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Review Article

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“The Armpit Temperature of a Healthy Englishman” Measurements of Temperature in the Context of Thermal Trauma

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Abstract

Both therapeutic and preventive approaches to thermal injuries necessitate an understanding of the physics of temperature measurement and heat transfer. The severity of burns depends on four primary factors, three of which are (a) the heat energy of the burning agent, (b) its specific conductance and (c) its temperature. The fourth is the infinite variability of tissue vulnerability of the victim. The measurement of temperature is fundamental to each of these; and is inherent in all disciplines involved in thermal injury. The French Jesuit, Jean Leuréchon (1593-1670) coined the term “thermometer” in 1624. The early calibration of thermometers was achieved by the designation of fixed (but arbitrary) upper and lower calibration points on earlier temperature scales. In the twenty-first century, clinical thermometers read to an accuracy of 0.1 degree Celsius and are calibrated against fixed points. The upper fixed point evolved from that of “the greatest heat of a summer’s day” used by Francesco Sagredo to Isaac Newton’s “armpit temperature of a healthy Englishman”. Anders Celsius (1701-1744) proposed a hundred-point scale with the boiling point of water designated as 0 degrees Celsius. This was inverted by Carl Linnaeus (he of the binomial system of nomenclature) in 1745 to give us the universal scale of temperature used today. All who work in trauma disciplines use scales of temperature in clinical management, in prevention advocacy, in design and in legislative decisions to reduce the morbidity and mortality of thermal injury.

Keywords: Thermal trauma; Severity of burns; Heat transfer; Burning agent; Morbidity and mortality; Tissue vulnerability

Introduction

The physics of thermal energy includes the subjects of heat as energy, thermal conductance and the measurement of temperature. Each of these themes is important in understanding both the threat and the consequences of thermal injury. Such factors are important in the clinical management of victims, both in the pre-hospital setting and in accident and emergency departments; and in preventive approaches to reduce the incidence of burns. In addition to the variation in these three physical properties of the burning agent, the fourth determinant of the severity of injury is the variability of tissue vulnerability. This latter in turn depends on the organs which are exposed and a plethora of individual host factors such as the age of the victim.

Fundamental to these four determinants of thermal injury is an understanding of the measurement of temperature. Such is of relevance to the entire trauma team, whether one is a doctor or nurse, therapist or paramedic, engineer or plumber, architect or builder, or a fire fighter literally at the coalface. Whether one is reactive in terms of rescue, first aid and clinical care, or pro-active in terms of the reduction of risk, an understanding of temperature and its measurement is helpful for all who practise in trauma disciplines.

Temperature is formally defined as “the degree of hotness” of a substance, whether this be solid, liquid or vapour. It is a property of the intensity of motion of the molecules which comprise the substance of the burning agent [1]. It is distinct from heat energy. Think of a blowtorch applied to a house brick for ten seconds and separately to a same-sized block of copper for the same period. Both have absorbed the same heat energy but the copper block is much hotter. By contrast, boiling water at 100°C and steam may be at the same temperature, but the extra energy of the latent heat of vaporisation embodied in the steam means its potential for tissue damage is much greater [2].

Similarly, specific conductance is distinct from temperature as all can attest who have seen the fire pit walkers of the South Pacific. Although the temperature of two different types of mineral rocks may be the same, those of low specific conductance will transfer their heat energy much more slowly [3]; and the fleeting contact of the human foot touching those selective stones will not result in burns.

Thermometry

The universal procedure of recording temperature depends on the accuracy of thermometers. This in turn depends on the accuracy of two fixed but arbitrary datum points (usually the freezing and boiling points of pure water) and subsequently on the fine calibration, measured in degrees, of the scale between them. From these two datum points the scale is extended upwards, not limitlessly but to many thousands of degrees. It is extended downwards to the point where all molecular motion stops, in the Celsuis scale at -273.08°C, or 0° on the Kelvin Scale of Absolute Temperature. Unlike the fixed points designated for practical calibration, this lower fixed point is not arbitrary, but is the point below which the concept of temperature has no meaning.

The history of thermometry is a complex and intriguing one, dating from Aristotelian beliefs that illness was an imbalance between the four essential “qualities” – heat, cold, moisture and dryness. Until the eighteenth century, the word “temperature” meant the tempering

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of those qualities [4]. Fifteenth century paintings portray the use of a nursemaid's bare foot to test the temperature of an infant's bath water [5].

Thermometers were first used clinically, in Europe, in the early eighteenth century. Hermann Boerhaave (1668-1738), Professor of Medicine at Leiden from 1709 to 1730, used a Fahrenheit thermometer in his clinic. He was interested in the effects of heat upon animals. He had his pupils, Prevoost and Fahrenheit; put a dog and a cat in an oven heated to the equivalent of 73°C. It was found that they died in 28 minutes, whilst a sparrow, under the same conditions, died after seven minutes [6].

Clinical thermometry was introduced by Professor Carl Reinhold August Wunderlich (1815-1877) at Leipzig. His text on the relationship of temperature and disease, Das Verhalten der Eigenwärme in Krankheiten, published in 1868, "is the very foundation of present clinical thermometry" [7]. Clinical thermometers also began to make their appearance in English hospitals (at the same time as stethoscopes) about 1866-67 and were in general use by 1870 [8]. In the twenty-first century, clinical temperatures are recorded to a tenth of a degree Celsius. Such accuracy is assumed [9], but its achievements has depended on centuries of dedicated research in the fields of meteorology and mathematics, as well as in those of biology and medicine [10].

The first instruments to display changes in temperature, thermoscopes (thermometers without a scale), were invented by Galileo in 1592 (Figure 1) and by his medical colleague and student, Sanctorius (1561-1636) circa 1613; and independently between 1606 and 1609 by Cornelius Drebbel (b.1572), a Dutchman working in London [4]; and by the physician, Dr Robert Fludd (1574 – 1651) in 1626 [11]. The French Jesuit, Jean Leuréchon (1593 – 1670), was the first, in 1624, to use the word "thermometer" to describe an instrument for measuring the degree of hotness [12]. The development of thermometers passed through three stages – that of (a) thermometers open to the air; (b) closed thermometers; and (c) experiments and trials of different types of calibration [10]. It was in this third context that clinical thermometry became possible.

The science of clinical thermometry depends on the arbitrary selection of fixed points (usually two) and the construction of an accurate linear scale between them. Many attempted this endeavour,

Figure 1: A Galilean thermo scope. A desk-top replica reading in the range of 17°-27°C, with an accuracy of 1°C.

dating from Francesco Sagredo's selection and numerical designation of three fixed points. His fixed points were the column height reached at greatest summer heat which he marked at 350 degrees, the temperature of snow (marked as 100 degrees) and the height of the column when his instrument was immersed in a snow-salt mixture (0 degrees). Other thermometer scales were invented by Robert Boyle (1627 – 1691), Robert Hooke (1635 – 1703) and Isaac Newton (1642 – 1727). Newton chose two fixed points – the melting point of ice (which he designated as 0°) and, as his upper fixed point, "the armpit temperature of a healthy Englishman" at 12 degrees. On Newton's scale water boiled at 34 degrees.

Later scales were invented by Rømer (1644 – 1710) from 1702. In one of Rømer's most developed instruments, he designated the upper fixed point as that of human blood heat – labelling it 22.5 degrees. Gabriel Fahrenheit (1686 – 1736) developed Rømer's concepts in a series of new scales, initially labelling the upper fixed point (again, that of blood heat) at 96 degrees. He later changed the upper reference point to that of boiling water, which he labelled at 212 degrees [10]. Other scales were developed by Réaumur (1683 – 1757) in France and by Joseph Delisle (1688 – 1768), a French astronomer working in St Petersburg. The Swedish astronomer, Anders Celsius (1701 – 1744) proposed a 100-point scale with a boiling point of water at 0 degrees and the melting point of snow at 100 degrees. His friend at Uppsala, the Professor of Medicine and Botany, Carl Linnaeus, he of the binomial system of nomenclature [13]: "invented the scale to give us the now familiar centigrade scale that matches the psychological feeling that hotter should correspond to a higher temperature" [10,14].

The Calibration of Thermometers

Thermometry of relevance to the treatment and prevention of burn injury relies on the expansion of a liquid, usually mercury or alcohol, as the temperature rises. Thermometry depends on accuracy, and this in turn on calibration. The upper datum point for the Rømer, Fahrenheit (later thermometers), Réaumur (later thermometers), Delisle (single fixed point), and Celsius and Linnaeus thermometers was the boiling point of water. In 1724 Fahrenheit had observed that that upper fixed point, that of boiling water, varied with changes in atmospheric pressure [15].

Changes in barometric pressure affected those early thermometers in two ways. First, in open thermometers, reduced air pressure gave higher readings at all fixed points on the scale. The earliest air thermometer corrected for air pressure was one designed by Guillaumo Amontons (1663-1705) and demonstrated to the Académie des Sciences in Paris in 1702 [16]. This first (barometric) problem was solved by sealing the thermometer tube, thus rendering the height of the column independent of air pressure. This was first achieved in 1654 by Ferdinando II de Medici, Grand Duke of Tuscany, who constructed a sealed bulb-and-tube system [16]. This was independent of where one placed the calibrating fixed points on the column.

The second challenge related to variations in the upper fixed point calibration that of the temperature of boiling water itself. This fact, albeit unrecognised by earlier inventors, had been a problem unknowingly affecting the scales of all scientists who were using either open or closed thermometers. Fahrenheit showed that the upper fixed point of his thermometer read lower as the barometric pressure decreased. It was this observation that an English physicist and inventor, Sir George

Shuckburgh (1751-1804) (later, after 1794, Sir George Shuckburgh Evelyn) [17] took as his starting point for the series of experiments which were to establish the precision of thermometric calibration which underpins clinical temperature-taking today [15].

Shuckburgh Evelyn was a scientist of extraordinary precocity, talent and industry [18]. In 1798, he was awarded The Royal Society’s Copley Medal, then the highest accolade in world science, for his researches and published work in thermometry, physics and astronomy. One of his memorials is the Shuckburgh Crater on the moon [19]; another is the pragmatic confidence which all can justifiably feel when taking and interpreting temperatures both of patients and places.

Shuckburgh realised that the accurate calibration of the upper fixed point of both the Celsius and Fahrenheit scales, the boiling point of pure water, depended on two variables. These were the barometric pressure of the moment, the result of changing meteorological conditions; and the height above sea level that the boiling point of water was observed. He wrote in 1779:

“The heat of boiling water having for some years been used as one of the terms for graduating the scale of thermometers…the heat of boiling water was variable, according to the pressure of the atmosphere” [20].

He addressed this problem by measuring the boiling point of water at various defined barometric pressures, corrected for changes in height. To do this he travelled throughout the winter of 1774 (in France) through the Alps to Rome, working on this project until the end of summer of 1776 [21]. He took his barometers, thermometers and water-boiling apparatus up various mountains in Europe and Great Britain, where he experimented. These observations necessitated him obtaining simultaneous (or close-in-time) barometric readings at the base of mountains and at their measured height, recording the temperature at which water boiled.

Shuckburgh’s work on barometry-thermometry was a popular field of interest in the late eighteenth century. A scientific colleague, Colonel William Roy FRS, also published work in this field in 1777 [22]. Another scientist, Tiberius Cavallo FRS, extended Shuckburgh’s work:

“The determination of the various degrees of heat shown by boiling water under different pressures of the atmosphere, has been attempted by various persons, but it was lately completed by accurate and numerous experiments of Sir George Shuckburgh, member of this [Royal] Society” [23].

Figure 2: The armorial bearings of The Royal Society, London, bestowed by King Charles II. The bloodhounds, as supporters, and the falcon on the crest are metaphors for keenness of observation in the pursuit of science. The motto, “Nullius in Verba” is freely translated as “Take nothing on trust or the hearsay of others [but pursue knowledge by personal keen observation]”.

For his discoveries in thermometry, barometry [24], astronomy and chronometry [25,26] and for his concept and quest for a time-based standard of length, he was awarded The Royal Society’s Copley Medal [27], the world’s most prestigious award for science in his era (Figure 2). His research made possible the accuracy of thermometry, subsequently clinical thermometry, on which patient care depends.

Conclusion

The prevention of thermal injuries and the severity of their consequent morbidity have been reduced by a range of design measures, by legislation, and by public education of the risks. Secondary preventive approaches have included better awareness of first aid measures at the site of injury, improved retrieval to burn centres and clinical regimens which have made deaths, especially in children who initially survive inhalational injury, a very uncommon event.

Each of these domains uses the relationship between temperature and thermal injury to define its algorithms for treatment, for advocacy and for the legislative regulation in burns prevention. The original meaning of “temperature”, the tempering of the body’s heat, continues its message if not its etymological definition, into the work of burns teams everywhere in the twenty-first century.

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