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Processing Storage and Display of Physiological Measurements

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Temperature provides a clear example of physiological measurement. Scientists in the 18th Century, including the great Fahrenheit and Celsius, developed mercury thermometers to measure temperature.

Mercury thermometers use the expansion of mercury in a narrow glass tube to convert temperature into the visible length of the mercury column. Once the thermometer has been calibrated by the manufacturer, a clinician reads off the temperature from the scales marked on the tube. Mercury thermometers for clinical use often had a maximum reading feature: the mercury expands with increasing temperature, but when the temperature drops (e.g. when the thermometer is removed from the patient’s body), the mercury column breaks but retains the maximum value until the thermometer is vigorously shaken.

Unfortunately, shaking a mercury-in-glass thermometer is a bad idea, and they have been phased out, but they illustrate key principles of physiological measurement.

The clinician is interested in a physiologically relevant physical variable, such as temperature. Temperature has to be converted to something the clinician can see and preferably record. The expanding column of mercury does this transformation. However, as Celsius himself noticed, mercury is not the only thing expanding: for accurate measurements, the expansion of the glass tube matters and has to be compensated for. Then there is noise, unwanted or irrelevant changes in temperature; for example, the patient may have just had a hot drink, and while the temperature being measured may be “correct” it will not be a clinically relevant temperature.

Temperature is one of many physical values that drift; the thermometer may take a few minutes to stabilize as it warms up to the patient temperature. At what point should a ‘final’ reading be taken? And which temperature do you want: mouth, under-arm (axillary), rectal, in-ear, ... ? What time of day? They all give different measurements, and there is no ‘standard’ value of normal body temperature.

Thermometers need to be calibrated, so the markings on them correspond to real temperatures (not millimeters!). Calibration highlights the difference between precision and accuracy: precision refers to how many numbers can be read off the markings, whereas accuracy refers to how well the numbers correspond to the actual temperature being measured.

For example, 37.01 °C is a precise temperature (we say ‘to four figures’), but if the patient is at 36 °C, it is not very accurate. Confusion between precision and accuracy bedevils digital equipment, since it is easy for a digital thermometer (or computer screen) to display something that looks precise like 37.45 °C as if it was accurate, which it may not be — only an expensive laboratory thermometer can achieve this sort of accuracy. Unfortunately, adding a digit to a display is much cheaper than making a thermometer more accurate, so high precision displays are rarely more than misleading marketing.

We probably want to measure temperature to within 0.1 ºC around 37 ºC. Thermistors, which we discuss below, can easily achieve this, though cheap ones are only accurate to around 5%. However, even these can be calibrated to measure more accurately — the main reason they are cheap is the manufacturer has not measured their parameters accurately, not that they are intrinsically inaccurate.

It is important to make sure clinical digital thermometers are regularly checked and recalibrated in case they drift, for instance caused by batteries ageing. Of course, cheaper thermometers drift more, so they need frequent recalibration. Sensors may also suffer from contamination; that is, if they get wet or dirty, the electronics may not be able to measure accurately.

**Thermistors**

Many thermometers use a thermistor to convert temperature to an electrical value that can be measured and displayed for easy reading. Thermistors are robust and reliable, and they come in many varieties. They have many uses, from handheld thermometers to thermometers on pulmonary artery catheters.

A resistor is a simple electrical device that satisfies Ohm’s Law over its operating range. If a current flows through a resistor, the voltage measured across the resistor is proportional to the resistance. Hence, \( V = IR \), for voltage in volts, current in amps (usually denoted I, not A), and resistance in ohms. Current in a resistor creates heat, which will change the resistance — in particular, too much current will burn a resistor out (which is the principle behind fuses, which are intended to burn out when current reaches a preset limit). Usually, one would choose resistors that have stable resistance over the range of intended
temperatures, but a thermistor is intended to change resistance with temperature. A thermistor therefore converts temperature to a measurable electrical value.

With a mercury thermometer you just convert distance (say, mm) to temperature (say, degrees C). With a thermistor you convert resistance (ohms) to temperature, but thermistors are more complicated because their resistance does not vary linearly with temperature. The Steinhart–Hart equation is used to do the conversion, but it is complex and relies on manufacturer’s data to use. Despite the complexity of the equation, it is still only an approximation.

Because the equation is complex, thermometers use a computer chip to do the calculation. Useful features like displaying the average or maximum value are then easy to provide by programming the computer appropriately.

**Resistance measurement**

Resistance itself is measured indirectly, usually by measuring voltage. The circuit shown in Figure 1 uses a potential divider to provide a voltage that depends on a thermistor’s resistance. The meter measures the voltage drop across the thermistor, and

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**Potential divider used to measure thermistor resistance**

Figure 1 The thermistor resistance can be worked out by measuring the voltage in this simple circuit, which is called a potential divider because it divides the battery voltage depending on the two resistors.

Ohm’s Law relates voltage $V$, resistance $R$ and current $I$. Ohm’s Law can be expressed equivalently as $V = IR$, $I = V/R$ or $R = V/I$, when they are measured in units of volts, ohms, and amps.

Referring to the circuit (left), the battery voltage is $V_{\text{battery}}$ so the current flowing, $I$, through the two resistors, is given by using $I = V/R$ thus:

$$I = \frac{V_{\text{battery}}}{R + R_{\text{therm}}}$$

Using Ohm’s Law again, the voltage $V$ measured by meter is given by using $V = IR$ thus:

$$I \times R_{\text{therm}} = \frac{V_{\text{battery}}}{R + R_{\text{therm}}} \times R_{\text{therm}}$$

Rearranging:

$$R_{\text{therm}} = \frac{V_{\text{battery}}}{R_{\text{therm}}} - V$$

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**Wheatstone Bridge to measure resistance — two ways to draw the same circuit**

Figure 2 $R_1$ and the thermistor make one potential divider; $R_2$ and the reference resistor, $R_{\text{var}}$, make the other potential divider. If $R_1 = R_2$, the meter measures zero when $R_{\text{var}}$ equals the thermistor resistance. The problem has changed from measuring absolute voltage (which needs calibrating) to measuring voltage differences (which is easier), and the voltage of the battery no longer matters — as long as it’s not zero! Note $R_{\text{var}}$ can be controlled by a computer so this circuit can measure resistance digitally.
hence the resistance of the thermistor can be calculated from Ohm’s Law (see Figure 1).

The Wheatstone Bridge adds a second potential divider with a known resistance (instead of a thermistor whose resistance is unknown). This clever circuit is usually drawn in a diamond shape, as shown on the right in Figure 2.

From analogue to digital measurement

There are problems with conventional circuits, particularly when there are long wires from the sensor and the measuring equipment (see Figure 3). The wires act both as a resistor and effectively as a radio aerial, picking up mains hum, stray voltages from the patient and other noise; batteries discharge so the reference voltages drift; and there may be other effects such as temperature changes and dirty connections affecting other components, not just the sensor itself. Small changes (e.g. in patient temperature) can therefore get swamped by noise. A good solution is to convert the measurement to digital as close as possible to the sensor. Digital signals are very robust, and can be sent over long distances without degrading. There are alternatives to thermistors that produce digital signals directly (see Box 1).

Once made digital, physiological measurements can be processed by a computer in many ways, generally called digital signal processing (DSP). Converting resistance to temperature is the very simplest sort of processing; more complex signal processing can provide averages or trends, and can remove noise (such as mains hum) for sensitive signals like ECGs.

Electrical safety

Any sensor must be electrically insulated from the patient, for two reasons. The patient must not be at risk of electric shock, and the measurement must not be affected by the patient’s body being in electrical contact with the sensor. The thermistor will therefore be electrically insulated. Unfortunately almost all electrical insulation is also a thermal insulation, though many insulators also have the advantage of providing protection from moisture and other chemicals. This means the temperature sensor will take longer to reach thermal equilibrium with the patient. For hygiene reasons, the insulated sensor is typically sealed in a stainless steel tube, and this will further increase the time to reach thermal equilibrium.

When directly measuring electric signals, such as EEG and ECG, obviously electrical insulation would be counterproductive. Therefore great care should be taken to ensure the measuring equipment and all wiring is safe, dry and shows no signs of wear.

Storage and display

Having got a physiological measurement inside a computer, almost anything can be done. Measurements and signals can be stored on disc (increasingly, solid state disc), SD cards, USB sticks, in a patient record system or in the cloud on one or more computers somewhere else, and they can be printed on charts or displayed on screens.

The ease of storing computer data indefinitely (particularly on removable media like USB sticks) creates a serious problem. Measuring equipment may be displaying data from a previous measurement or previous patient (particularly if one is analysing trends over days); worse, some devices have demonstration modes that fabricate realistic physiological data to show off how the device can be used.

Always check the display is showing data from the actual patient at the right time and date, and that it is not running any sort of demo mode! If measurements are transmitted using wifi or Bluetooth...
Varieties of temperature sensors

**Thermistors** are robust, small and easy to use. They have a non-linear, usually negative temperature coefficient — meaning their resistance decreases with increasing temperature. Thermistors may be made out of metal oxide beads and usually have resistance around 10 kΩ, typically decreasing by 200 Ω per degree C.

**Resistance thermometer** (or resistance temperature detector, RTD) — some materials like platinum have a resistance that increases with temperature, and therefore make ideal temperature sensors. RTDs are not as sensitive as thermistors but are suitable for high precision applications; they are stable and very accurate. Platinum sensors are often made out of small coils of wire and have a low resistance of about 100 Ω, typically increasing by a fraction of an ohm per degree C.

**Thermocouples** — a combination of metals that produce a small voltage proportional to temperature (the Seebeck effect). Thermocouples are small and robust, and respond quickly to temperature changes. Thermocouples provide very low voltages (typically 20 μV per degree C) that increases with temperature, so they need complex circuitry that is likely to drift. (Many thermocouples can be connected in series to form a thermopile, not for more accurate measurement, but to make higher voltages; they are often found in gas fire controls.)

**Infrared sensors** — any hot body gives off radiation, and its temperature can be deduced from the radiation. Infrared sensors are combined with integrated circuits into a single package that provides a voltage proportional to the measured temperature (e.g. the MLX90614). Infrared sensors have the advantage that they respond to temperature very fast, but the disadvantage they are sensitive to any infrared, perhaps not originating from the object whose temperature is being measured. Typically, infrared sensors give an average reading for any infrared they detect. Infrared sensors are ideal for in-ear ( tympanic) temperature measurement, as they require no physical contact and inside the ear there is no ambient infrared to interfere with the measurement.

**Integrated sensors** — many sensors (whether using infrared or semiconductor junctions, which have a voltage drop that varies with temperature) can be built into integrated circuits. For example, the TMP35 has an analog output voltage proportional to the Celsius temperature, and nothing needs doing other than measuring the voltage, and the DS18B20 has a digital network output — which makes it reliable to use for remote sensing as it can be connected directly to a computer.

**Chemical sensors** — chemical sensors are most familiar in temperature strips: plastic strips that can be held on the patient's forehead, and which change colour with temperature. No electricity is required, so they are simple and reliable, but they are not convenient for recording temperature.

*This list is not exhaustive; for example, other applications, such as domestic thermostats and cookery thermometers, often use simple ‘battery free’ technologies such as bimetallic strips.*

Box 1

instead of wires, it is possible the measuring equipment is picking up signals from a different patient. In many applications data protection is an important issue, particularly if data is stored on a measuring instrument or removable media or transmitted over a network to a potentially unknown or uncontrolled computer.

Some displays are easy to misread or do not have enough contrast to read in poor lighting. Seven segment displays are common, and are very easy to misread particularly at angles where some segments may be hidden from view. Some displays only provide an overview of measurements, and for digital images (e.g. MRI scans) they may show artifacts — features on the image caused by display limitations. Tiny steps apparent in ECGs and EEGs are caused by similar problems. When devices are switched on, they should light up all features and symbols in their displays to check they work correctly.

Those early scientists Fahrenheit, Celsius and Kelvin would be amazed at how easy measurement has become, but the dramatic changes in technology should be warning that things will continue to change.

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**FURTHER READING**