HEAT FLUX TRANSDUCER MEASUREMENT ERROR IN RELATION TO CLOTHING AND TISSUE INSULATION — A SIMPLIFIED VIEW

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INTRODUCTION

Heat flux transducers (HFTs) are useful devices for the direct measurement of heat exchange between the body and the environment. As with all systems, however, the very act of making a measurement perturbs the system under observation to some degree. With HFTs, this perturbation can be considerable under certain conditions of use. In simple terms, the measured heat flux is less than the true heat flux because of the extra thermal insulation introduced by the transducer itself.

Correction of the measured heat flux to arrive at true heat flux has been the subject of numerous studies, and several equations have been derived to achieve this correction (1-3). None of them, however, provide an estimate of the error introduced by the transducer. This information could be useful in planning a study, since correction of the measured heat flux often entails making additional high precision temperature measurements in order to use the equations. Depending upon the objectives of the study, the size of the error may not warrant the extra effort of obtaining these precise temperatures.

This paper presents a graphic method of estimating the magnitude of the error to be expected under specific experimental conditions. If the precision temperature measurements are made and the correction equations are applied, the graph can be used to estimate either the clothing or the tissue insulation, assuming the other parameter is known.

METHODS

Consider heat being transferred from the body core (at temperature T_c) through body tissues and clothing insulation to an ambient environment (at temperature T_a). Let the thermal resistances of the HFT, the tissue beneath the HFT, and the insulation over the HFT be. R, R_{tis}, and R respectively. Note that the clothing insulation referred to is the total insulation between the skin (or HFT) and the "infinite sink" of the environment. Note also that this insulation need not involve clothing – in the case of nude subjects or uncovered skin it could be simply a layer of still or unequilibrated air or water.

The true or correct heat flux (H_{corr}) passing through only the tissue and the insulation is given by Eqn 1:

$$H_{corr} = (T_c - T_a) / (R_{tis} + R_{ins}) \qquad [1]$$

while the measured heat flux (H_{meas}) passing through the tissue, the HFT, and then the insulation is given by Eqn 2

$$H_{meas} = (T_c - T_a) / (R_{tis} + R_{hft} + R_{ins}) \qquad [2]$$

The heat flux correction factor is given by the ratio H_{corr} / H_{meas} and can be reduced to the form shown in Eqn 3

$$H_{corr} / H_{meas} = 1 + 1 / (R_T + R_I) \qquad [3]$$

where R_T and R_I are the ratios of the thermal resistances of the body tissues and clothing insulations, respectively, to the thermal resistance of the HFT being used. If R_T and R_I are used as the ordinate and abscissa of a log-log plot, then plotting Eqn 3 for various values of the correction factor produces a family of limes, each representing a constant correction factor as R_T and R_I vary. Thus, knowing the thermal resistance of the HFT from the manufacturer or from independent measurements, and having reasonable estimates of the body tissue and clothing insulations from measurements or from values published in the literature, one can readily obtain an estimate of the correction factor that would apply under the given test circumstances.

RESULTS

Data from a series of water immersion experiments designed to measure the ratio H_{corr} / H_{meas} for a broad range of simulated "tissue" insulation showed excellent agreement with the theoretical relationships described above. In addition, physiological data from a human forearm water immersion experiment in which tissue insulation was carefully measured using an implanted multi-junction thermocouple probe (4) again confirmed the theoretical relationships.

The correction equations predict, and experimental results confirm, that the measurement error introduced by HFTs is minimized under conditions where tissue is vasoconstricted and insulation such as clothing covers the body. The effects on the measurement error of changing tissue and/or clothing insulation are vividly clear from the graphic presentation of Eqn 3. What is most informative is to limit the variation in R_T to the physiological range (about 1.6 - 40 using popular commercial HFTs) and observe the effects of variations in R_I on the measurement error. Using typical values for R_{hft}, useful ranges of R_I can be calculated and marked on the graph. For example, a layer of still water 1 - 2 mm thick would result in an R, range of 0.2 - 0.4. In this range the correction factor lines are almost vertical, thus independent of changes in the insulation (i.e., thickness) of the water. The correction factor is, however, very sensitive to changes in tissue insulation under these circumstances, ranging from as much as 1.5 for vasodilated tissue down to 1.03 for vasoconstricted tissue (i.e., 50 - 3% error). By comparison, with clothing insulation ranging from 1 - 4 clo, R, varies from about 20 - 80, and the correction factor lines are almost horizontal in this region. In fact, the correction factor now varies from about 1.05 - 1.01 (i.e., 5 - 1% error) and is almost unaffected by changes in the vasomotor state of the tissues.

CONCLUSIONS

A theoretical equation has been derived to show how the themal resistance of an HFT interacts with body tissue and clothing insulations to underestimate the true heat flux. This relationship can be graphed to facilitate estimation of the magnitude of the measurement error knowing the clothing and tissue insulations. Alternatively, the graph can be used to examine the sensitivity of the correction factor to variations in body tissue or clothing insulation under various test conditions.

Allowing tissue insulation to vary over the physiological range, measurement errors ranging from 3 - 50% can be expected from nude skin during water immersion, the magnitude depending almost entirely upon the vasomotor state of the tissues. For subjects clothed in 1 - 4 clo of insulation, the measurement error is greatly reduced to between 1 - 5% . Considering other sources of experimental error and variation in physiological parameters, it may be reasonable to use uncorrected values of heat flux under these circumstances, thereby obviating the requirement for additional high precision temperature measurements.

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