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Body temperature measurement uncertainty arising from ear canal geometry and temperature gradients

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ABSTRACT

We report the results of a numerical thermal model of the ear canal and tympanic membrane. The model was used to assess the uncertainty contributions in determining body temperature arising from lower ear canal temperature gradients. We find that for reasonable assumptions of such gradients the standard uncertainty contribution is < 0.1 °C.

1. Introduction

After mercury-in-glass thermometers were phased out of clinical use in the 1980s the use of ear thermometers for determining body temperature has become widespread across the world [see for example [1, 2]]. The ear canal measurement site has been long recognised as a reliable representation of core body temperature. This is mainly due to its location: the lower ear canal and tympanic membrane are well insulated and also, in part, share the same blood supply, with the ear canal supplied by the external carotid artery and the tympanic area by the internal and external carotid artery. Finally, the measurement site is near the hypothalamus which, among other functions, regulates body temperature. This is something which other body temperature measurement sites cannot reproduce, for example measurements from skin/forehead thermometers, or even oral thermometers, should, in principle, be corrected to represent core body temperature, a process which can lead to additional uncertainty.

However, despite the lower ear canal/tympanic membrane being a good measurement site the magnitude of the uncertainty arising from lower ear canal temperature gradients, and hence uncertainty in the inferred core body temperature, has not been widely studied. Here we model both published lower ear canal temperature gradients [3] and also a range of assumed lower ear canal temperature gradient scenarios ranging from no gradient (to provide a baseline for the study) to an extreme temperature gradient which is unlikely to arise in practice. This latter case provides an upper bound for the uncertainties.

From the thermal model of the ear canal and tympanic membrane we estimate the effect of the temperature gradients on the resultant uncertainty in the determination of core body temperature.

2. Thermal model

The physical structure of the ear canal used in the model is taken from a physiological description [4]. This represents an average adult ear canal physiology, with an elliptical tympanic membrane of 8 mm and 10 mm minor and major axis respectively and a curved ear canal of 35 mm length (Fig. 1).

The assumption for the modelling is that the thermometer probe is introduced into the upper ear canal with only the temperature gradient between the tympanic membrane and the thermometer probe in the lower ear canal affecting the measurement.

Six different temperature gradients are simulated

- no gradient (upper bound) with the tympanic membrane and the lower ear canal fixed at 37.0 °C.
- a linear temperature drop from 37.0 °C at the tympanic membrane to 20.0 °C at the thermometer probe tip (this is the extreme scenario).
- the temperature profile described in [3].
- a linear profile with a 1 °C temperature drop from the tympanic membrane to the thermometer probe.
- a linear profile with a 2 °C temperature drop from the tympanic membrane to the thermometer probe.

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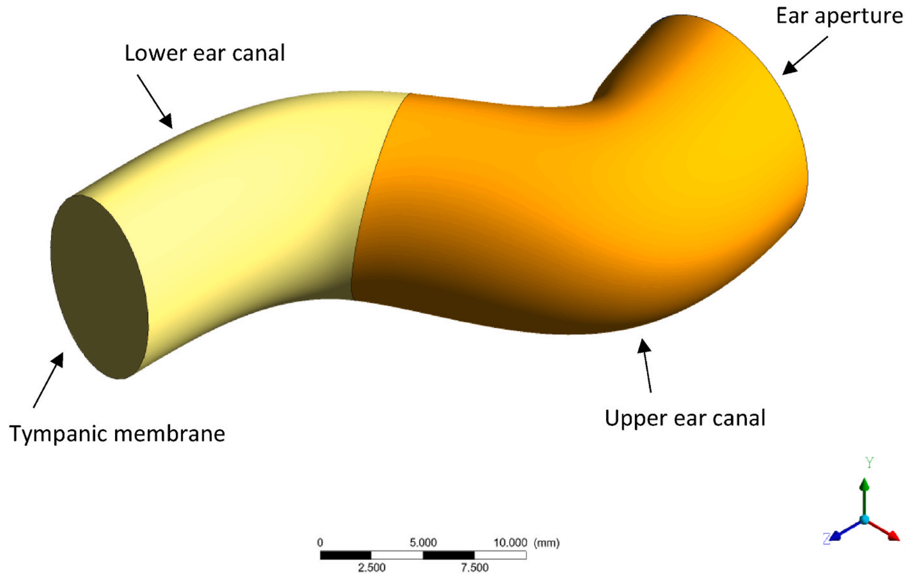

Fig. 1. Ear canal model.

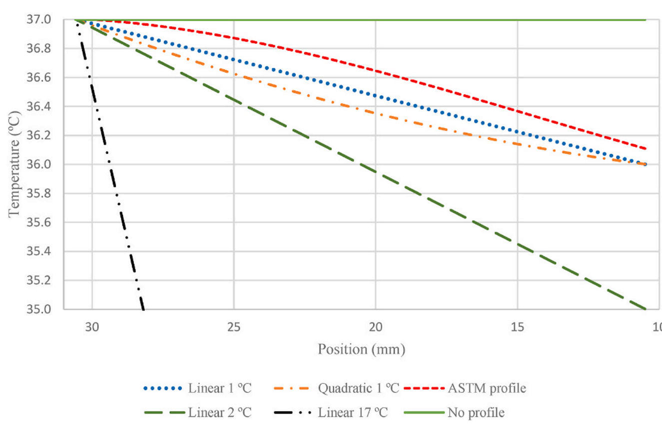

Fig. 2. Temperature profiles simulated in the lower ear canal.

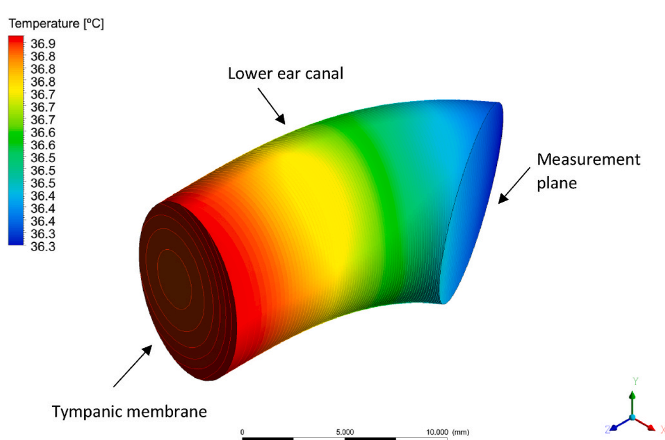

Fig. 3. Typical model of 1 °C linear temperature gradient from the tympanic membrane to the measurement plane.

- a quadratic profile with a 1 °C temperature drop from the tympanic membrane to the thermometer probe.

The thermal radiance (and hence inferred temperature) at the measurement plane is essentially the average radiance of the lower ear canal/tympanic membrane combination with the different assumed temperature gradients given above. In all the simulated cases, the tympanic membrane has an external radiation temperature of 37 °C and an emissivity of 1.00 and the ear canal has the external radiation temperature as per the assumed temperature gradients and an emissivity of 1.00. To check the sensitivity of the model to different values of skin emissivity a value of 0.94 was also modelled and the difference between the results for the two emissivities were completely negligible amounting to <0.005 °C.

These 6 temperature gradients are represented in Fig. 2.

Fig. 3 shows the temperature gradient for the linear profile with a 1 °C temperature drop from the tympanic membrane to where the simulated measurement probe tip resides.

3. Results of the model

Here we describe the results of the thermal model and the impact on core body temperature uncertainty. In this case the temperature uncertainty is characterised by the difference (properly a temperature error) from the core body temperature, which is set to 37.0 °C in the model, and the temperature that the thermal radiation has in the measurement plane. The position of the measurement plane was set by the length of a typical ear thermometer probe penetration into the upper ear canal, which is typically around 1.5 cm. By this technique, the probe is aligned within the lower ear canal and facing the tympanic membrane directly. More complex geometry, including partial obscuration of the tympanic membrane by the lower ear canal (worse alignment of the probe) was not simulated. The impact of thermometer uncertainty is not relevant to the model results but is discussed below in the more general context of improving body temperature measurement.

In Table 1 gives the six model scenarios. In all cases the tympanic membrane is assumed to have a uniform temperature of 37.0 °C.

The temperature difference between the tympanic membrane and the thermal radiation in the measurement plane is in effect the temperature error. From this the uncertainty contribution arising from lower ear canal temperature gradients can be estimated. These uncertainty values are converted into standard uncertainties following the process described in the ISO Guide to Uncertainty in Measurement (GUM) [5]. Assuming a rectangular probability distribution the semi-range of the difference is then divided by the square-root of three to obtain one standard uncertainty.

Table 1
Different model scenarios for the temperature gradients in the lower ear canal.

Distance from tympanic membrane/mm	No temperature gradient of lower ear canal/°C	17 °C temperature linear profile of lower ear canal/°C	Estimated temperature gradient as given in the ASTM standard/°C[a]	1 °C temperature linear profile of lower ear canal/°C	2 °C temperature linear profile of lower ear canal/°C	1 °C temperature quadratic profile of lower ear canal/°C
0 (at tympanic membrane)	37.0	37.0	37.0	37.0	37.0	37.0
5	37.0	32.2	36.9	36.7	36.4	36.6
10	37.0	28.0	36.6	36.5	35.9	36.4
15	37.0	23.7	36.4	36.2	35.5	36.1
20 (at measurement plane)	37.0	20.0	36.1	36.0	35.0	36.0

[a] We here reduce the value of the temperature of the tympanic membrane given in Figure X1.4 of the ASTM standard by 0.3 °C. to give a tympanic membrane temperature of 37.0 °C. This is consistent with the other modelling scenarios.

Table 2
Temperature difference (i.e. error) between core body temperature (tympanic membrane) and temperature at the simulated measurement plane for different assumed lower ear canal temperature gradients. The estimated one standard deviation uncertainties arising from these values are also given.

	No gradient/°C	17 °C linear gradient/°C	ASTM gradient/°C	1 °C linear gradient/°C	2 °C linear gradient/°C	1 °C quadratic gradient/°C
Temperature difference/°C	0.00	3.30	0.13	0.29	0.48	0.24
One standard uncertainty/°C	0.00	0.95	0.04	0.08	0.14	0.07

The temperature difference (error) and one standard uncertainty values are given in Table 2.

4. Discussion

The thermal gradients in the lower ear canal are likely to have a small impact on the overall uncertainty of the body temperature measurement with an ear thermometer. Current medical thermometer device standards [for example 3] state that the maximum permissible laboratory error for the temperature range 36 °C to 39 °C shall be no greater than 0.2 °C; later on in the standard (Section 7.2.5) this is stated as ±0.2 °C.[1] The uncertainty estimates derived from the thermal models for reasonable assumptions of gradients (the ASTM standard value and the 1 °C linear and quadratic gradient) are all below this value. These results confirm what was already widely expected, namely that the measurement site is a good site for core body temperature.

Open questions remain concerning the use of ear thermometers for body temperature measurement. These are mainly either physiological and device related and are discussed elsewhere [6–8]. In summary these concerns are:

From a *physiological* point of view the measurement site has some drawbacks. Ensuring the thermometer has a clear view of the tympanic membrane and lower ear canal is important when critical body temperature measurements are undertaken. For example, the presence of ear wax or fluid in the ear may significantly or completely obscure the view of the measurement site leading to false low readings.

In addition, some individuals may have an ear canal which is more crooked than normal, again leading to the measurement site being partially or even largely obscured. Some thermometer manufacturers have recommended a form of "ear tugging" while taking measurements, in an attempt to straighten the ear canal; others have said it is unnecessary. However it is unclear how often the geometry of the ear canal is an issue, and it can also be assessed through pre-examination of the ear.

There are a number of *device* related issues which impact in-service uncertainty; the most serious of which can be addressed through appropriate protocols. The most important is thermometer calibration drift and, to retain low measurement uncertainty, the ear thermometer should be regularly calibrated against a traceable calibrated reference standard [9]. What this means is that the calibration of the ear thermometer needs to be linked by an unbroken chain of measurement to assured temperature standards. This is only achieved if the calibration provider is ISO17025 accredited [10]. If this isn't the case then the calibrations performed by the provider may be unreliable, leading to, at best, offsets from true temperature when the calibrated thermometers are brought back into service. Another factor that should be taken into account is if the thermometer has been exposed to a shock of some form, for example either by dropping on a hard surface or exposed to high temperatures Before being subsequently used the performance of the device should be checked by a calibration to ensure it is still fit-for-purpose.

Good practice guidance in the use of ear thermometers is currently under development by the Consultative Committee for Thermometry [11]. The guidance is being developed by world leading experts in thermometry from around the world and it is hoped to release this for widespread dissemination and use by the end of 2021 [12].

5. Conclusions

Here we examine the impact on lower ear canal temperature gradients on the uncertainty of core body temperature measurement. Our findings for realistic assumptions of the gradients are that this contribution is likely to be negligible compared to other sources of uncertainty; either those arising from physiological or device-in-use effects.

CRediT authorship contribution statement

Pablo Castro Alonso: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Roles, Writing – original draft. **Graham Machin:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision,

[1] It must be said here that the clinical thermometer standards appear to treat uncertainties in a way that is not consistent with the GUM. For example the ASTM standard states that the maximum permissible laboratory error (MPE) is 0.2 °C (Section 5.3.1.1) but later in the document (Section 7.2.5) it states "ASTM laboratory accuracy requirements in the display range 36 °C to 39 °C for IR thermometers (*meaning ear thermometers* author added) is ±0.2 °C". It is not clear whether the latter has an expansion factor of $k = 1$ or $k = 2$ nor how or if this value is related to the MPE which (if treated according to international uncertainty analysis practice should be divided by 2 (to get the semi-range) and then $\sqrt{3}$ to get one standard uncertainty).

Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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