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Non-Invasive Temporal Artery Thermometry: Physics, Physiology, and Clinical Accuracy

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ABSTRACT

Temporal artery (TA) thermometry was developed in answer to requests by pediatricians for a replacement for: 1) ear thermometry due to inaccuracy; and 2) rectal thermometry due to parents' (and most clinicians') growing dislike of the method. The underlying technology development spans some 20 years, borrowing heavily from methods invented for industrial processes and medical research. Although the forehead has been used since antiquity to detect fever, its accuracy had always been questionable until physiological artifacts were understood and overcome, and mathematical modeling of arterial heat balance at the skin has made it possible to produce accurate core temperatures entirely non-invasively with just a scan of the forehead. Clinical studies have been conclusive as to TA superiority to ear thermometry, and well on the way to being conclusive as to TA at least as accurate as rectal. The physics are relatively straightforward, but the physiological requirements are not. Underlying physiological artifacts cause errors of more than 2 deg C in non-invasive thermometry and must be reduced by an order of magnitude to provide medically useful temperatures. Patented TA technology incorporates methods of dealing with physiological artifacts to overcome these errors. Mass screening for SARS containment with this method is examined.

INTRODUCTION

The new interest in mass screening people for fever has launched a renewed interest in non-invasive thermometry and the use of IR devices for such applications. Unfortunately, these attempts at screening have probably done little to detect actual fevers, and appear to provide false assurance that carriers of SARS are being successfully detected.[1] This paper presents the underlying science of how several physiological artifacts render such measurements problematic, and how a successful new method of non-invasive thermometry overcomes them.

The temporal artery area is a site with a long history of temperature measurement, actually dating back to the early centuries before Christ, and the first recorded references to palpation of the head for assessment of fever. Demonstrably, the temporal artery is easily accessible, and there are no mucous membranes present; eliminating the risk of contaminates, and despite lying so close to the skin surface, it presents no risk of injury from being touched.

The temperature at the outer surface of the head is not the same as the arterial temperature of interest, since there is local cooling of the arterial blood supply due to a variety of local influences at the skin. Furthermore, attempts to model the cooling are confounded by the high variability of skin perfusion due to thermoregulatory response, up to 100 to 1 range in blood flow in some skin areas.

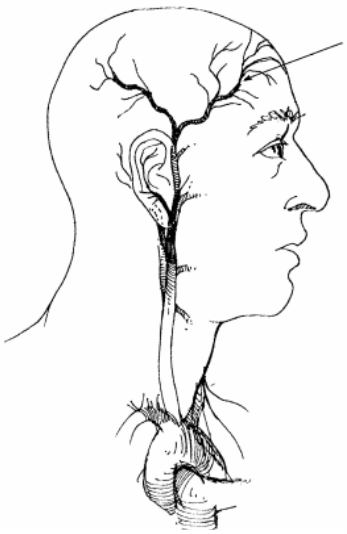

Figure 1. Frontal branch of the superficial temporal artery

The frontal branch of the superficial temporal artery (Figure 1) demonstrates the necessary requirements for the skin thermometry method: it is easily accessible, contains no mucous membranes, and most importantly, it has no or very few arteriovenous anastomoses (AVA).[2] Lack of AVA's means that perfusion rate is reliable under essentially all conditions, and the blood flow is relatively free of vasomotor control in response to thermomoregulatory stimuli. This property is unique to the temporal artery when considering all accessible cutaneous blood vessels. The high and reliable perfusion

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allows accurate mathematical computations of the heat lost to the environment due to the cutaneous flow, and thus an accurate calculation of the source arterial temperature at the heart. Figures 9 and 10 (color images at end of paper) show the temporal artery (TA) prominently in two subjects. The camera resolution must be at least 0.1°C to show it clearly.

The method of correcting the temperature for the cooling effect at the skin is called Arterial Heat Balance (AHB). An equation may be derived by equating the heat supplied to the tissue by arterial blood flow = $wc\ (T_c - T_s)$, with the heat loss at the skin to the ambient = $hA\ (T_s - T_a)$, which results in the AHB equation: [3]

$$T_c = (1 + h/pc)(T_s - T_a) + T_a$$

where T_c = core arterial temperature, T_s = skin temperature at the TA, T_a = ambient temperature, h =heat transfer coefficient, $p = w/A$ = blood perfusion rate per unit area at the skin, and c = specific heat of blood. AHB can be used anywhere in or on the body to compute source arterial temperature from local skin temperature T_s, if local ambient temperature T_a and the values of the parameters are known.

Important properties of the AHB model can be immediately ascertained:

If $h = 0$, which means the heat loss is zero, then $T_c = T_s$, i.e. skin temperature is the same as core temperature.
If $p = \infty$, which means the perfusion is infinite, then $T_c = T_s$.
If $T_a = T_c$, which means that ambient temperature is near core temperature, then $T_c = T_s$.

The basic idea is to make h/pc as small as possible so that any uncertainty in T_c is as small as possible.

When T_s is as high as possible, h/pc will be as low as possible, thus maximizing accuracy. T_s is highest right at the TA, but its location is not precisely known. Therefore we ***SCAN*** the skin area over the TA (see Figures 2, 11) to detect the ***PEAK*** T_s which then is used in the AHB equation. A fast scan rate (~1000 frames per second is used) during the 2-3 second forehead scan is necessary to be sure of detecting an accurate peak. The heat loss coefficient h must be reproducible, which means that the scanned skin area must be exposed. The perfusion rate p must be constant and high, which is the cardinal characteristic of TA for this application.

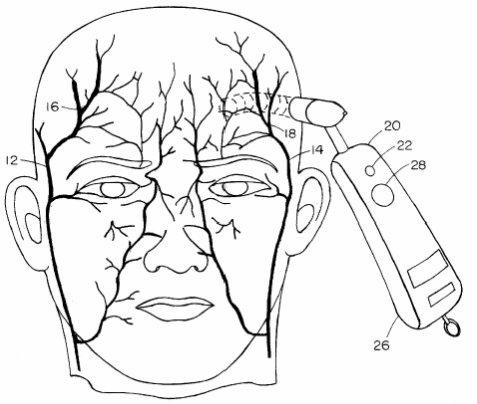

Figure 2. Scanning the temporal artery.

The AHB equation is completely general for steady state conditions, although it might be modified to include nonlinearities and other second order effects to improve accuracy. It can be applied to various thermometry methods to assess errors as follows.

1. ***Ear thermometry***: The heat loss coefficient h is highly variable depending on the direction the sensor is pointed when the probe is inserted. Deep tissue near the tympanic membrane is well insulated by the cavity effect, thus producing a low value of h and an accurate temperature. Superficial external ear tissue is much more exposed, and will produce h values an order of magnitude greater. The perfusion rate p is very low in the ear tissue, thus amplifying the effect of variations in h. The result is a highly variable measurement, which produces differences of more than 1°C depending on where the IR sensor is pointed. (Figure 3)

2. ***Oral thermometry***: Measurements in the oral cavity are heavily influenced by evaporation, which dramatically

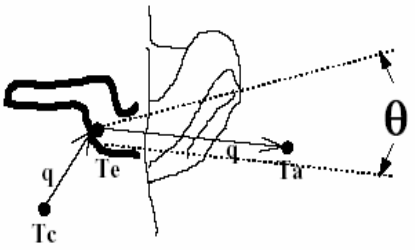

Figure 3. Superior aspect of ear canal. Thermal energy q supplied via arterial blood at temperature Tc to the ear tissue at temperature Te is balanced by radiation loss through angle theta to ambient temperature at Ta.

influences ***h***, changing by orders of magnitude depending on air motion, local dew point, and precisely where the thermometer probe is placed. However the perfusion rate ***p*** is very high in the oral cavity, tending to reduce the inaccuracy caused by high and variable ***h***. The overall result is a measurement that is always lower than arterial temperature, and varies significantly. A seminal study by Tandberg and Sklar (Figure 4) showed that increased respirations reduce oral temperature by about 1°C per 25 resp/minute.[4]

3. ***Rectal thermometry***: The heat loss factor ***h*** is determined by the insertion depth, and can be variable, particularly in infants. The perfusion rate ***p*** is very low except under heavy exercise conditions. There is the added time lag error due to low perfusion of a large tissue mass, which can be many hours for adults. Mathematically, the AHB equation would be derived for unsteady state conditions to include heat storage.[5] The result is more a variable measurement than is commonly assumed.

4. ***TA thermometry***: The SCAN guarantees finding the TA without any difficulty. The heat loss coefficient ***h*** has only small variations depending on local skin properties (except for perspiration). The perfusion rate ***p*** is very high. The result is a consistent measurement, largely independent of technique. Perspiration is managed by extending the SCAN to a spot on the neck behind the earlobe (Figure 12), thus recording the temperature at this site as the peak if the TA is cooled by perspiration. Since the body's thermoregulatory response produces maximal skin perfusion just prior to and during diaphoresis, almost all skin areas will have perfusion rates close to that observed at the TA, and thus can produce an accurate body temperature by using the AHB equation calibrated for TA. The spot behind the ear is convenient for the scan and remains relatively dry (Figure 13). For a normothermic person the area behind the ear is vasoconstricted and cool (Figure 14), and the SCAN will ignore this cooler reading. This method has been clinically proven by comparisons to pulmonary artery catheter temperatures.[6]

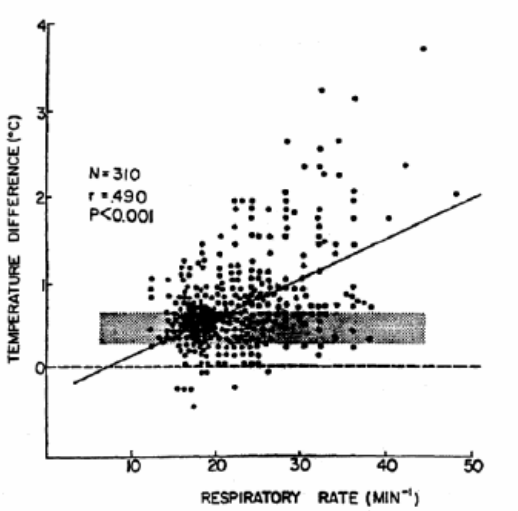

Figure 4. Reproduced and quoted from Tandberg and Sklar: "Temperature Differences (Rectal minus Oral) in 310 Patients with a Wide Range of Respiratory Rates. The straight line best fit is shown. The stippled area demonstrates the traditional 'normal' difference between rectal and oral temperature (0.3 to 0.65°C).

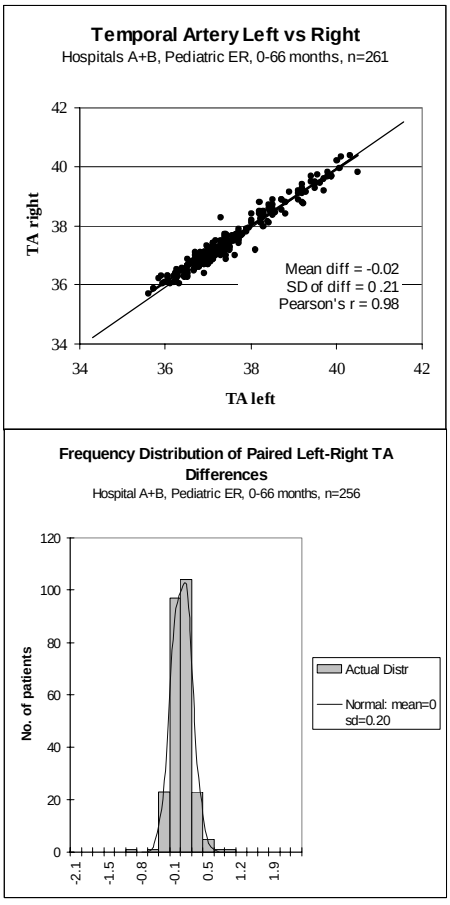

Figure 5. TA left-right reproducibility.

CLINICAL RESULTS

The TA thermometer was validated by initial studies performed by qualified clinical researchers in prestigious institutions. Reproducibility of both the instrument and physiological assumptions was established by comparing paired left-right readings (Figure 5). Validation versus rectal is shown in Figure 6 and versus pulmonary artery catheter in Figure 7 and Table 1. Exergen and its clinical research partners concluded that the TA method was indeed suitable for routine clinical use.

Independent clinical studies were then conducted for purposes of establishing clinical performance for publication. Several of these are:

1. TA thermometer proven more accurate than ear thermometry[7] and more accurate than rectal thermometer in responding to change in fever.[8] (Boston Children's Hospital and Harvard Medical School)
2. Found to be "a rapid, noninvasive screening tool for detection of rectal fever.[9] (Johns Hopkins Hospital and School of Medicine)
3. Proven at least as accurate as rectal measurement.[10] (Hospital for Sick Children and the University of Toronto)
4. Interchangeable with a pulmonary artery catheter.[6] (Massachusetts General Hospital)
5. Interchangeable with an esophageal thermistor.[11] (Hospital for Sick Children and the University of Toronto)
6. Found to be indispensable for pediatric practice use in a recent 2300 patient study.[12] (Children's Hospital Medical Center of Akron)

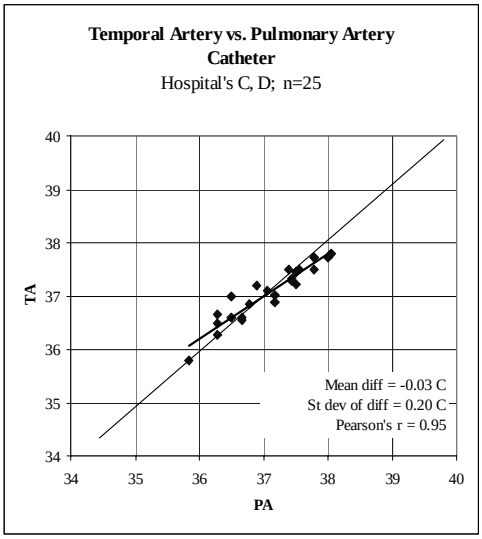

Figure 7. Validation of TA versus pulmonary artery thermistor

Table 1. Validation of TA versus pulmonary artery thermistor. Data from Carroll et al 2003.

			Paired readings vs. PA	
Reading Site	**n**	**Temperature ± sd**	**Difference**	**p-value**
Pulmonary artery (PA) thermistor	86	37.0 ± 0.7	-	-
Temporal artery (TA)	85	37.1 ± 0.8	+0.1 ± 0.7	0.17
Rectal	15	37.5 ± 0.8	-0.1 ± 0.6	0.69
Oral	30	36.2 ± 0.9	-0.8 ± 0.8	<.001

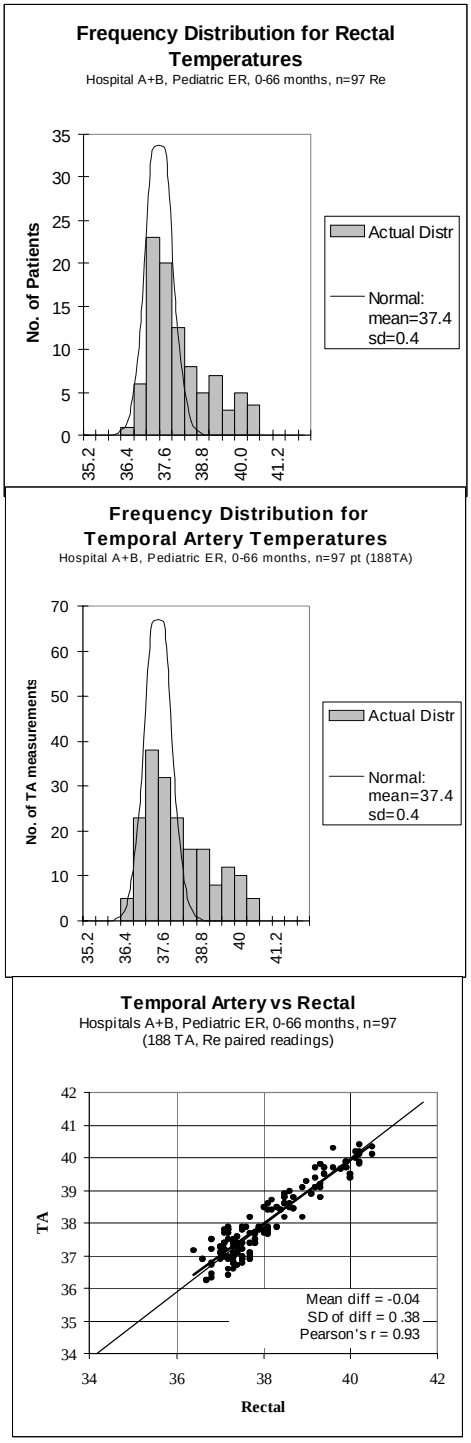

Figure 6. Validation of TA vs. rectal temperature

SARS SCREENING

With the outbreak of SARS in China, there were extensive searches for thermometers which could be used for rapid non-invasive screening for fever. The TA thermometer is one that was in heavy demand due to its proven clinical accuracy in fever detection. A number of factories in the affected areas used TA thermometry to scan workers prior to entering the factory (Figure 15), as well as schools, hospitals, businesses and places of worship. One person with a TA thermometer can screen up to ~600 persons/hr. This is a practical rate for a factory or an office, and can easily be used at airports which employ security procedures similar to those in the US, without any additional delay to the passenger. However, there was a great deal of interest at airports to use IR imagers, so it is productive to examine the variables which must be considered to provide a reliable fever detection system.

An IR camera (or any remote IR radiometer) must contend with two sources of measurement uncertainty: the radiometer uncertainty and the physiological uncertainty. The analysis below only deals with the physiological uncertainty. It appears from specifications of the best devices that absolute accuracies for IR imagers are limited to about ±1°C. Spot radiometers designed for medical applications can achieve absolute accuracies of 0.2°C, and the best (professional TA thermometers – Figure 16) achieve 0.1°C absolute accuracy.

The calculation method below uses the probability theorem that the variance (square of the standard deviation) of a uniformly distributed variable (all values in the range are equally likely) is equal to its range squared divided by 12. This allows us to compute uncertainties in statistical terms.

Table 2. Radiometer temperature reading uncertainties due to several physiological variables

		Estimated standard deviation of temperature uncertainty		
Physiological Variable	**Est. Range**	**Remote IR**	**TA thermometry**	Note
Skin emissivity	0.97 ± 0.02	0.31°C	0.03°C	1
Skin ambient temperature	±5°C	0.58°C	0.06°C	2
Variable perfusion on face	±1°C	0.58°C	0.06°C	3
Perspiration on the face	±1°C	0.58°C	0.06°C	4
95% confidence interval of errors due to identifiable skin physiological variables		2.09°C	0.21°C	5

Notes:

1. Patented Automatic Emissivity Compensation System reflective cup reduces emissivity error and reflected energy error. (Figure 17)
2. Patented Arterial Heat Balance System reduces this error.
3. Patented scan of the temporal artery reduces this error.
4. Patented touch behind the ear method reduces this error.
5. Square root of the sum of the squares of standard deviation of errors, times two.

Skin emissivity is not a well established property, and almost certainly varies with color and texture. One reference shows marked variation at wavelengths shorter than about 8 micron (Figure 8).[13] The overall temperature uncertainty estimates for TA appear to account for about half of the variability observed in the short term reproducibility tests (Figure 5). There are certainly other physiological variables, as well as user variability, which are not modeled that affect readings, that require further research to identify and characterize.

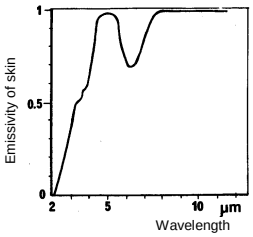

Figure 8.

The large uncertainty for the remote IR device is consistent with observed poor performance in detecting fevers. Since the entire range of normal temperatures is only

about 2°C, which represents ±2 SD,[12] a measuring device with 2 SD = 2°C will have very poor sensitivity in fever detection, and very high false positives if adjustments are made to the fever threshold to improve sensitivity. An identical twin provides a very good reference to normalize all variables, and fever detection is very clear by comparing them (Figure 18).

There may be some attractiveness to developing imagers with the physiological model improvements employed in TA thermometry for certain applications. However, it is very difficult to justify such an approach at airports, where each X-ray security point could be equipped with a highly competent and proven TA thermometer costing about $400 (Figure 16), or even a light duty consumer model available in retail stores for $50 (Figure 19), compared to an IR camera costing $50,000 to $100,000 which may not reliably detect fevers.

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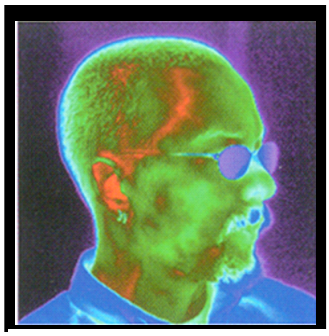

Figure 9. IR image of the temporal artery

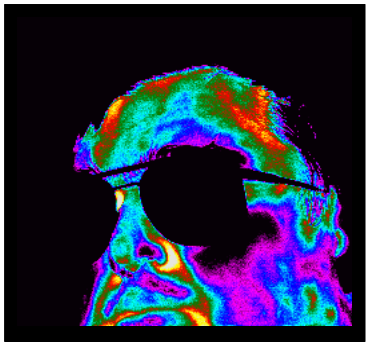

Figure 10. IR image of the temporal artery

Figure 11. Scanning the temporal artery

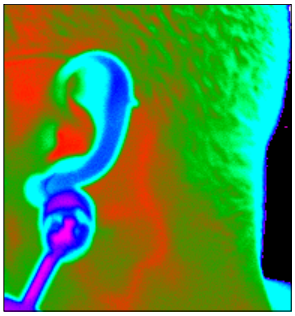

Figure 12. Measuring behind the ear

Figure 13. Diaphoretic person

Figure 14. Normothermic adult

Figure 15. TA thermometers scanning factory workers at plant entrance

Figure 16. TAT-5000 professional model.

Figure 17. TA thermometer with patented reflective cup for emissivity compensation

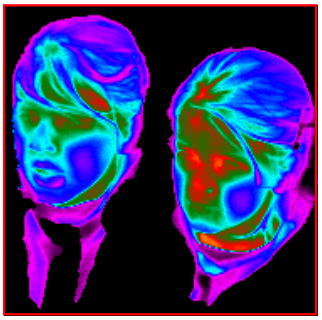

Figure 18. Twins: one normal and one febrile.

Figure 19. TAT-2000C thermometer available in retail stores for home use