eo.ucar.edu/skymath/tmp2.html).

Some of the earliest devices that were used to measure temperature were called thermoscopes. In 1592 Galileo developed a rudimentary temperature-measuring instrument that had no scale and therefore no numerical readings. This temperature measuring device comprised a glass bulb having a long tube extending downward into a container of colored water (some say Galileo in 1610 is supposed to have used wine (see Figure 3.2)). Some of the air in the bulb was expelled before placing it in the liquid, causing the liquid to rise into the tube. As the remaining air in the bulb was heated or cooled, the level of the liquid in the tube would vary reflecting the change in the air temperature. An engraved scale on the tube allowed for a quantitative measure of the fluctuations. The air in the bulb is referred to as the *thermometric medium*, i.e. the medium whose property changes with temperature (Cork, 1942; Quinn, 1990).

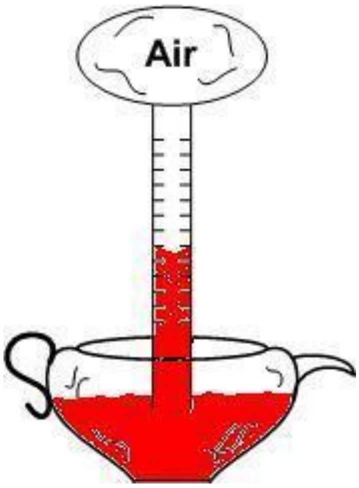


Figure 3.2: Wine Florentine thermoscope

A large step forward was achieved by Santorio who invented a mouth thermometer. Santorio (1561–1636) was an Italian physiologist, and a professor at Padua. He made quantitative experiments in temperature, and made other physiological measurements such as respiration, and weight. He produced several designs, but all were cumbersome and required a long time to measure the oral temperature. In 1641, the first sealed thermometer that used liquid rather than air as the thermometric medium was developed for Ferdinand II, Grand Duke of Tuscany. This thermometer used a sealed alcohol–in-glass device, with 50 "degree" marks on its stem but no "fixed point" was used to zero the scale. These were referred to as "spirit" thermometers. In 1664, Robert Hook, Curator of the Royal Society, used a red dye in the alcohol. His scale, for which every degree represented an equal increment of volume equivalent to about 1/500 part of the volume of the thermometer liquid, needed only one fixed point. He selected the freezing point of water. Hook showed that a standard scale could be established for thermometers of a variety of sizes. Hook's original thermometer became known as the standard of Gresham College and was used by the Royal Society until 1709 (http://www.brannan.co.uk/thermometers/invention.html).

In 1665, Christiaan Huygens added a scale extending from the freezing point to the boiling point of water, the original centigrade system. In 1702, the astronomer Ole Roemer of Copenhagen based his scale upon two fixed points: snow (or crushed ice) and the boiling point of water, and he recorded the daily temperatures at Copenhagen in 1708 - 1709 with this thermometer. In 1709 the alcohol thermometer was invented by Daniel Gabriel Fahrenheit (1686-1736). Fahrenheit based his new scale on a mixture of ice and ammonium chloride as the lower point. Also, Fahrenheit in 1724 used mercury as the thermometric liquid (he found mercury more useful than water), as it expanded and contracted more rapidly. Mercury's thermal expansion is large and fairly uniform, it does not adhere to the glass, and it remains a liquid over a wide range of temperatures. Also, its silvery appearance makes it easy to read. On this scale, Fahrenheit measured the boiling point of water to be 212. Later he adjusted the freezing point of water to 32 so that the interval between the boiling and freezing points of water could be represented by the more rational number 180. Temperatures measured on this scale are designated as degrees Fahrenheit (°F) (Pearce, 2002).

The thermometer was not generally used for medical applications until Hermann Boerhaave (1668–1738), with his students Gerard L.B. Van Swieten (1700–72), Anton De Haen (1704–76), and separately George Martine, started to use the thermometer at the bedside. De Haen studied diurnal changes in normal subjects and observed changes in temperature with shivering or fever. He also observed the acceleration of the pulse when the temperature was raised and therefore he found that temperature was a valuable indication of the progress of an illness, although his colleagues were not impressed, and therefore the thermometer was not widely used (Pearce, 2002).

However, the technological developments of the thermometer had continued and in 1742, the Swedish astronomer Anders Celsius (1701-1744) reintroduced the centigrade scale into practice. Centigrade means "consisting of or divided into 100 degrees". The Celsius scale has 100 degrees between the freezing point (0 C) and boiling point (100 C) of pure water at sea level air pressure. The term "Celsius" was adopted in 1948 by an international conference on weights and measures. Also, in 1745, Carolus Linnaeus of Upsula, Sweden, described a scale in which the freezing point of water was zero, and the boiling point 100, making it a *centigrade* (one hundred steps) scale (http://www.eo.ucar.edu/skymath/tmp2.html).

The Celsius scale is defined by the following two items that will be discussed later in this section:

(i) The triple point of water is defined to be 0.01°C.
(ii) A degree Celsius equals the same temperature change as a degree on the ideal-gas scale.

When using the Celsius scale the boiling point of water at standard atmospheric pressure is 99.975°C in contrast to the 100 degrees defined by the Centigrade scale. To convert from Celsius to Fahrenheit: multiply degrees Celsius by 1.8 and add 32.

°F = 1.8 x °C + 32
K = °C + 273.

J.A.C. Charles (a French physician) in 1780 demonstrated that for the same increase in temperature, all gases exhibited the same increase in volume. Because the expansion coefficient of gases is almost the same, it is possible to create a temperature scale based on a single fixed point rather than the two fixed- point scales, such as the Fahrenheit and Celsius scales. This brings us back to a thermometer that uses a gas as the thermometric medium (http://www.eo.ucar.edu/skymath/tmp2.html).

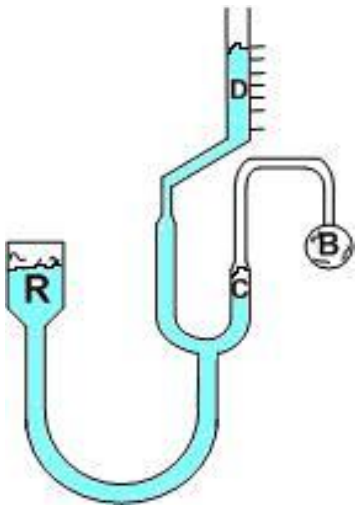


Figure 3.3: Constant volume gas thermometer

In a constant volume gas thermometer a large bulb B of gas, hydrogen for example, under a set pressure connects with a mercury-filled "manometer" by means of a tube of very small volume. The level of mercury at C may be adjusted by raising or lowering the mercury reservoir R. The pressure of the hydrogen gas, which is the "x" variable in the linear relation with temperature, is the difference between the levels D and C plus the pressure above D (Cork, 1942; Quinn, 1990).

Despite improvements in the developments of the thermometer, its use in the medical setting remained largely neglected until the late 19th century when in 1868, Carl Wunderlich published temperature recordings from over 1 million readings in over 25000 patients made with a foot-long thermometer used in the axilla. He established a range of normal temperatures from 36.3 to 37.5 °C. Temperatures outside this range suggested disease. Aitkin in 1852 made a mercury instrument with a narrower tube sited above a bulb reservoir. This ensured that the mercury did not drop back after the reading had been taken. The size of this thermometer (used by Carl Wunderlich and Aitkin) was a major disadvantage. It was only until Thomas Clifford Allbutt (1836–1925) designed in 1866 a conveniently portable 6-inch clinical thermometer, able to record a temperature in 5 min. This new thermometer replaced a foot-long model, which required 20 minutes to determine a patient's temperature. The measurement of temperature soon became an inescapable routine (Pearce, 2002).

In a parallel universe, William Thomson, Lord Kelvin (1824-1907), among his other achievements, took the whole process one step further with his invention of the Kelvin Scale in 1848. The Kelvin scale measures the ultimate extremes of hot and cold. Kelvin developed the idea of absolute temperature, what is called the "Second Law of Thermodynamics", and developed the dynamical theory of heat. In 1887 P. Chappuis conducted extensive studies of gas thermometers with constant pressure or with constant volume using hydrogen, nitrogen, and carbon dioxide as the thermometric medium. Based on his results, the *Comité International des Poids et Mesures* (International Committee of Weights and Measures) adopted the constant-volume hydrogen scale based on fixed points at the ice point (0°C) and the steam point (100°C) as the practical scale for international meteorology. Experiments with gas thermometers have shown that there is very little difference in the temperature scale for different gases. Thus, it is possible to set up a temperature scale that is independent of the thermometric medium if it is a gas at low pressure. In this case, all gases behave like an "Ideal Gas" and have a very simple relation between their pressure (p), volume (V), and temperature (T):

$$pV = (\text{constant})T$$

This temperature is called the *thermodynamic temperature* and is now accepted as the fundamental measure of temperature. There is a naturally-defined zero on this scale - it is the point at which the pressure of an ideal gas is zero, making the temperature also zero. With this as one point on the scale, only one other fixed point need be defined. In 1933, the International Committee of Weights and Measures adopted this fixed point as the triple point of water (the temperature at which water, ice, and water vapor coexist in equilibrium); its value is set as 273.16. The unit of temperature on this scale is called the kelvin, after Lord Kelvin, and its symbol is K (no degree symbol used).

To convert from Celsius to Kelvin, add 273.

$$K = °C + 273.$$

In 1871 Sir William Siemens, proposed a thermometer whose thermometric medium is a metallic conductor whose resistance changes with temperature. The element platinum does not oxidize at high temperatures and has a relatively uniform change in resistance with temperature over a large range. The *Platinum Resistance Thermometer* is now widely used as a thermoelectric thermometer and covers the temperature range from about -260°C to 1235°C.

Back in to the clinical thermometer, during World War II a pioneering biodynamicist and flight surgeon with the Luftwaffe, Theodore Hannes Benzinger, invented the ear thermometer and much later in 1984, David Phillips invented the infra-red ear thermometer. Dr. Jacob Fraden, CEO of Advanced Monitors Corporation, invented the world's best-selling ear thermometer, the Thermoscan® Human Ear Thermometer.

Many different kinds of temperature sensors are currently used by themselves or installed in different type of probes (surface, indwelling), catheters or needles making contact with or introduced to the object site of the body. A description of such sensors will be the subject of the next section.

4. Temperature Sensors/Transducers and thermometers

Both the words '*sensor*' and '*transducer*' are used in the description of measurement systems. The word 'sensor' is most popular in the United States of America (USA) whereas the word 'transducer' has been more frequently used in Europe. A dictionary definition of '*sensor*' is a device that detects a change in a physical stimulus and turns it into a signal which can be measured or recorded. A corresponding definition of '*transducer*' is a device that transfers power from one system to another in the same or in the different form. A sensible distinction is to use '*sensor*' for the sensing element itself and '*transducer*' for the sensing element plus any associated circuitry. All transducers would thus contain a sensor and most (though not all) sensors would also be transducers. In the context of this chapter both words will be used interchangeably (Cromwell et al, 1980).

The past decade has seen the introduction of many new clinical thermometers to replace the traditional mercury-in-glass thermometer. These include contact or non contact temperature sensors. Some of the most common temperature sensors used in the development of the majority of clinical thermometers such as thermocouples, thermistors, Resistance Temperature Detectors (RTDs), semiconductor temperature sensors, liquid crystal temperature sensors, and infra-red radiation sensors will be discussed in this section (Michalski et al, 1991; Crawford et al, 2006).

4.1 Contact temperature sensors

Contact temperature sensors measure their own temperature. One infers the temperature of the object to which the sensor is in contact by assuming or knowing that the two are in thermal equilibrium, that is, there is no heat flow between them.

4.1.1 Thermocouples

Thermocouples are one of the most popular contact temperature sensors. They can measure a wide range of temperatures, are interchangeable and have standard connectors. Around 1821 the German-Estonian physicist Thomas Johann Seebeck discovered that the junction between two metals generates a voltage which is a function of temperature (http://www.picotech.com/applications/thermocouple.html). Such an effect is known as the thermoelectric or Seebeck effect (Togawa et al, 1997; Michalski et al, 1991). Although, almost any two types of metals can be used to make a thermocouple, a number of standard types are used because they give predictable output voltages and tolerate large temperature gradients. A photograph and a diagrammatic representation of one of the most popular thermocouples, the K type thermocouple, are shown in Figure 4.1. Standard tables show the voltage produced by thermocouples at any given temperature, so for example in Figure 4.1, the K type thermocouple at 300°C will produce 12.2 mV.

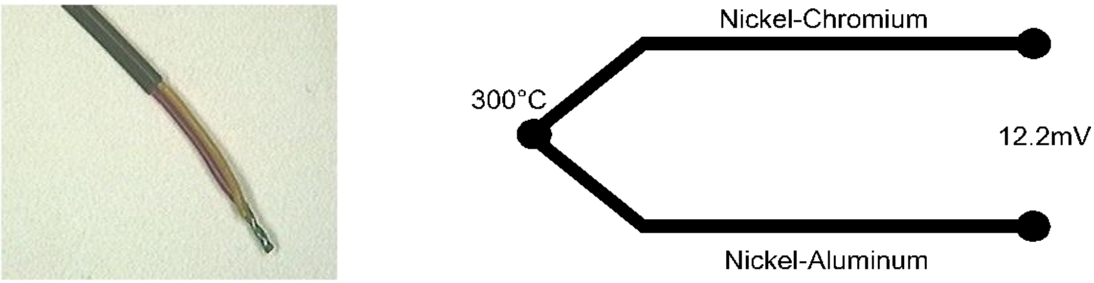


Figure 4.1: K-type thermocouple

It is not possible to simply connect up a voltmeter to the thermocouple as shown in Figure 4.1 to measure this voltage, because the connection of the voltmeter leads will make a second, undesired thermocouple junction. To make accurate measurements, this must be compensated for by using a technique known as cold junction compensation (CJC). Connecting a voltmeter to a thermocouple makes several additional thermocouple junctions (leads connecting to the thermocouple, leads to the meter, inside the meter etc). The law of intermediate metals states that a third metal, inserted between the two dissimilar metals of a thermocouple junction will have no effect provided that the two junctions are at the same temperature. This law is important in the construction of thermocouple junctions. Thermocouple junctions are made by welding the two metals and not soldering them together as this ensures that the performance is not limited by the melting point of solder. Thermocouple standard tables allow for this second cold thermocouple junction on the assumption that it is kept at exactly 0°C. This is done with a constructed ice bath, thus the term 'cold' junction compensation. Maintaining an ice bath is not practical for most measurement applications, so instead the actual temperature at the point of connection of the thermocouple wires to the measuring instrument is recorded (Togawa et al, 1997).

Typically cold junction temperature is sensed by a precision thermistor or a semiconductor temperature sensor which is in good thermal contact with the input connectors of the measuring instrument. This second temperature reading, along with the reading from the thermocouple itself is used by the measuring instrument to calculate the true temperature at the thermocouple tip. Understanding of CJC is important as any error in the measurement of cold junction temperature will lead to the same error in the measured temperature from the thermocouple tip.

As well as dealing with CJC, the measuring instrument must also allow for the fact that the thermocouple output is non-linear. The relationship between temperature and output voltage is a complex polynomial equation (5^{th} to 9^{th} order depending on thermocouple type). The integrated circuit amplifier in Figure 4.2 has a compensation circuit for the reference temperature assembled in the same package (Analog Devices AD594/595). The AD594/5 is a complete instrumentation amplifier and thermocouple cold junction compensator on a monolithic chip. It combines an ice-point reference with a pre-calibrated amplifier to produce a high level, low impedance, 10 mV/°C linear voltage output directly from the thermocouple signal. The nominal absolute accuracy at 25°C is ± 1°C, and the effect of package temperature is less than ± 0.025°C per 1°C. Thus, a stability of ± 0.25°C will be attained by limiting the package temperature in a range of ± 10°C (Togawa et al, 1997).

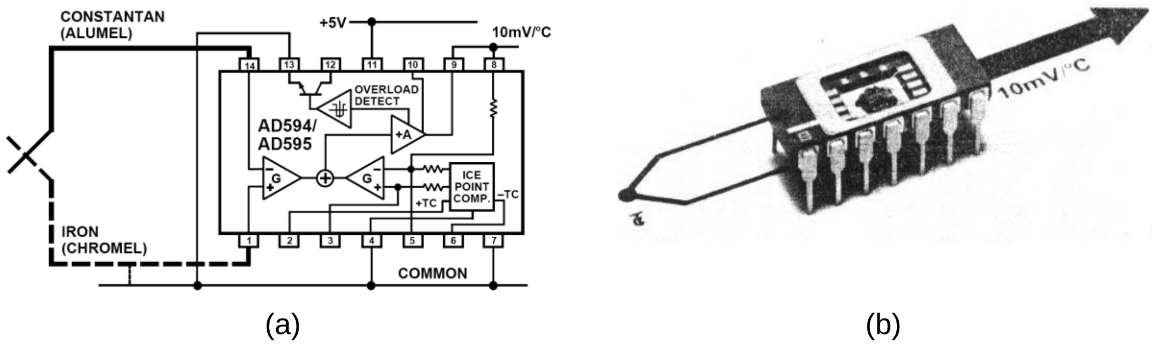


Figure 4.2: (a) Thermocouple amplifier having a compensation circuit for the reference temperature; (b) diagrammatic functionality of the Integrated chip (IC) (Analog Devices AD594/595)

Thermocouples are available either as bare wire 'bead' thermocouples (Figure 4.1) which offer low cost and fast response times, or they are built into probes. A wide variety of thermocouple probes are available, such a needle, insulated, catheter, capsule, direct immersion, surface mount, micro-thermocouples, suitable for different measuring applications (industrial, scientific, food temperature, clinical thermometry, etc). Each type of thermocouple is made using different techniques. Details of such techniques can be found in the literature. When selecting probes care must be taken to ensure they have the correct type of connector. The two common types of connector are 'standard' with round pins and 'miniature' with flat pins.

Thermocouple Types

As mentioned above, when selecting a thermocouple consideration should be given to the thermocouple type, insulation and probe construction. Such considerations will have an effect on the measurable temperature range, accuracy and reliability of the readings. Below is a guide to thermocouple types (http://www.picotech.com/applications/thermocouple.html).

Type K (Chromel (Ni-Cr alloy) / Alumel (Ni-Al alloy)): The "general purpose" thermocouple. It is low cost and, owing to its popularity, it is available in a wide variety of probes. They are available in the −200 °C to +1200 °C range. Sensitivity is approximately 41 µV/°C.
Type E (Chromel / Constantan (Cu-Ni alloy)): Has a high output (68 µV/°C) which makes it well suited to low temperature (cryogenic) use.
Type J (Iron / Constantan): Limited range (−40 to +750 °C) makes type J less popular than type K. The main application is with old equipment that cannot accept modern thermocouples. Type J's have a sensitivity of ~52 µV/°C.
Type N (Nicrosil (Ni-Cr-Si alloy) / Nisil (Ni-Si alloy)): High stability and resistance to high temperature oxidation makes type N suitable for high temperature measurements without the cost of platinum (B, R, S) types. They can withstand temperatures above 1200 °C. Sensitivity is about 39 µV/°C at 900°C.

Thermocouple types B, R, and S are all noble metal thermocouples and exhibit similar characteristics. They are the most stable of all thermocouples, but due to their low sensitivity (approximately 10 µV/°C) they are usually only used for high temperature measurement (> 300 °C).

Considerations for using thermocouples

Most measurement problems and errors with thermocouples are due to a lack of understanding of how thermocouples work. Some of the more common problems to be aware of are:

Connection problems. Many measurement errors are caused by unintentional thermocouple junctions. In the event that longer length thermocouple leads are needed then the correct type of thermocouple extension wire should be used.

Lead Resistance. Thermocouples are made from thin wire and this can cause the thermocouple to have a high resistance which can make it sensitive to noise and can also cause errors due to the input impedance of the measuring instrument. It is recommended to keep the thermocouple leads short and then using thermocouple extension wire (which is much thicker, so has a lower resistance.

Decalibration is the process of unintentionally altering the makeup of thermocouple wire. The usual cause is the diffusion of atmospheric particles into the metal at the extremes of operating temperature. If operating at high temperatures, check the specifications of the probe insulation.

Noise. The output from a thermocouple is a small signal, so it is prone to electrical interference pick up. Most measuring instruments reject any common mode interference so interference can be minimized by twisting the cable together to help ensure both wires pick up the same interference signal.

Common Mode Voltage. Although the thermocouple signal is very small, much larger voltages often exist at the input to the measuring instrument. These voltages can be caused either by inductive pick up or by 'earthed' junctions. Common mode voltages can be minimized using the same cabling precautions outlined for noise, and also by using insulated thermocouples.

Thermal Shunting. All thermocouples have some mass. Heating this mass takes energy so will affect the temperature you are trying to measure. If thermocouples with thin wires are used, consideration must be paid to lead resistance. The use of a thermocouple with thin wires connected to much thicker thermocouple extension wire often offers the best compromise.

Advantages and disadvantages of thermocouples

Thermocouples are wonderful sensors to experiment with because of their robustness, wide temperature range and other unique properties (immune to shock and vibration, useful over a wide temperature range, simple to manufacture, require no excitation power, there is no self heating and they can be made very small). Because of their physical characteristics, thermocouples are the preferred method of temperature measurement in many applications including clinical applications. No other temperature sensor provides this degree of versatility. On the down side, the thermocouple produces a relative low output signal that is non-linear. These characteristics require a sensitive and stable measuring device that is able provide reference junction compensation and linearization. Also, the low signal level demands that a higher level of care be taken when installing to minimize potential noise sources (Togawa et al, 1997; Michalski et al, 1991).

4.1.2 Thermistors

The Thermistor was invented by Samuel Ruben in 1930. The semiconductor thermistor is usually made up of small beads of complex materials such as cobalt, nickel, iron, zinc and glass, the resistance of which is very temperature dependent. Thermistors were so named by Bell Telephone Laboratories and the name is a short form for thermal resistors (http://www.kele.com/tech/monitor/Temperature/TRefTem4.html).

Thermistors are used inside many devices as temperature sensing and correction devices as well as in specialty temperature sensing probes for commerce, science and industry including in the new digital thermometers used in medicine. Also, thermistors are generally used on pulmonary artery catheters for thermal dilution measurements of cardiac output. Thermistors typically work over a relatively small temperature range, compared to other temperature sensors such as thermocouples, but are highly sensitive within this range as resistance falls exponentially with temperature (Figure 4.3). The main disadvantage of thermistors is the nonlinear resistance versus temperature characteristic. However, thermistors remain highly popular due to their cost, miniaturized size and convenience (Togawa et al, 1997; Michalski et al, 1991).

There are basically two broad types of thermistors, the *NTC-Negative Temperature Coefficient*, used mostly in temperature sensing and the *PTC-Positive Temperature Coefficient*, used mostly in electric current control. The resistance of the thermistor has a negative temperature coefficient around -0.04/K and its sensitivity is about 10 times that of a platinum wire temperature probe. Such sensitivity makes the thermistor a suitable temperature sensing element for use in physiological temperature measurement where relatively higher resolution is required in a narrow temperature range (Togawa et al, 1997). In a thermistor the relationship between its resistance and the temperature is highly nonlinear. The resistance of a thermistor changes negatively and sharply with a positive change in temperature, as shown in Figure 4.3.

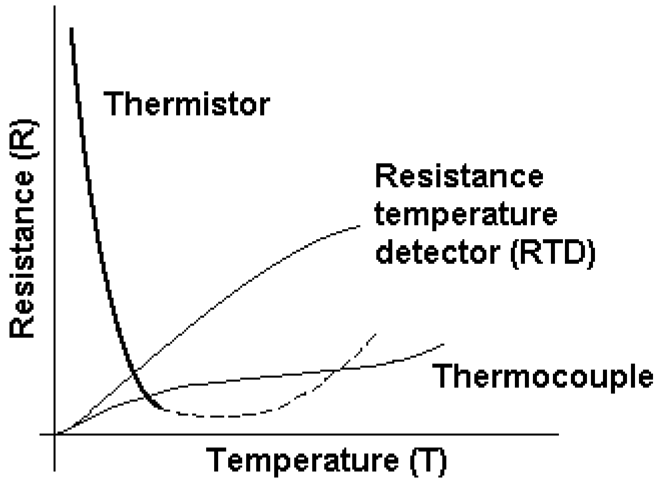


Figure 4.3: Thermistor characteristic curve of resistance versus temperature.

The thermistor resistance-temperature relationship can be approximated by,

$$R = R_{Ref} \times e^{\beta\left(\frac{1}{T} - \frac{1}{T_{Ref}}\right)} \qquad (4.1)$$

where T is temperature (in Kelvin), T_{Ref} is the reference temperature, usually at room temperature, R is the resistance of the thermistor in ohms (Ω), R_{Ref} is the resistance at T_{Ref}, β is a calibration constant depending on the thermistor material, usually between 3,000 and 5,000 K.

The thermistor resistance can easily be measured, but the temperature is buried inside an exponential. To solve for temperature (T) a natural logarithm is applied to both sides of the equation (4.1),

$$\frac{1}{T} = \frac{1}{T_{Ref}} + \frac{1}{\beta}\left[\ln(R) - \ln(R_{Ref})\right]$$

$$\Rightarrow T = \frac{T_{Ref} \times \beta}{\beta + T_{Ref}\left[\ln(R) - \ln(R_{Ref})\right]}$$

Alternatively, some references use the negative temperature coefficient (NTC) α to describe the sensitivity of a thermistor,

$$\alpha = \frac{1}{R}\frac{dR}{dT}$$

$$\Rightarrow \alpha = -\frac{\beta}{T^2}$$

Typically, the value of α falls between -2% ~ -8%. Using the above equations, the temperature can be directly obtained from the measured resistance.

Various types of thermistor probes for general use or medical use are commercially available. Figure 4.4 shows examples of thermistor probes.

Figure 4.4: Thermistor probes

From the characteristic curve (see Figure 4.3), it can be seen that not only is the thermistor nonlinear, but it also has a negative temperature coefficient (i.e., its resistance decreases with increasing temperatures). A typical circuit shown in Figure 4.5 is used to convert thermistor ohms to a dc voltage.

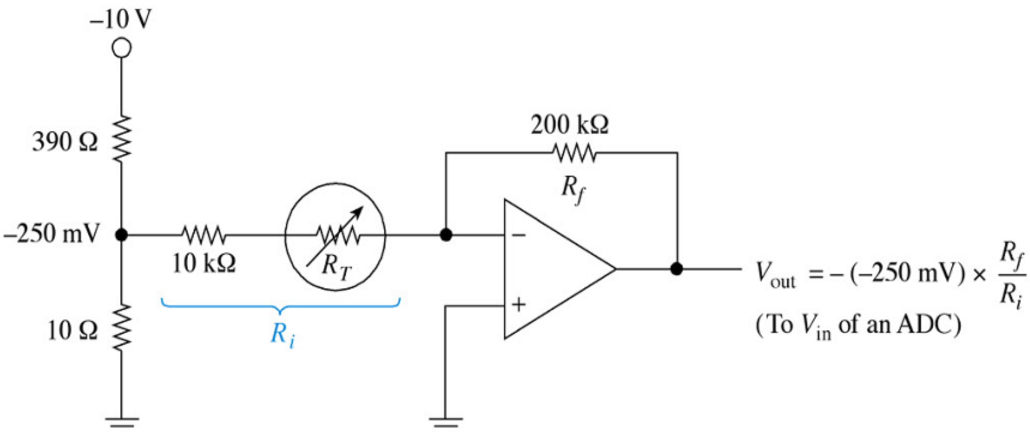


Figure 4.5: Circuit used to convert thermistor ohms to a dc voltage

The output of the circuit is found using the formula

$$V_{out} = -V_{in} \times \frac{R_f}{R_i}$$

where V_{in} is a fixed reference voltage V_{Ref} and R_i is the sum of the thermistor's resistance, R_T, plus 10 kΩ. Using specific values of R_T found in the manufacturer's data manual, a table can be created, which shows V_{out} as a function of temperature. For the development of a digital thermometer the output voltage, Vout, can then be fed into microcontroller which will determine the temperature of the thermistor by converting the analogue input, either voltage or current, to a temperature value. This is accomplished using either a "look-up" table or by programming into the software the equations that relate resistance to temperature.

Another familiar method of utilizing a thermistor to measure temperature is to use a Wheatstone bridge with the thermistor as one leg of the bridge. The circuit in Figure 4.6 is one example of a circuit that utilizes a thermistor to sense temperature. As temperature increases, the voltage output increases. The selection of R_1, R_2 and R_3 will determine the sensitivity of the circuit as well as the temperature range for which the circuit is best suited.

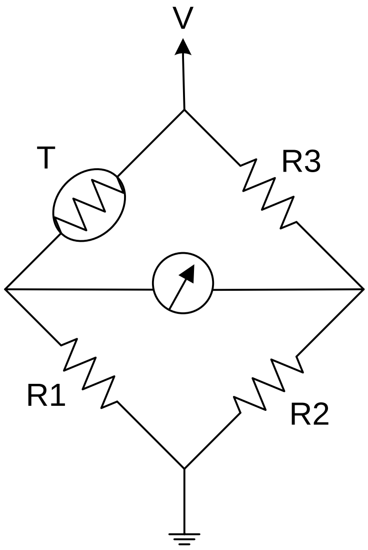


Figure 4.6: Wheatstone Bridge - Voltage Mode

4.1.3 Resistance Temperature Detectors (RTDs)

Resistance thermometers or resistance temperature detectors (RTDs), are wire wound and thin film temperature sensors that change in resistance with varying temperature. Resistance thermometers are slowly replacing the well known thermocouples in many industrial applications as they have greater stability, accuracy and repeatability. The resistance tends to be almost linear with temperature and platinum is usually used because of its linear resistance-temperature characteristic, its chemical inertness and stability with temperature. Resistance thermometers require a small current to be passed through in order to determine the resistance which can lead to self-heating. Their main advantages include a wide operating range, high accuracy and a high suitability for precision applications. Compared to thermistors, resistance thermometers are less sensitive to small temperature changes and have a slower response time (http://www.temperatures.com).

4.1.4 Semiconductor Thermometer Devices

Semiconductor thermometers are usually produced in many types and shapes in the form of Integrated Circuits (ICs). Most are very small and their fundamental design results from the fact that semiconductor diodes have voltage-current characteristics that are temperature sensitive. That means that semiconductor triodes or transistors are also temperature sensitive. These devices have temperature measurement ranges that are small compared to thermocouples and RTDs, but, they can be quite accurate and inexpensive and very easy to interface with other electronics for display and control. The major uses are where the temperature range is limited to within a minimum temperature of about - 25°C to a maximum of about 200°C.

A typical example is the LM35 series (National Semiconductor) precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature (see Figure 4.7). The LM35 thus has an advantage over linear temperature sensors calibrated in kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling. The LM35 does not require any external calibration or trimming to provide typical accuracies of ± ¼°C at room temperature and ± ¾°C over a full - 55 to + 150°C temperature range.

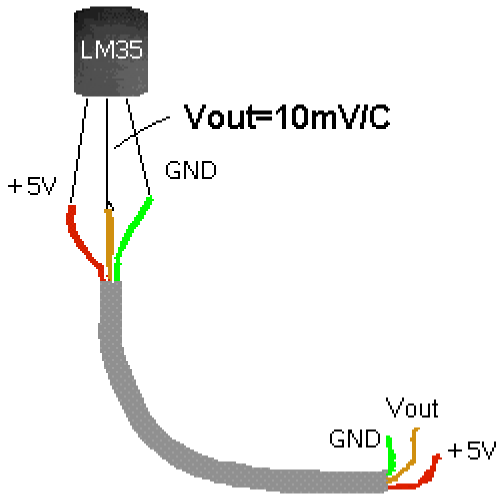


Figure 4.7: LM35 Integrated Circuit linear temperature sensor

4.1.5 Liquid crystal temperature sensors

Friedrich Reinitzer an Austrian Scientist and Otto Lehman have discovered and coined the term “liquid crystal” (a substance that can be between a liquid and a solid state). Nowadays the use of the properties of liquid crystals can be found in the most state of the art technologies such as liquid crystal displays (LCDs) (watches, computer screens, televisions) including clinical thermometers (http://kicp-yerkes.uchicago.edu/2003-winter/pdf/ywi2003-liquid_crystals.pdf).

Liquid crystal temperature sensors are thin flat pieces of plastic with heat activated chemical dots (heat-sensitive liquid crystals) superimposed on the surface, designed to change color in accordance with the temperature sensed. They are used for the development of a disposal clinical liquid crystal thermometer or plastic strip thermometer. Disposable liquid crystal thermometers are mainly used on the skin such as the forehead but they can also be used in the mouth or rectum. When a plastic strip thermometer is placed on the skin it will look initially black in color and then the colors will possibly change depending on the temperature to red, yellow, green or blue. Liquid crystal thermometers are made with a substance called cholesteric liquid crystals. Under the microscope liquid crystals look like small rod-like structures. In their solid state, the liquid crystal rod-like structures form parallel layers to each other. In their liquid state the rods are shifted at various angles in relationship to each other and in the liquid-crystal state the rods form layers but adjacent layers run in slightly different directions from those above or below them. This is demonstrated in Figure 4.8.

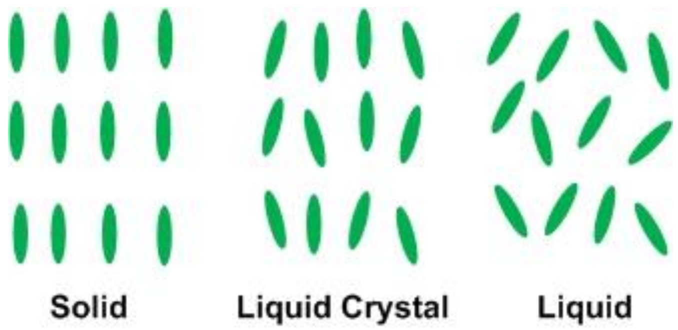


Figure 4.8: Cholesteric liquid crystals in their solid, liquid crystal and liquid states

The distance that the liquid crystals twist over is called the pitch (Figure 4.9), and it determines the color of the light that will be reflected.

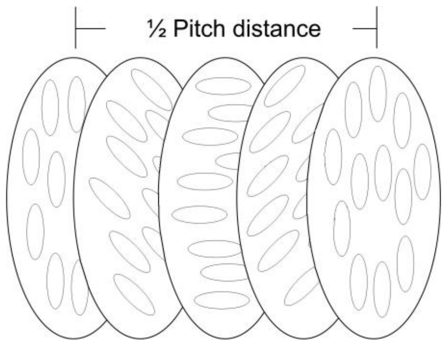


Figure 4.9: Distance that the liquid crystals twist over.

Liquid crystals, when exposed to different temperatures change state from solid to liquid to gas and that has an effect on the pitch distance (decreases with heat) and the angle (increases with heat) of twisting between the rods. Such changing parameters determine the colour of light that will be reflected. For example, when the distance equals half of the wavelength of red light the liquid crystal will reflect red light. If the distance is shortened to half a wavelength of blue light, it will reflect blue.

4.2 Noncontact Temperature Sensors

Noncontact temperature measurement can be realized using radiation heat transfer (Togawa et al, 1997). Noncontact temperature measurement is the preferred technique for small, moving, or inaccessible objects. The uses of noncontact temperature sensors are many but sometimes the understanding of their use is, in general, relatively poor. Part of that complication is often the need to deal with emissivity, or more precisely with spectral emissivity. This quality defines the fraction of radiation emitted by an object as compared to that emitted by a perfect radiator (blackbody) at the same temperature. Emissivity is determined in part by the type of material and its surface condition, and may vary from close to zero (for a highly reflective mirror) to almost 1 (for a blackbody simulator). Emissivity is used to calculate the true temperature of an object from the measured brightness or spectral radiance. Because an object’s emissivity may also vary with wavelength, a radiation thermometer with spectral response matching regions of high emissivity should be selected for a specific application. Emissivity values are listed in the literature for a variety of materials and spectral bands, or these values can be determined empirically (http://www.omega.com/temperature/Z/NoncontactTM.html).

In many industrial plants noncontact sensors are not yet standardized to the extent that thermocouples and RTDs are. More recently the medical world has adopted the infrared (IR) ear noncontact thermometer (this will be discussed in the following sections), that is basically a single waveband radiation thermometer (http://www.temperatures.com).

4.2.1 Infrared (IR) sensing thermometers

Infrared thermometers are useful because they do not need physical contact with the thermal source. These infrared sensors absorb and detect infrared emission given off by a heated surface (Figure 4.10). The incoming radiation is converted to an electric signal, which corresponds to a particular temperature. Near the human body temperature, the peak of the thermal radiation is in the far-infrared region, thus, infrared radiometers are used in medical thermometry (Togawa et al, 1997). A typical infrared clinical thermometer is the ear or tympanic thermometer. The sensor can be introduced intermittently into a speculum in the external auditory meatus. The sensor is in sight of the eardrum and when required, it gathers information from the tympanic membrane over a period a one second. The data is then processed to produce a temperature reading. Such a device has been found to correlate well with the pulmonary artery temperature during rewarming in cardiopulmonary bypass surgery. However, both research and practice have shown that user technique is very important for an accurate temperature. An infrared ear thermometer will display the temperature of whatever it is directed at. Therefore, correct placement in the ear canal is critical. If the probe tip is not well into the ear canal, the chances are the coolest portions of the ear canal will be measured. If, on the other hand, the probe tip is inserted well into the canal the reading is much more likely to include the warmest part of the ear, the tympanic membrane and give a true reading of core body temperature. A major advantage of this technique is that the readings can be made quickly and the site of measurement is generally easily accessible (http://www.graduateresearch.com/thermometry/).

Figure 4.10: Infrared thermometer sensor for non contact temperature measurements
(Image credit: http://www.melexis.com/Sensor_ICs_Infrared_and_Optical/)

5. Clinical thermometers

Since the mercury in glass thermometer was introduced at the start of the 20th century the measurement of body temperature has become easy and accurate (Togawa, 1985; Togawa et al, 1997). This thermometer has proven for many years to be a reliable, easy to use and low cost device. However, there are many occasions when the use of such a glass thermometer might not be the best choice, especially when fast response and continuous temperature monitoring is required. The traditional mercury thermometer has gradually been replaced by the more “user friendly” digital thermometer. Since the accuracy is comparable with both instruments and mercury contamination is also a serious issue in hospitals, the use of mercury thermometers is no longer recommended (Press and Quinn, 1997).

Over the last several years many different kinds of clinical thermometers have been introduced, using the various temperature sensors/transducers described in section 4. These thermometers have been designed and developed for application in various parts of the body such as the rectum, the mouth, the axilla, the esophagus, the bladder, the ear, the temporal artery, the skin, etc. This section will outline the most widely used clinical thermometers.

5.1 Rectal thermometry

A typical rectal temperature probe is a flexible catheter with a thermistor (see section 4.1.2) at the tip. Rectal temperature provides accurate measurements of core temperature and rectal thermometry has traditionally been considered the gold standard for temperature measurement (McCarthy, 1998; Brown et al, 1992; Cereda and Maccioli, 2004). Rectal thermometers could be either the traditional glass thermometer or an electronic digital thermometer as shown in Figure 5.1. Despite its wide acceptance rectal thermometry also presents some limitations (Robinson et al, 1998; Cereda and Maccioli, 2004). Rectal temperatures are slow to change in relation to changing core temperature, and they have been shown to stay more elevated (0.2 to 0.3°C) than those obtained in any other parts of the body (Eichina et al, 1951; Cranston et al, 1954; Isley et al, 1983). Rectal readings are also affected by the depth of the measurement (usually 8 to 15 cm from the anal sphincter), conditions affecting local blood flow and the presence of stool (Togawa et al, 1997). Rectal perforation is also another major limitation especially in infants and small children (Blainey, 1974; Kenney et al, 1990). Rectal thermometry has the capacity to spread contaminants that are commonly found in stool and therefore proper sterilization techniques are necessary. Despite the limitations, rectal thermometry can be a reasonable choice to monitor temperature because patients can tolerate it even though most patients are uncomfortable with this method of temperature assessment, and the majority of children resent it (Cereda and Maccioli, 2004).

Figure 5.1: Typical oral and rectal thermometers

5.2 Oral thermometry

Oral thermometry is the most common method of taking a temperature. Traditionally the mercury-in-glass thermometer was used for measuring temperature where the temperature sensor was positioned under the tongue (sublingual). Nowadays the mercury-in-glass thermometer has been replaced by mercury free glass thermometers (manufacturers use galinstan, a liquid alloy of gallium, indium, and tin, as a replacement for mercury) or digital thermometers where with the press of a button, you can get an easy-to-read temperature in about 60 seconds (Figure 5.1). The sublingual site is easily accessible and reflects the temperature of the lingual arteries. Oral temperature measurement is easily accessible and less prone to operator error, and quickly reflects changes in core body temperature. However, oral temperature is easily influenced by the ingestion of food or drink and mouth breathing (Jaffe, 1995). Also, for the correct measurement of temperature when using a sublingual probe the mouth should remain sealed, with the tongue depressed for 3 to 4 min (for glass thermometers), which can be a difficult task especially with children, unconscious or uncooperative patients. Also, such a temperature modality might not be safe either, as patients may accidentally bite or break the thermometer. Safety is increased by using non-breakable probes instead of glass probes. The main advantage of this method is easy accessibility and it is noninvasive. Oral thermometers are not recommended with infants or very young children because of the above limitations. The accuracy of the oral thermometer is somewhere between that of the rectal and the axillary thermometers, however its accuracy will increase when it is properly applied.

5.3 Axillary thermometry

Axillary (armpit) thermometry relies usually on traditional temperature measurement using a mercury-in-glass temperature sensor (or mercury free glass temperature sensor) or digital thermometer, such as the ones shown in Figure 5.1, placed over the axillary artery (Seguin and Terry, 1999). Such a technique can be influenced by environmental conditions and also by vasoconstriction and vasodilation of the underlying vasculature. Axillary thermometry is an easy and very practical method to use (compared with oral or rectal measurements). The thermometer should be kept clamped under the arm against the chest for three to four minutes. The time to record temperature using this technique is one of its limitations; however axillary thermometry will allow repeatable temperature measurements without any significant discomfort. Unfortunately, this technique has been found to be the worst estimate of core temperature in children (Jaffe, 1995; McCarthy, 1998) and showed low sensitivity and specificity in detecting fever. Despite this limitation, the axillary thermometry has been recommended by the American Academy of Pediatrics as a screening test for fever in neonates because of the risk (very low) of rectal perforation when using a rectal thermometer (Kresch, 1994).

5.4 Esophageal thermometry

Esophageal temperature is mainly monitored during anesthesia (Hooper and Andrews, 2006). Usually after induction of general anesthesia a flexible esophageal thermistor type probe (76 cm in length) is inserted through the mouth or the nose in to the lower one-third of the esophagus. The length of the probe is covered with a white PVC sleeve which prevents exposure of the lead wire and also acts as a barrier to moisture. The tip of the thermistor is insulated and therefore reduces any risk of electrical shock or burn. The top of the probe is round and smooth for non-traumatic insertion (Figure 5.2). Esophageal temperature can be considered an accurate and precise estimate of core temperature in almost all conditions. However, the misplacement of the esophageal temperature probe close to the trachea where there is a flow of cooler gases (more proximal positioning) can lead to falsely lowered temperature values (Whitby and Dunkin, 1971).

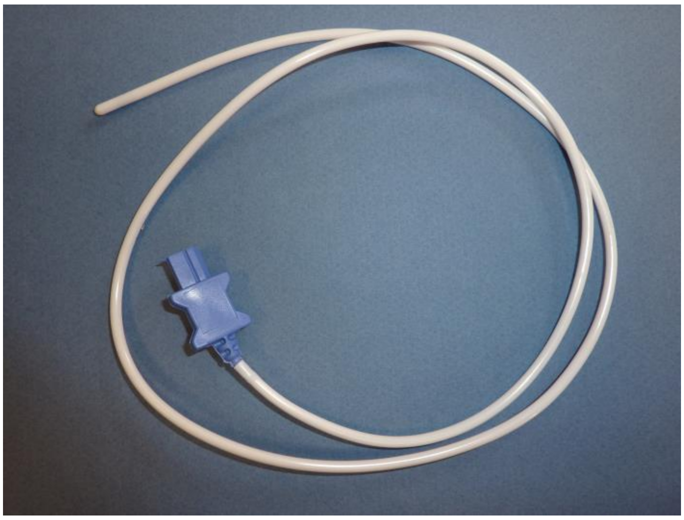


Figure 5.2: Esophageal thermometer

Also, there is evidence that esophageal temperature can artifactually decrease during thoracotomy and rapid infusion of cold fluids and can also be affected by the temperature of the inspired gases (Bissonnette et al, 1989). Another reported limitation is patient discomfort and trauma, especially postoperatively when the patient is not fully anaesthetized and the probe has been inserted into the esophagus through the mouth (it is more tolerable when the probe is inserted through the nose) (Whitby and Dunkin, 1968). Also, in rare cases complications such as esophageal perforations and burns have been reported.

5.5 Pulmonary Artery Catheter (PAC) thermometry

Temperature measured invasively in the pulmonary artery is considered to be the 'gold standard' in temperature monitoring, but it is highly unsuitable for a majority of patients due to its invasiveness (Bock et al, 2005). The pulmonary artery multiport catheter, frequently referred to as a Swan-Ganz catheter, in honor of its inventors Jeremy Swan and William Ganz, is inserted through a major vein (often the internal jugular, subclavian, or femoral veins) and a thermistor is embedded in the tip (about 3 cm behind the tip) of the PAC lying in the pulmonary artery. This method is often used as a reference for other monitoring devices (Milewski et al, 1991; Bock et al, 2005). The use of this measurement site is restricted to critically ill patients in whom a pulmonary artery catheter is required for hemodynamic monitoring.

5.6 Bladder thermometry

Bladder temperature is monitored using a thermistor-tipped Foley's bladder catheter (Figure 5.3) (Togawa et al, 1997). The Foley Catheter with temperature sensor is used for urinary drainage and simultaneous monitoring of bladder temperature. Bladder temperature is determined primarily by urine flow and high flow rates are necessary for the bladder temperature to reflect core temperature. Low urinary flow makes bladder temperature difficult to interpret in relation to true core temperature. Based on several studies, bladder temperature is reliable, accurate and safe for core temperature monitoring. The temperature can be best achieved when the urinary output is high. During hypothermia, this method is less reliable. The temperature in the bladder is close to core temperature (Cork et al, 1983), and found to correlate highly with rectal, esophageal and pulmonary arterial temperature. However, the accuracy of this measurement site decreases with low urinary output and during surgery in the lower abdomen.

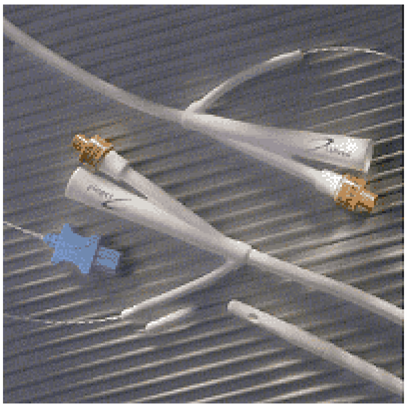


Figure 5.3: The Foley Catheter with temperature sensor
(Image credit: http://www.arizant.co.uk/)

5.7 Tympanic thermometry

As a result of the vicinity of the eardrum to the carotid artery, the brain, and the hypothalamus, tympanic temperature is often considered a gold standard of core temperature measurement and is used as a reference for other sites. To measure this temperature, a transducer is placed in contact with the tympanic membrane. The first devices used to measure tympanic membrane (TM) temperature did so by being in direct contact with the tympanic membrane (Figure 5.4).

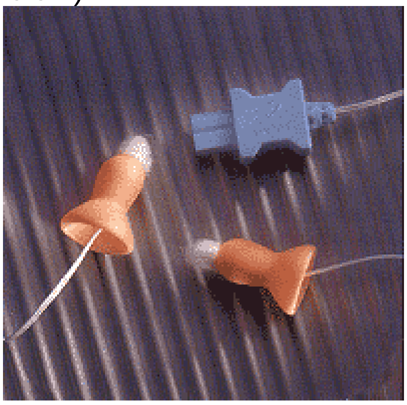


Figure 5.4: Tympanic temperature probe
(Image credit: http://www.arizant.co.uk/)

Small thermocouples and thermistor probes have been used for tympanic temperature measurements since 1963 when Benzinger and Taylor described tympanic temperature sensors in which copper-constantan wires were connected side by side as the tip and drawn into fine polyethylene tubing (Togawa et al, 1997). In 1969, it was shown that such a device measured core temperature better than a rectal thermometer (Benzinger and Benzinger, 1972). However, thermistors in direct contact with the TM are not practical for everyday use. For contact tympanic thermometers direct visualization with an otoscope is required for correct positioning of the probe as malpositioning might cause inaccurate measurement (Webb, 1973). Additionally, bleeding and perforation of the eardrum from contact tympanic probes have been reported, (Wallace et al 1974, Tabor et al 1981) and again great care is required when positioning. For these reasons, tympanic temperature is measured mainly for research purposes and in those conditions in which knowledge of brain temperature is particularly desired such as during hypothermic cardiopulmonary bypass (Webb, 1973).

Instead of being in direct contact with the TM, today's tympanic thermometers measure the thermal radiation emitted from the TM and the ear canal, and have therefore been called infrared radiation emission detectors (IRED). Tympanic infrared thermometry (noncontact) has been receiving most of the attention over the last few years in the clinical setting and a large number (over 100 since the early 1990s) of peer reviewed articles have been published demonstrating its applicability in the clinical setting and comparing its accuracy and sensitivity over other more traditional temperature measuring techniques, some of them described in this report. Some of these comparison studies will be reported in the following sections.

The thermal radiation emitted is in proportion to the tympanic membrane's temperature, therefore the infrared radiation emission detector accurately estimates tympanic membrane temperature (Chamberlain et al, 1995). The blood supply of the tympanic membrane is similar in temperature and location to the blood bathing the hypothalamus, the site of the body's thermoregulatory centre and therefore, an ideal location for core temperature estimation (Terndrup et al, 1997; Childs et al, 1999). Crying, otitis media or earwax have not been shown to change tympanic readings significantly.

Tympanic thermometers became available on the commercial market in the early 90's. *First-Temp* ear thermometer, manufactured by Intelligent Medical Systems, Carlsbad, California was the first ear thermometer on the market and sold at a list price of $695. Nowadays you can purchase a state of the art tympanic thermometer such as Braun Thermoscan Pro 4000

Ear Thermometer manufactured by *Welch Allyn, Inc,* Skaneateles Falls, NY at a price of around $200. TM thermometers at lower price ranges of $20-$40 are also available.

Figure 5.5: A commercial tympanic thermometer
(Image credit: http://www.welchallyn.com/)

A tympanic thermometer can measure the infrared radiation of the TM in two ways. A thermopile (composed of thermocouples either connected in series or in parallel) sensor with a light pipe installed at the tip of the probe detects the level of heat in the area directly proximal to the TM by taking multiple readings very quickly. Also a measurement can be done by employing a pyrosensor, which is a heat flow detector that measures the speed at which the thermal energy flows through a sensor, takes a ‘snapshot’ of the heat that it records from the TM, just like photographic film. Both methods have demonstrated comparable accuracy. The tip of the TM probe is inserted into the external auditory canal (Figure 5.6) (O’Hara and Phillips, 1986; O’Hara and Phillips, 1988; Betta et al, 1997).

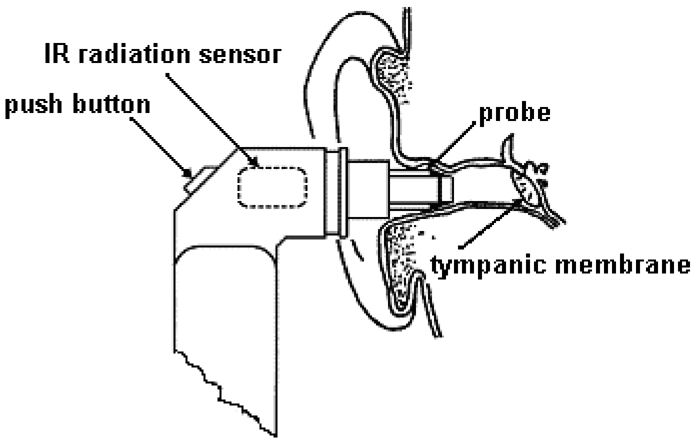


Figure 5.6: Tympanic Infrared temperature measurement with a probe placed into the external auditory canal (Modified from Bettay et al., Physiol. Meas. 18 (1997) 215–225).

In conclusion ear temperature measurement with an infrared tympanic thermometer offers a reasonable estimate of core temperature within 1 to 2 s and can be tolerated by awake patients, allowing its use in those situations in which esophageal temperature is difficult to obtain such as during regional anesthesia. Although ear temperature measurement is frequent in the recovery room, intensive-care unit, and in general on many hospital floors its intraoperative use is probably still relatively rare.

5.8 Temporal artery thermometry

EXERGEN Corporation, have recently (late 1990s) developed and presented the TemporalScanner™ Temporal Artery non-invasive infrared Thermometer (Pompei, 1999).

The temporal artery and surrounding tissue was investigated as a new, potentially more suitable site (Sandlin, 2003). The temporal artery area is a site with a long history of temperature measurement, actually dating back to the early centuries B.C., and the first recorded references to palpation of the head for assessment of fever (Pompei 1999). As a temperature measurement site, the temporal artery is easily accessible and usually quite a visible site, poses no risk of injury for the patient, and contains no mucous membranes (eliminating the risk of contaminates) (Ikeda et al, 1997). Also, perfusion of the temporal artery remains relatively constant, thus ensuring the stability of blood flow required for the measurement method. EXERGEN Corporation developed and validated three infrared devices, one a professional model for clinical use, one for home use, and the other a professional model for use in neonatal intensive care (Pompei 1999).

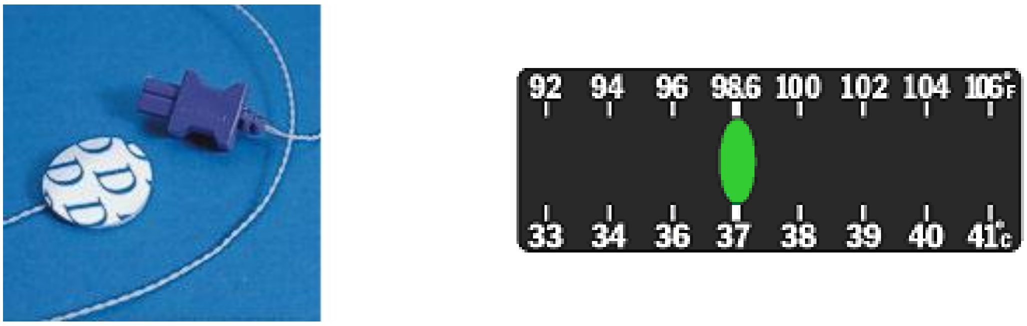
Figure 5.7: A commercial temporal artery thermometer
(Image credit: http://www.exergen.com/)

As the new temporal artery thermometer measures temperature at the outer surface of the head the absolute temperature will not be the same as the arterial temperature of interest (core temperature). A technique known as the Arterial Heat Balance method (AHB) which accounts for temperature losses due to ambient temperature is employed (Pompei 1999). In more detail, the difference between normal ambient temperatures and arterial temperature is in the range of 17°C and if the cooling effect at the skin surface from the radiated heat loss to the environment is taken into consideration measurement errors of more than 3°C could be present (Pompei, 2006). The AHB method incorporated into the infrared thermometer accounts for the radiated heat loss by measuring ambient temperature at the same time it is measuring the absolute temperature of the skin surface (2000 times per second) over the temporal artery. It then computes arterial temperature by restoring the measured heat loss to the absolute peak surface temperature measurement. Also, the AHB method solves the heat balance equation multiple times per second, selects the highest of the readings and discards all others. The final temperature displayed is the solution to the algorithm, which gives the maximum reading during a particular episode (Pompei 1999).

5.9 Skin Thermometry

Temperature of the skin is often measured using thermocouples or liquid crystals enclosed in adhesive pads (Cereda and Maccioli, 2004). A thermocouple skin temperature sensor and a liquid crystal temperature sensor are shown in Figure 5.8a and Figure 5.8b respectively. These sensors have been applied on various regions of the body, usually the shoulder, toe or forehead. Interpretation of skin temperature values can be difficult and must be done cautiously as they cannot be considered to reflect the core temperature. As discussed above, for the temporal artery temperature measurements, even when the skin temperature reading is adjusted with an offset, the resulting value might not accurately estimate core temperature

(Cork et al, 1983). The differences in temperature between periphery and core continuously change during anesthesia and such changes can be due to the duration of anesthetic, use of body warmers such as blankets, environmental temperature, and vasomotor status (Bissonnette et al, 1989).



(a) (b)

Figure 5.8: (a) A thermocouple skin temperature sensor (Image credit: http://www.arizant.co.uk/); (b) A liquid crystal temperature sensor (Image credit: http://www.novamed-usa.com)

However, skin temperature sensors are used quite extensively especially in cases when esophageal or other invasive temperature probes would be impractical such as during regional anesthesia. In fact most of anesthesiologists who monitor temperature during regional anesthesia use skin temperature sensors (Frank et al, 1999). Also, skin thermometers such as the liquid crystal strip thermometers are safe to use as they do not contains glass, latex or mercury and they are accurate within 0.2°F (0.1°C) (Vaughan et al, 1982). Such temperature sensors have been reported to work well enough for screening in older children (Resinger et al, 1979).

5.9 Pacifier thermometry

The pacifier is a digital baby thermometer intended for oral measuring of body temperature in babies and toddlers up to 3 years of age. The pacifier digital baby thermometer allows the parents to take their baby's temperature accurately and conveniently and without causing distress. The thermometer comprises two parts; the first part includes a silicone orthodontic comfort nipple to place in the baby's mouth, a base element, and a washer. The second part includes a thermometer housing and thermometer electronics that fits into the washer for attachment to the base (Figure 5.9). The thermometer includes a flexible thermocouple that extends into the hollow nipple and includes an end that rests on the end of the nipple interior. The nipple is made of silicone and is heat conductive whereby the temperature of the baby's tongue is effectively transmitted to the thermocouple. The temperature is then displayed by the thermometer (Press and Quinn, 1997; Braun, 2006).

Figure 5.9: Digital pacifier thermometer
(Image credit: http://www.summerinfant.com/)

5.10 Ingestible thermometry

Ingestible temperature sensors used for monitoring core temperature (humans and animals) have been described as early as the 1960s but they have never received widespread clinical application. HQ Inc. in Palmetto, Florida designed and now manufactures an ingestible (pill form) temperature sensor (*CorTemp*™). The sensor was developed with an aim to monitor core temperature of football players during the game and wirelessly transmit core body temperature to trainers on the sidelines. Originally the pill was developed in the mid-1980s by NASA so the space agency could monitor the body temperatures of astronauts on the space shuttle. There is little published technical information regarding this sensor but in brief the biocompatible ingestible sensor contains a temperature-sensitive quartz crystal oscillator. Once inside the gastrointestinal tract, the crystal sensor vibrates at a frequency related to the temperature of the substance (body) surrounding it, producing a magnetic flux and transmitting the signal harmlessly through the body. The *CorTemp™* Ambulatory Data Recorder picks up, displays and stores the data in a solid-state memory until the data is downloaded into a PC platform. The sensor is covered with a protective silicone coating, is approximately 10 mm in diameter and 20 mm long and is energized by an internal silver-oxide battery. The technology is expensive and works for only 1 - 2 days (Mittal et al, 1991; Byrne and Lim, 2007).

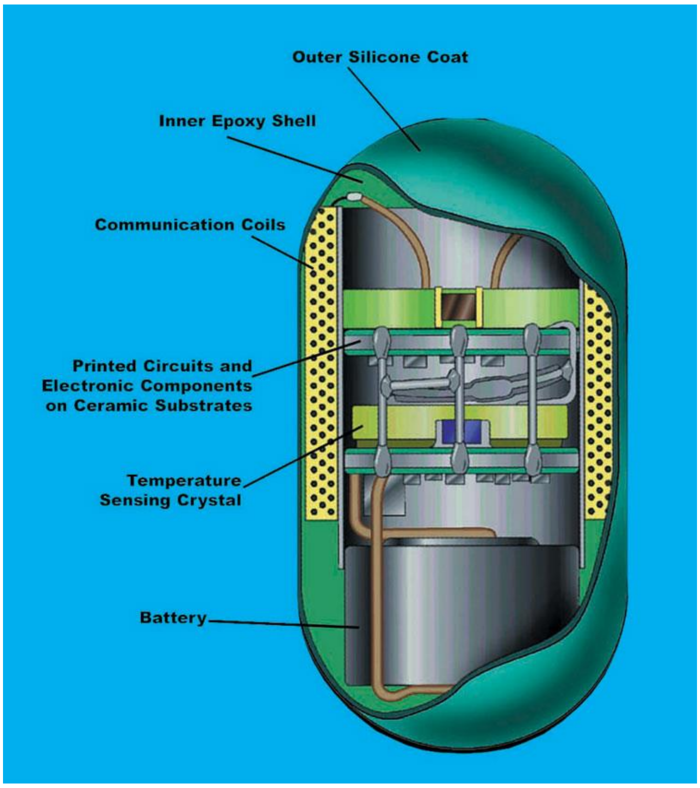


Figure 5.10: Ingestible temperature sensor (*Cortemp*™, HQ Inc)
(Image credit: http://www.hqinc.net/)

6. Application, evaluation and comparison of thermometry and measurement routes

6.1 Introduction

Probably the most common reason to monitor body temperature is to examine the patient's thermal balance. The body can counterbalance for small increases or decreases in temperature by activating the thermoregulatory system. Extremes in temperature can affect hypothalamic functions, disrupt thermoregulation and lead to death. Thus it is important to continuously monitor temperature and at different sites of the body. Since it is not easy to measure directly the temperature of the hypothalamus, proximal sites such as the tympanic membrane, the pulmonary artery and esophagus are better suited (Miller, 2000).

A response to an increase in body temperature is to remove excess moisture from body tissues by way of perspiration. A response to a decrease in body temperature is for the body to generate heat by shivering. Shivering is an involuntary contraction and expansion of muscle tissue. Heat is also conserved by vasoconstriction of the poorly perfused tissues. Temperature in the pulmonary artery continues to be unchanged and hence is not ideal for monitoring these responses. Unless the hypothalamic functions fail or heat cannot be appropriately conserved or generated, the pulmonary artery only shows a gradual decrease in temperature. Both fever and hyperthermia are important cases to be detected as they can cause disruption to the central nervous system due to a rapid increase in temperature.

For example it is important to monitor temperature during regional and general anesthesia. When general anesthetic is given, core temperature of patients is a vital measurement. Anesthesia can greatly alter the thermoregulatory system, causing a decrease in cold-response limit and an increase in warm-response limit. This results in prevention of thermoregulatory defenses. Hyperthermia is an acute condition wherein the amount of heat produced or absorbed by the body is much more than it can dissipate. This can result in failure of the hypothalamic functions, that is, the hypothalamus fails to trigger necessary cooling mechanisms. The mechanisms of the body that regulate heat are unable to deal with this heat efficiently, and hence there is an uncontrollable increase in body temperature. Unless necessary steps are taken to cool the body, irreversible brain damage and death will occur.

Therefore, accurate temperature measurement is critical to the assessment and management of temperature fluctuation in the acutely ill patient. Temperature monitoring, using the above described non-invasive and invasive technologies, is now widely used in many fields of medicine, such as in anesthesia, surgery, and intensive care, for all types of patients (neonates, children and adults) (Krenzischek et al, 1995; Young and Sladen, 1996; Frank et al, 1999; Cattaneo et al, 2000; Gilbert et al, 2002; Van Dam et al, 2003; Busic and Das-Gupta, 2004; Kaukuntla et al, 2004; Nussmeier, 2005; Tabbutt et al, 2006; Hooper and Andrews, 2006). There is a plethora of reports in the literature describing the use of such techniques in different clinical applications and the majority of such reports not only discuss the application of a particular clinical thermometer but also engage in the comparison between different thermometers. It will be almost impossible for this section to cover every possible application and evaluation study relating to different thermometers; however, an effort is made to provide a review of studies comparing selected invasive and non-invasive temperature measurement methods discussed previously in this chapter.

6.2 Comparison of multiple clinical thermometers

A study that compares skin core temperature-corrected liquid crystal thermography, axillary electronic, and oral electronic thermistor readings with temperatures obtained by infrared tympanic membrane thermometry from 215 Post Anesthesia Care Unit (PACU) patients has been conducted by Darm et al in 1994. Critical measurement of patient body temperature in the PACU is an important parameter in patient management and failure to achieve minimal acceptable body temperature standards has been associated with physiological derangement, the application of additional therapy, and prolonged PACU stays. Regression analysis results from this study suggested that when compared with tympanic temperature, the oral method is more accurate and has greater precision than either the liquid crystal or axillary methods, concluding that the incidence of hypothermia depends on the method chosen to assess body temperature is a significant nursing implication.

Patel et al (1996) compared esophageal, tympanic membrane, and forehead skin temperatures in 40 patients undergoing elective surgeries. They concluded that there was a lack of agreement between the clinically accepted measurements (lower esophageal and tympanic membranes and the skin temperature measurement. The data suggested that forehead skin temperature is not interchangeable with standard core temperature measurements, and that sole reliance on the forehead skin measurement in the perioperative setting could adversely affect patient care. Also, a study by Jensen et al (2000) attempted to compare a number of electronic tympanic, oral, axillary, and rectal measurements with those taken with a standard rectal mercury thermometer in a group of 200 patients in a county hospital in Denmark. They found that the rectal electronic measurements were closest to the rectal mercury readings, with a mean (SD) of -0.05^{o}C (0.12^{o}C), whereas the other measurements gave unacceptable SDs of temperature differences ranging from 0.41^{o}C to 0.53^{o}C. They concluded that the electronic rectal temperature measurements are the most accurate and they did not recommend electronic tympanic, oral, or axillary measurements.

A comparative study on the accuracy of liquid crystal forehead, digital electronic axillary, infrared tympanic and glass-mercury rectal thermometers in 200 infants and young children aged 0 - 48 months (Kongpanichkul and Bunjongpak, 2000) showed that tympanic thermometry had the best performance while forehead thermometry had the poorest. The authors concluded that the three clinical thermometers are not suitable as a substitute for a glass-mercury rectal thermometer in assessment of fever in infants and young children. More recently Lefrant et al (2003) conducted a temperature study in 42 intensive care patients comparing urinary bladder, esophageal, rectal, axillary, and inguinal temperatures versus pulmonary artery temperature. Temperature was simultaneously monitored with PAC, urinary, esophageal, and rectal electronic thermometers and with axillary and inguinal gallium-in-glass thermometers. A total of 529 temperature measurement comparisons were carried out. They concluded that in critically ill patients, urinary bladder and esophageal electronic thermometers are more reliable than the electronic rectal thermometer which is better than inguinal and axillary gallium-in-glass thermometers to measure core temperature.

Monitoring temperature in critically ill children is an important component of care, yet the accuracy of methods is often questioned. Temperature measured in the pulmonary artery is considered the 'gold standard', but this route is unsuitable for the majority of patients. An accurate, reliable and less invasive method is, however, yet to be established in pediatric intensive care work. To determine which site most closely reflects core temperature in babies and children following cardiac surgery Maxton et al (2004) compared pulmonary artery temperature to the temperature measured at rectal, bladder, nasopharyngeal, axillary and tympanic sites. In this study, bladder temperature was shown to be the best estimate of pulmonary artery temperature, closely followed by the temperature measured by the nasopharyngeal probe. The results support the use of bladder or nasopharyngeal catheters to monitor temperature in critically ill children after cardiac surgery.

In 2005, Farnell et al 2005 conducted a study to assess the accuracy and reliability of two non-invasive methods, the chemical (Tempa.DOT) and tympanic thermometer (Genius First Temp M3000A), against the gold standard pulmonary artery catheter, and to determine the clinical significance of any temperature discrepancy using an expert panel. A total of 160 temperature sets were obtained from 25 adult intensive care patients over a 6-month period. Their finding showed that the chemical thermometer was more accurate, reliable and was associated with fewer clinically significant temperature differences compared with the tympanic thermometer.

6.3 Evaluation of Temporal thermometry

As described in section 5.8 infrared arterial temperature can be measured with a device that is positioned at the temporal area. Greenes and Fleisher (2001) assessed the accuracy of the non-invasive temporal artery (TA) thermometer in infants and compared its accuracy with that of a tympanic thermometer, using rectal thermometry as the criterion standard. A sample of 304 infants younger than 1 year was included in the study. They found that the TA thermometer has limited sensitivity for detecting cases of fever in infants. However, they pointed out that the TA thermometer is more accurate than the tympanic thermometer in infants, and it is better tolerated by infants than rectal thermometry.

Roy et al (2003) have also compared a non-invasive temporal artery thermometer with rectal and ear thermometry. In this case temperatures were measured in healthy patients 0 to 18 years of age. This study provided information about temporal artery temperatures in healthy infants and children that can serve as a basis for interpreting temperature measurements in ill children when the same instrument is used. In a recent (Schuh et al, 2004) trial in a busy pediatric emergency department, the temporal artery device was shown to have a sensitivity of about 80% to identify fever (as determined by rectal measurements). It was concluded that temporal artery thermometry may be a promising tool for screening children at low risk in the ER but cannot yet be recommended for home use or hospital use when definitive measurements are required. Also, Schuh et al (2004) compared the temporal artery thermometer with the rectal thermometer in 327 children <24 months of age. The conclusion was that the temporal thermometer cannot replace the rectal thermometer and was found to be inadequate for the detection of fever.

Later on, a study by Myny et al (2005) was conducted to evaluate the accuracy and variability of the Temporal Artery Thermometer (TAT) in ICU-patients. Fifty seven adult patients with indwelling pulmonary artery catheters (PAC) were studied. Body temperature was measured simultaneously with the TAT and the Axillary Thermometer (AT), and was compared with the temperature recording of the PAC. The authors concluded that the temporal scanner has a relatively good reliability with an acceptable accuracy and variability in patients with normothermia. The results were comparable to those of the AT, but they did not seem to give any substantial benefit compared to rectal, oral or bladder thermometry. In the same year, Hebbar et al (2005) compared seventy-five temperature pairs that were obtained from 44 pediatric intensive care unit patients. They found that temporal artery and axillary temperature measurements showed variability compared to rectal temperatures with marked variability in febrile children. Neither was sufficiently accurate to recommend replacing rectal or other invasive methods. In conclusion, as temporal artery and axillary provide similar accuracy, temporal artery thermometers may serve as a suitable alternative for patients in whom invasive thermometry is contraindicated.

Studies by Kistemaker et al (2006) and Suleman et al (2002) evaluated the reliability of an infrared forehead skin thermometer (SensorTouch) for core temperature measurements. Kistemaker et al (2006) conducted two experiments in which the body temperature was measured with a rectal sensor, with an esophageal sensor and with the SensorTouch. They concluded that the SensorTouch did not provide reliable values of the body temperature during periods of increasing body temperature, but the SensorTouch might work under stable conditions. Suleman et al (2002) studied 15 adults and 16 children who developed mild fever, a core temperature of at least 37.8 degrees C, after cardiopulmonary bypass. Temperature was recorded with the SensorTouch thermometer and from the pulmonary artery (adults) or bladder (children). They found that the SensorTouch accuracy was poor in the adults and suboptimal in infants and children.

6.4 Evaluation of Tympanic thermometry

Ear temperature measurement using an infrared tympanic thermometer is nowadays widely used, especially in neonatal and pediatric temperature monitoring, and offers a reasonable estimate of core temperature (Shinozaki et al, 1988; Dew, 2006). However, despite its popularity its intraoperative use is probably still relatively rare. Androkites et al in 1998 conducted a study to determine whether infrared tympanic membrane thermometry can replace mercury-in-glass temperatures as an assessment tool for detecting fevers earlier and more reliably in a pediatric oncology outpatient setting. A total of 313 patient visits had infrared tympanic temperatures and axillary temperatures taken simultaneously (obtained by using mercury-in-glass thermometers). Their results showed that tympanic thermometry resulted in a significantly higher temperature reading than the axillary method, and they concluded that to prevent unnecessary medical intervention, it is recommended that mercury-in-glass thermometers verify elevated tympanic temperatures.

Also, in 1999 Childs et al investigated tympanic membrane temperature as a measure of core temperature with an aim to determine the variability of a single user's tympanic membrane (ear) temperature measurements. They studied forty-two, afebrile, healthy children, and 20 febrile children with acute burns. In afebrile children measurements made in both ears (and within just a few minutes of each other) differed by as much as 0.6°C. In the group of febrile, burned children, core temperature was measured hourly at a number of sites (ear, rectum, axilla, bladder). They found that the measurement error of one recording from the next is probably acceptable at about 0.1 to 0.2°C. They recommended that to limit the variations in temperature between one ear and the other, measurements should be restricted to one of the ears whenever possible and the same ear used throughout the temperature monitoring period. They suggested that nurses and parents should take more than one temperature reading from the same ear whenever possible.

In a direct comparison between tympanic and rectal temperature in febrile patients Sehgal et al (2002) studied sixty febrile children. Two readings of ear temperature were taken in each child with an infrared thermometer. Rectal temperature was recorded by a digital electronic thermometer. Comparison of both the techniques was done and it was observed that mean ear temperature was 38.9 ± 0.90^{o}C and that for rectal temperature was 38.8 ± 0.80^{o}C. The difference between readings taken from two ears was not significant. They concluded that the tympanic thermometer which is a non-invasive and non-mucous device is accurate over a wide range of temperature and could be very useful.

Infrared ear thermometry was also evaluated in 50 critically ill patients (Leon et al, 2005) in order to find its accuracy compared to axillary temperature (tempAx). A total of 429 simultaneous measurements of axillary temperature (tempAx) and tympanic temperature (tempTT) were made. The authors concluded that the infrared tympanic thermometer produced highly reliable measurements when compared to tempAx measured using a conventional mercury-in-glass thermometer. In a more recent study by Woodrow et al (2006) the tympanic thermometer was compared with the no-touch temporal thermometer. This research compared 178 simultaneous measurements from five clinical areas. The two thermometers were found not to be equivalent with a rather ambiguous final conclusion that this research could not identify which thermometer was more accurate.

More comparative studies of the infrared tympanic thermometer in children have been conducted in the past few years. Nimah et al (2006) conducted a study to determine whether infrared tympanic thermometry (ITT) measurements more accurately reflect core body temperatures than axillary, forehead, or rectal measurements during fever cycles in children. Thirty six critically ill children less than seven years of age with indwelling bladder catheters were recruited. The authors found that ITT measurements more accurately reflected core temperatures than any of the other measurement sites during febrile and afebrile periods in children. They concluded that ITT measurements are a reproducible and relatively non-invasive substitute for bladder or rectal measurements in febrile children.

Dodd et al (2006) investigated the sensitivity and specificity of infrared ear thermometry compared to rectal thermometry to detect fever in children. Their results suggested that infrared ear thermometry would fail to diagnose fever in three or four out of every 10 febrile children (with fever defined by a rectal temperature of 38°C or above).

In another pediatric study El-Radhi and Patel (2006) investigated 106 infants. Their body temperature was measured in the daytime with an infrared tympanic thermometer and at the axilla with an electronic thermometer and at the rectum. They found that there was a greater agreement of the tympanic measurement with the rectal measurement than the axillary with the rectal in both febrile and afebrile infants concluding that tympanic thermometry is more accurate than measurement of temperature with an electronic axillary thermometer, and thus recommended it for use in the pediatric emergency setting.

In 2007 Moran et al undertook a prospective trial to compare the accuracy of tympanic, urinary, and axillary temperatures with that of pulmonary artery (PA) core temperature measurements. A total of 110 adult patients were enrolled in a prospective observational cohort study. The accuracy of tympanic (averaged over both ears), axillary (averaged over both sides), and urinary temperatures was referenced (as mean difference, delta degrees centigrade) to PA temperatures as standard in 6,703 recordings. Their results showed that agreement of tympanic with pulmonary temperature was inferior to that of urinary temperature, which, on overall assessment, seemed more likely to reflect PA core temperature.

Also, Devrim et al (2007) conducted a study with an aim to compare tympanic infrared thermometers with the conventional temperature option, a mercury-in-glass thermometer. They recruited a total of 102 randomly selected pediatric patients and simultaneous temperature measurements were performed via axilla and external auditory canal with 3 different techniques. For external auditory recordings, infrared tympanic First Temp Genius for clinical use and Microlife IR 1DA1 for home usage were used. Classic mercury-in-glass thermometers were used for axillary recording. For each method, 886 measurements were performed. Their results showed that there was a significant difference between the recordings with different thermometers, and this variance was present in both higher and lower readings. They concluded by recommending that home-use infrared tympanic thermometer could be used for screening but must not be considered as a tool to decide patients follow-up.

6.5 Evaluation of liquid crystal thermometry

Forehead skin temperature measured by a strip of liquid-crystal material was compared to esophageal, rectal, and axillary temperatures measured by thermistor probes in patients having general anesthesia for coronary artery bypass grafting (Burgess et al, 1978). They found that during rapid warming, forehead skin temperature rose concurrently with the other temperatures measured but remained significantly different. They concluded that liquid-crystal strip may be useful as a safe, convenient method for routine monitoring of temperature trends during general anesthesia in patients whose exact core temperature need not be continuously monitored. However, they noted that infant patients undergoing extracorporeal circulation, major abdominal, vascular, or neurosurgical procedures, or patients with a history of temperature regulatory problem are probably best monitored by a method which more exactly reflects core temperature.

Later on Vaughan et al (1982) studied 71 adult post surgical patients by comparing simultaneous measurement of core (tympanic membrane) and shell (liquid crystal adhesive temperature strip) cutaneous temperature. Their results suggested that shell temperature (temperature strip) is not a reliable or valid trend indicator of core temperature (tympanic membrane) in postanesthetic adults. Also, Allen et al in 1990 have evaluated the ability of forehead liquid crystal thermometry, rectal temperature, and axillary skin temperature to trend distal esophageal temperature during rapid warming on cardiopulmonary bypass. In 24 patients undergoing open heart surgery, temperatures were measured during the rapid warming phase on bypass (12-35 min). Polynomial regression analysis revealed that liquid crystal thermometry (LCT), but not axillary or rectal temperatures, correlated with esophageal temperature. They concluded that forehead LCT may be useful to monitor temperature trends and to detect rapid elevations in body temperature when more invasive temperature monitoring is inappropriate or unavailable.

A two part study by Brull et al (1993) compared liquid crystal (CR) skin temperature with other temperature monitors which are used routinely during surgery in order to assess whether liquid crystal skin thermometry can reflect accurate core temperature. The first part compared CR with esophageal (OS) temperature during general inhalational anesthesia. The second part compared CR with OS, pulmonary artery (PA), and bladder (BL) temperatures during the periods of rapid temperature change associated with cardiopulmonary bypass (CPB). This study suggested that CR, an inexpensive and noninvasive means of temperature monitoring, reflects trends in temperature changes in the clinical setting.

6.6 Evaluation of Brain/Intracranial thermometry

The introduction of brain temperature monitoring technology has made it possible to examine the difference between core and brain temperatures. Intracranial temperature measurement may play a pivotal role for prognosis and treatment of neurological and neurosurgical patients (Alessandri et al, 2004; Childs et al, 2005; Childs et al, 2006). A review by Mcilvoy (2004) examined the published literature comparing core temperatures (blood, rectal, bladder, and esophageal) with brain temperatures (measured by direct contact with the brain or measured in any of the spaces surrounding the brain, excluding intraoperative measurements). Fifteen studies (between 1990 and 2002) found that the brain temperature was higher than all measures of core temperature with mean differences of 0.39 to 2.5°C. Three of the studies have found statistical significance after a t-test. Temperatures greater than 38°C were found in 11 studies. This review demonstrates that brain temperatures have been found to be higher than core temperatures. However, Mcilvoy (2004) found that existing studies are limited by low sample sizes, limited statistical analysis, and inconsistent measurements of brain and core temperatures.

6.7 Evaluation of skin thermometry

There are many studies comparing the accuracy, reliability, validity, and responsiveness of skin temperature thermometers and this section will cover some recent studies.

Burnham et al 2006 conducted a study to compare a thermistor thermometer (thermistor) and two different infrared thermometers (one designed to measure tympanic temperature and one for skin temperature). Reliability and validity were evaluated by making two separate measurements from the skin at identical spots of each hand, forearm, shoulder, thigh, shin, and foot in 17 healthy subjects. Intramuscular temperature was recorded at the hand and shin sites. They found that the performance of the infrared thermometers was equal to or superior to that of the traditionally used thermistor. All three devices were highly reliable and valid, whereas the infrared skin device was slightly more responsive.

Buono et al (2007) carried out a study to determine the validity of non-contact infrared thermometry to measure mean skin temperature in resting and exercising subjects in cold, thermo-neutral and hot environments. The subjects for the study were six healthy volunteers. Skin temperature was measured at three sites: the forearm, chest and calf on each subject using both contact thermistors and a non-contact infrared thermometer. The results of the study strongly suggested that infrared thermometry is a valid measure of skin temperature during rest and exercise in both hot and cold environments.

6.8 Evaluation of pacifier thermometry

Rectal temperature measurement is considered the most accurate way of assessing temperature in infants, but sometimes may be difficult to obtain correctly. On the other hand axillary temperature is easily obtained but is often inaccurate. Tympanic temperature devices are commonly used, but some studies have indicated doubt about their accuracy, especially in infants and young children. Some of the studies evaluating the pacifier thermometer are discussed below.

Banco et al (1988) assessed the utility and accuracy of a temperature-sensitive pacifier in screening for fever in ill children less than 2 years of age. Of 189 candidates for study, 83 (42%) did not use pacifiers, and of the 106 who did, 25 (24%) could not sustain a suck for five minutes of direct observation. Among those 81 children who could sustain five minutes of sucking, only two of 20 children with rectal temperatures above 100°F (37.8°C) were correctly identified as febrile. They concluded that the temperature-sensitive pacifier did not accurately identify fevers in most infants who are shown to have fevers by rectal temperature determination, suggesting that the use of this pacifier for screening fever in ill infants cannot be recommended. About a decade later Press and Quinn (1997) conducted a study with an aim to determine the correlation between supralingual temperatures obtained with a new electronic pacifier thermometer (Steridyne) and rectal temperatures obtained with a digital electronic thermometer. They studied 100 patients, aged 7 days to 24 months. They concluded that the pacifier thermometer was found to be an accurate means of temperature measurement when recorded temperatures were adjusted upward by 0.5°F. The approximate 3 minutes required for a final temperature determination makes the pacifier thermometer most appropriate for use in low-volume ambulatory care settings and in the home. However they recommended further investigation of the device.

In 2003 Callahan conducted a study on the reliability of perceived, pacifier, rectal and temporal artery (TA) temperatures in infants. A sample of 200 babies younger than 3 months of age presenting to an emergency department was evaluated for parental perception of fever and with TA, pacifier, and rectal temperatures. He found that the sensitivity and specificity of perceived and TA detection of fever were similar at 91% and 79% and 83% and 86%, respectively. Febrile pacifier readings had a sensitivity of 99%, but a specificity of only 46%. He concluded that rectal thermometry must remain the standard for infants younger than 3 months of age. More recently Braun (2006) conducted a study with an aim to determine the validity/reliability of one type of pacifier thermometer in approximating core body temperature using a prospective, within-subjects design, comparing pacifier and rectal temperatures in children (n=25), ages 7 days to 24 months, in one pediatric hospital-based setting. The correlations between the rectal and adjusted pacifier temperature was 0.772 and between 3-and 6-minute pacifier temperatures was 0.913. These data provide support to previous assertions that pacifier thermometry is an acceptable method of temperature approximation in young children.

6.9 Evaluation of ingestible telemetric thermometry

Sparling et al (1993) monitored core temperature during exercise using an ingestible sensor and a rectal thermistor in six trained subjects (three cyclists, three runners) during 30 to 90 minutes of progressive cycling or treadmill exercise. Testing was conducted 3 - 9 hours after ingestion of the capsule. The telemetric temperature was lower than the rectal temperature both at rest and during exercise in every subject. The mean temperature difference increased by 58% from rest (0.59°C) to peak exercise (0.93°C). These preliminary results demonstrated a consistently lower temperature from the capsule sensor located within the GI tract compared to rectal thermistors.

More recently Byrne and Lim (2006) studied the agreement between intestinal sensor temperature (Tintestinal), esophageal temperature (Tesophageal) and rectal temperature (Trectal) across numerous previously published validation studies. Also, they reviewed the application of this technology in field-based exercise studies. They found that the Tintestinal responds less rapidly than Tesophageal at the start or cessation of exercise or to a change in exercise intensity, but more rapidly than Trectal. The intestinal thermometer has been used in many applications such as sport and occupational applications, continuous measurement of core temperature in deep sea saturation divers, distance runners and soldiers undertaking sustained military training exercises. They concluded that the ingestible telemetric temperature sensor represents a valid index of core temperature and shows excellent utility for ambulatory field-based applications.

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