Effects of surface emissivity and viewing angle on errors in thermography

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SUMMARY. The effects of surface curvature on errors in thermography are considered. Use of the linear approximation of the Stefan-Boltzmann relation suggests that reflected radiation will he responsible for much of the error in estimation of surface temperatures by thermography, and that at oblique angles of view temperature anomalies may be obscured without showing large errors in absolute temperature.

Key words: thermography; errors; experimental work.

The effects of surface curvature on the radiation emitted from a curved surface reaching a thermal scanner, have been previously discussed in detail by Watmough, Fowler and Oliver (1970). These authors showed that over a wide range of surface emissivites the apparent emissivity of a curved surface should vary very little for angles of view between the normal and $\pi/4$, but that at greater angles progressively increasing differences would be expected between the signal incident on the detector from an element of emitting surface at an angle ϕ to the line of view and that incident from a point at the same temperature viewed along the normal. Though thermal scanning is perhaps now less promising as a tool in cancer detection, many other clinical uses have been proved, for example in the detection and monitoring of treatment of joint lesions and vascular anomalies, quantification of the likely causes of error in thermography therefore remains important. The present paper discusses a further source of error in thermography due to variation in the reflected radiation, which may in many circumstances exceed that considered by Watmough et al, and will always occur with it.

Theory

The relation between the emissivity of a surface at normal incidence ($_{o\lambda}$) and its refractive index (n_λ) at the same wavelength (Coulson 1955) is:

$$1 - {}_{o\lambda} = \left(\frac{n\lambda - 1}{n\lambda + 1}\right)^2 \qquad (1)$$

from which Watmough et al obtain:

$$\varepsilon_{\phi\lambda} = 1 - \tfrac{1}{2}\left\{\frac{\beta - \cos\phi}{\beta + \cos\phi}\right\}^2 \left\{1 + \left[\frac{\beta\cos\phi - \sin^2\phi}{\beta\cos\phi + \sin^2\phi}\right]^2\right\} \qquad (2)$$

(In the original paper, this equation appears incorrectly with the index inside the first bracket). Here β is $(n_\lambda^2 - \sin^2\phi)^{1/2}$, where ϕ is the « Angle of View » between the normal to the surface and the line of sight of the scanner. Watmough et al (1970) give error curves of differences in energy emitted, based on this equation, for a range of surface emissivities. However, Steketee (1973) has since confirmed the results of Mitchell et all (1967) which show that the overall emissivity of the human integument is close to 0.98. This value has therefore been used in producing Fig. 1 which shows the predicted variation of emissivity with viewing angle for skin, since Watmough & Olive (1968 a, b) obtained similar values for 2-5 pm radiation.

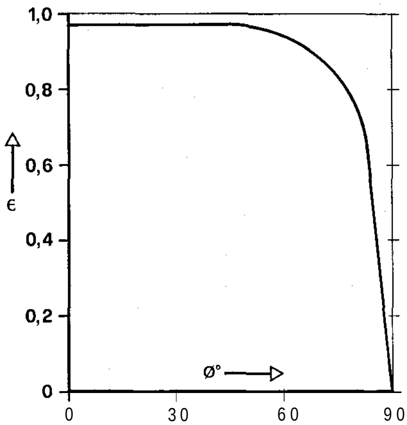

Fig. 1. Variation of emissivity ε with angle of view predicted by theory for a smooth surface with ε=0.98 at normal incidence.

If we denote the skin temperature by T_s, and that of the surrounding environment by T_e, the « black body » radiation appropriate to the skin temperature is:

$$E_b = \sigma T_s^4 \tag{3}$$

and the radiation incident on the skin from the environment:

$$E_e = \sigma T_e^4 \tag{4}$$

Most contemporary scanners are sensitive to energy in the waveband from 2 to 5 µm. However for the present purposes we will neglect the distinction between the total radiation reaching the scanner and that in the waveband to which it is sensitive, justify this later. The radiation reaching the scanner which is emitted by the surface is then:

$$E_s = \varepsilon \sigma T_s^4 \tag{5}$$

so that the difference (AE) from the black body emission appropriate to surface temperature is therefore given by:

$$\Delta E = E_b - E_s = (1-\varepsilon)\ \sigma T_s^4 \tag{6}$$

However there is a second source of radiation which reaches a scanner, as radiation from the surroundings will also be reflected towards a scanner by the surface. In any waveband the emissivity and absorption of a surface are equal, so that the skin will absorb a fraction of the radiation incident from the surroundings. More important in the present context is the reflection of the remainder, so that, assuming the environment is an isotropic source of radiation, the quantity of radiation from the environment reaching a scanner after reflection from the skin will be:

$$E^1 = (1-\varepsilon)\ \sigma T_e^4 \tag{7}$$

The difference between the black body radiation equivalent to skin temperature and that received by a scanner viewing the surface is therefore:

$$\Delta E = (1-\varepsilon)\ (\sigma T_s^4 - \sigma T_3^4) \tag{8}$$

so that ΔE will be negative if $T_e < T_s$.

Clinical thermographic examinations are usually carried out in rooms where the temperature differences between the subject and the environment are fairly small. Either the Stephen-Boltzman equation, or the higher power dependence of E on T at shorter wavelengths, may by linearised for small temperature intervals to the form:

$$AE = CAT \tag{9}$$

with acceptable errors for the present purpose. Equation 8 then becomes

$$\frac{AT}{T_s - T_e} = (1-\varepsilon) \tag{10}$$

where AT is the error in the estimation of the absolute temperature. The locus is a simple straight line (Fig. 2) which predicts that the error of a thermographic temperature measurement is proportional to:

(a) the deviation of the surface emissivity from unity

(b) the difference between the temperature of the skin and environment.

For example, for a 10°C difference between ambient temperature and skin temperature, the error in the estimation of the absolute skin temperature at normal incidence will be 0.2 K. This is unimportant because temperature anomalies are the object of investigation, and the emissivity is effectively constant at 0.98 for values of ϕ between the normal and 45" and only just falls below 0.95 at 60°. At $\phi=60°$ the error due to a 10°C difference from ambient temperature will be approximately 0.6 K, for $\phi=70°$ it will rise to 1.3 K and close to the tangent the indicated temperature becomes that of the surrounding environment. The predicted variation of error AT with ambient temperature is shown in Fig. 3 for environmental temperatures at 5 K intervals from (T_s+5) to (T_s-15).

The error can also be considered in a different way, which is perhaps more relevant to the clinical case: the signals of interest in the clinical applications of thermography are anomalies in the temperature distribution. The variation of T with ϕ can also be regarded as giving the *proportion* of the true signal which originates from the surface inspected. For the lower curve of the female breast in mammography, or for the inner surfaces of legs, the error in the *absolute* temperature may be relatively small, since much of the skin's « environment » is other tissue at a similar temperature, but the signal from an anomaly will be obscured almost as effectively as that from the outer tangential surfaces of the body due to the reduced emissivity at glancing angles.

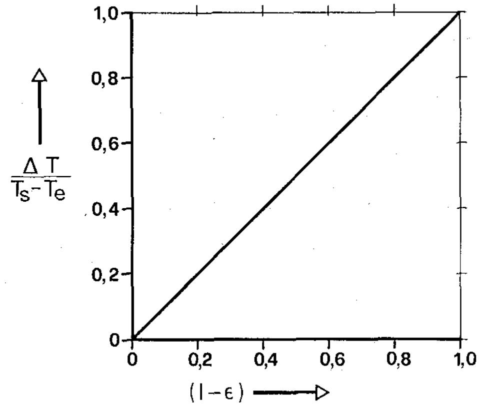

Fig. 2. Variation of the ratio of temperature error AT to the difference between true skin temperature and environmental temperature, as a function of skin emissivity. Locus predicted- by linear approximation of radiative exchange.

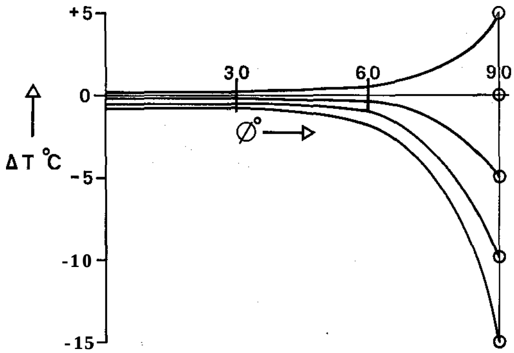

Fig. 3. Predicted variation of temperature errors of thermographic observation against angle of view. Lines are shown for ambient temperatures at intervals of 5°C from 5°C above skin temperature to 15°C below skin temperature.

Conclusions

The present paper supports the conclusions of Watmough et all (1970) that errors in thermographic observations of skin temperature distributions are likely to be small for angles of view up to n/4. However, it is demonstrated that the thermal radiation environment of smooth anatomical surfaces will have a major influence on the error in temperatures observed for angles of view greater than n/4, and that such errors are likely to be proportional to the difference between the temperature of the skin of the subject and his environment, and to the deviation of the skin emissivity from unity.

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