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Individual variability of tissue temperature profile in the human forearm during water immersion

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ABSTRACT

The purpose of the present study was to investigate the effect of a range of water temperatures (T_w from 15 to 36°C) on the shape of the tissue temperature profile of the resting human forearm at thermal stability. Tissue temperature (T_t) was continuously monitored by a calibrated multicouple probe during 3 hours immersion of the forearm. The probe was implanted approximately 9 cm distal from the olecranon process along the ulnar ridge. T_t was measured every 5 mm, from the longitudinal axis of the forearm (determined from computed tomography scanning) to the skin surface. For all temperature conditions, the temperature profile inside the limb was linear as a function of the radial distance from the forearm axis ($p < 0.01$) when the temperature data were averaged for the different groups at each water temperature tested. However, interindividual variability regarding the shape of the temperature profile was observed, in addition to intraindividual variability in 5 of the 15 subjects. A linear profile was observed in 50% of the subjects, a profile with convex curvature in 30%, and a profile with concave curvature in the remaining 20%. No significant relationship was observed between the occurrence rate of the different shapes of temperature profile and the water temperature. These data suggest that anatomical structures like bone and artery located at proximity to the pathway of the thermal probe implantation could have influenced the shape of the individual temperature profile inside the forearm.

KEYWORDS: Cold stress, cold water immersion, intramuscular temperature, thermal stress.

INTRODUCTION

The tissue temperature profile in the human limbs has been described in several studies for various experimental conditions, including rest (Pennes, 1948; Reader and Whyte, 1951), exercise (Saltin et al., 1968) and during various thermal stresses (Bazett and McGlone, 1927; Sargeant, 1987). Generally, it has been observed that the tissue temperature increases with the distance inside the limb; the highest temperatures were recorded at the longitudinal axis of the limb, and were always lower than the rectal temperature of the subject (Bazett and McGlone, 1927; Buchthal et al., 1944; Pennes, 1948). In addition, it has been reported that the tissue temperature profile in a limb becomes steeper as the ambient temperature decreases (Bazett and McGlone, 1927; Reader and Whyte, 1951).

Different shapes of limb temperature profile have been reported for resting conditions during different thermal stresses. Saltin et al. (1968), Petrofsky and Lind (1975) and Sargeant (1987) observed linear tissue temperature profiles, while Pennes (1948), Kuehn et al. (1970) and Williams and Karl (1980) mainly reported parabolic profiles. Reader and Whyte (1951), Bazett and McGlone (1927) and Clarke et al. (1958) observed linear, parabolic and even more complex profiles. From these studies, there is no general consensus on the shape of the temperature profile in limbs under resting conditions. Furthermore, none of the above studies have presented a mean temperature profile for a group of subjects, and no information is available on the individual variability of the tissue temperature profile in limbs.

Burton (1934) suggested from his theoretical approach that the temperature profile inside a limb having a cylindrical geometry is dependent on the magnitude and uniformity of the heat generated or liberated inside the tissues. According to his theory, an hyperbolic temperature profile should be observed in the absence of heat production inside a limb, while uniform heat production should produce a parabolic profile. On the other hand, a linear temperature profile would suggest non-uniform heat production inside the limb (Burton, 1934). In addition, Tikuisis and Ducharme (unpublished observations) have observed that a cold stress induces a non-uniform radial heat generation or liberation inside a limb (more heat being present near the longitudinal axis of the limb than at the periphery). At thermal neutrality a more uniform radial pattern of heat generation inside the limb is observed, mainly because of the very small thermal gradient. From these observations, it was therefore expected that the shape of the temperature profile in a limb will shift from a linear profile during cold stress to a parabolic profile at thermal neutrality.

The objectives of the present study were to investigate the effect of a range of water temperatures on the shape of the tissue temperature profile in resting human forearm at thermal steady-state, and to characterize the individual variability of the temperature profiles. It was hypothesized that the rate of occurrence of linear and parabolic temperature profile would decrease and increase, respectively, as the water temperature was increased. This study also presents additional information regarding the individual variability of other thermal data recorded during the immersions of the forearm such as blood flow, heat flux, arterial blood temperature, and rectal temperature of the subjects.

MATERIAL AND METHODS

Subjects. Fifteen healthy male subjects, aged 18 to 30 years, volunteered to participate in the study. Before all testing, the health status of all subjects was assessed by a medical authority. The subjects were also fully informed of the purpose of the study, the potential risks associated with the experimental procedures, and of their right to withdraw from experimentation at any time without prejudice. Written informed consent was obtained from all subjects prior to experimentation. The experimental protocol was approved by the Institute's Human Ethics Committee.

Experimental design. The subjects were asked to avoid performing any vigorous exercise during the period of the study, and to abstain from smoking and using any medication, drug or other stimulant (including caffeine and alcohol) for at least 12 hours before the experiments. All experiments were performed at the same time of the day (within 30 min) beginning usually at 12h00, during the fall 1988 and winter 1989.

The subjects reported to the laboratory on four occasions, within a three-week period. On the first two visits, height and body weight were recorded, body surface area was calculated (Dubois and Dubois, 1916), and the length and the circumference of both forearms taken at their widest girth were measured. Computed tomography (CT) scans of the forearms were performed at the exact site of the tissue temperature measurements. Forearm circumference and radius, the longitudinal axis of the forearm, and the relative proportions of bone, muscle, and skin+fat at the multicouple probe implantation site were calculated precisely from a photograph of the CT scan using computerized planimetry (Graphics Tablet HP9111A, Hewlett-Packard). Since the intraindividual variability between forearm anthropometric characteristics was small ($< 2\%$), the anthropometric measurements of both forearms were pooled for each subject in Table 1.

Preparation of the subject. On the day of the experiment, the subject inserted a calibrated thermistor (Yellow Spring Instrument, Model 400, Yellow Springs, OH) approximately 16 cm beyond the anal sphincter to measure rectal temperature (T_{re}). The skin of the forearm at the probe implantation site was then shaved and disinfected with a Betadine solution (10% povidone-iodine topical solution USP; Purdue Frederick Company, Toronto). A topical anæsthetic (Skin refrigerant, ethyl chloride, Graham-Field, N.Y.) was then sprayed locally on the skin to freeze both the cutaneous and subcutaneous tissues, down to the fascia; this procedure did not anæsthetize the underlying skeletal muscles (W. P. VanHelder, personal communication).

An 18-gauge i.v. longdwell thin-wall catheter (Becton & Dickinson Rutherford, NJ) was then introduced into the tissues of the forearm until the catheter's tip reached the desired depth below the skin's surface (i.e. at the longitudinal forearm axis). The inner needle of the catheter was then withdrawn, and the probe, previously marked to allow an accurate determination of its position (hence, each junction in the multicouple probe), was then inserted into the tissues until its tip was leveled with the tip of the catheter. The latter was then carefully and completely withdrawn from the forearm, so that only the probe remained inside the muscle tissue. The probe was fixed to the skin with a waterproof dressing (Tegaderm 3M, St-Paul, MN) to avoid any displacement of the probe's tip in the resting muscle during the immersion, and to minimize the risk of infection. The method used to insert the multicouple probe inside the forearm tissues is an adaptation of the technique previously described by Edwards et al. (1974). The fine multicouple probe used in this study was designed to measure tissue temperatures (T_t) at different depths in the forearm. The T_t were measured every 5 mm from the longitudinal axis of the forearm to the skin surface, at the widest girth of the forearm; this corresponded to the first proximal third (superficial muscle: *flexor carpi ulnaris*; deep muscle: *flexor digitorum profundus*), approximately 9 cm distal from the olecranon process along the ulnar ridge (Fig. 1). All details pertaining to the design and to the calibration of the multicouple probe have been presented elsewhere (Ducharme and Frim, 1988).

Following the implantation of the multicouple probe, a 40 gauge type T thermocouple, calibrated to within 0.05 °C against a quartz thermometer (HP 2804A, Hewlett-Packard), was positioned within a few mm from the site of the implanted probe to measure skin temperature (T_{sk}). This method of skin temperature measurement has proven to be a reliable technique for the measurement of surface temperature (Stoll and Hardy, 1949).

Two waterproofed heat flux transducers (HFT) (Model HA13-18-10-P(C), Thermonetics Corporation, San Diego, CA) were taped to the skin on each side of the site of the implanted probe (Blenderm, 3M Corporation, St-Paul, MN) to measure heat flux from the skin of the forearm ($\dot{H}_{sk}$). Each HFT was recalibrated before the experiment using a method described elsewhere (Ducharme, 1990; Ducharme et al., 1990). Thermally conductive grease (Wakefield Engineering, Wakefield, MA) was applied underneath the HFTs to optimize the heat transfer between the skin and the device. A correction for the effect of the thermal resistance of the HFT on the measured heat flux was applied to $\dot{H}_{sk}$ (Ducharme et al., 1990).

Pre-immersion measurements. Once the subjects were fitted with all the measurement devices, they rested in a supine position under thermoneutral conditions (air temperature, T_a of 25.2 ± 1.1°C, relative humidity of 40 ± 2%) for one hour, while being only lightly dressed (T-shirt and casual pants). During that period, $\dot{H}_{sk}$, T_t, T_{sk}, and T_{re} were recorded continuously, using a computer controlled data acquisition system (HP-3052A, Hewlett-Packard). A mean value of data taken over a 1-min period was calculated for each measured parameter. The first measurement was performed approximately 10 min after the implantation of the probe. The $\dot{H}_{sk}$ values presented are the means of the values taken from the two HFTs.

At the end of the 60-min rest period, a 20 gauge catheter (Critikon, Johnson & Johnson, Markham) was inserted into the brachial artery under local anæsthesia (xylocaine 2%), the puncture site being 5 to 6 cm proximal to the multicouple probe implantation site. A fine (40 gauge) calibrated type T thermocouple probe was then inserted into the catheter to measure continuously for 30 s (using a computer controlled data acquisition system; HP-3052A, Hewlett-Packard) the arterial blood temperature ($T_{bla(o)}$) at the distal portion of the brachial artery. The arterial blood temperature at the end of the immersion (T_{bla}) was estimated from the $T_{bla(o)}$ value corrected for any fluctuation of the rectal temperature during the 3-h immersion, and also for the effect of the counter-current heat exchange occurring in the arm as follows:

$$T_{bla} = [T_{bla(o)} + (T_{re(end)} - T_{re(o)})] + (0.075\ T_w - 2.700) \qquad (1)$$

where $T_{re(end)}$ and $T_{re(o)}$ represent the rectal temperature taken at the end of the immersion and at the time at which $T_{bla(o)}$ was measured, respectively. The last component of Eq. 1 (0.075 T_w - 2.700) represents the correction of $T_{bla(0)}$ for the counter-current heat exchange which was estimated from the study of Bazett et al. (1948; using data from Fig. 3 for forearm immersion at T_w = 19.3°C), assuming no effect at water temperature (T_w) of 36°C, and a linear dependency with water temperature. The first assumption is supported by the very low temperature differences expected in the forearm between the venous and arterial blood temperatures during water immersion at 36°C, and the second assumption is supported by the data of Bazett et al. (1948) for air exposure.

Blood flow ($\dot{Q}$) was then measured in the forearm in which the probe had been inserted, with the subject sitting comfortably and resting the forearm under investigation on a surface at the level of the heart. The plethysmograph Whitney gauge technique (Whitney, 1953) was applied, using a mercury-in-silastic circumference gauge (Parks Electronics Laboratory, Aloha, OR). The gauge was calibrated before each experiment, using an accurate home-made linear calibrator. This calibration procedure was found to be accurate at ±5%; the source of error mainly due to the lack of compensation for the tissue compressibility (Brengelmann and Savage, 1986). A pressure cuff was placed on the upper arm, and inflated to a pressure of 50 mm Hg for 5-10 s. The resistance output generated by the stretching of the gauge was then read by a plethysmograph (Model 270-A, Parks Electronics Laboratory, Aloha, OR). This procedure was repeated 5 times, over a 10-min period. Experiments performed in our laboratory have demonstrated that the response and sensitivity of the gauge were not affected by the nature and the temperature of its environment (15 to 36°C), as long as there was no temperature gradient along the device (unpublished data). These results support the conclusion of Detry et al. (1972), Brengelmann et al. (1973), and Brengelmann and Savage (1986) that temperature compensation is uneccessary.

Immersion protocol. Once all pre-immersion measurements were completed, the subject immersed his forearm and hand for three hours in a well-stirred water bath maintained at a constant temperature of either 15, 20, 30, 33 or 36°C (Haake F3 circulator temperature controler, Haake EK 51-1 immersion cooler, Haake E 52 circulator heater, Saddle Brook, N.J.). The forearm was lying in the water bath at the level of the subject's heart. The range of water temperature was set by the presence of the hunting reaction (lower limit of 15°C; Lewis, 1930) or a negative heat loss at thermal stability (upper limit of 36°C). $\dot{H}_{sk}$, T_t, T_{sk}, and T_{re} were recorded continuously during the experiment, as described previously. At the end of the 3-h immersion, a second series of blood flow measurements was performed, with the forearm still resting in the water bath. Each subject experienced, over a two-week period two different water temperatures which were chosen randomly, one for each forearm. A total of thirty immersions were performed, six for each water temperature condition.

Statistical analysis. Linear regression analysis, independent Student's t-tests, and the tests for the equality of lines (based on slope and intercept) were performed using the BMDP Statistical Program (Biomedical Computer Programs, 1983, Los Angeles, CA). The classification of the temperature profiles into linear, convex and concave was determined statistically by looking at the significant improvement at the 0.05 level of the regression of T_t against r/r_{sk} using the F-test (Drager and Smith, 1966). When the fit was found to be significantly improved by a non-linear regression, the temperature profile was considered to be curvilinear. Where applicable, data are expressed as means ± SE. The level of statistical significance was set at $p < 0.05$, unless otherwise stated.

RESULTS

No shivering activity was observed during any of the forearm immersions. Rectal temperature (T_{re}) increased during the 3-h immersion period by 0.25 ± 0.03°C ($p<0.001$) for all water temperature conditions, either due to the circadian cycle (Aschoff et al., 1974) and/or to tissue vasoconstriction in the extremities caused by the local cold stress (Aschoff, 1944). T_{re} measured during the last ten minutes of the immersion averaged 37.45 ± 0.04°C for all subjects and water temperatures (T_w) tested.

The forearm tissue temperatures fluctuated by only 0.03 ± 0.01°C, and the forearm heat loss by 1.18 ± 0.21 W • m^{-2} during the last 10 min of each 3-h immersion. Therefore, we consider that the forearm had achieved a thermal steady-state after 3 hours of immersion at water temperatures ranging from 15 to 36°C. All temperature and heat flow data were corrected for the thermal conductivity along the wires and the insulation of the HFTs, respectively, and are expressed as the mean value for the last 10 min of the 3-h immersion.

Tissue temperature of the forearm at thermal steady-state. Fig. 2 depicts the thermal profile in the forearm at steady-state for each experimental condition tested. There was a significant inverse linear relationship at each temperature tested between the forearm tissue temperature at steady-state and the distance from the longitudinal axis of the forearm, correlation coefficient values (**r**) ranging from -0.80 to -0.95 ($p<0.001$). The slope of these relationships decreased linearly with increasing water temperature from -2.13 ± 0.25 °C • cm^{-1} at 15°C to -0.16 ± 0.02 °C • cm^{-1} at 36°C ($r=0.95$, $p<0.001$). The tissue temperature profile in the forearm immersed at 33°C was not significantly different from that measured following exposure to air at 25°C. In each experimental condition, the maximal tissue temperature was measured at the longitudinal axis of the forearm. Furthermore, the forearm tissue temperature at a given distance from the longitudinal axis (r) was linearly related to T_w (**r** ranging from 0.96 to 0.99, $p<0.001$), the slope of these relationships ranging from 0.57 ± 0.04°C • °C^{-1} at $r = 0.0$ cm to 0.95 ± 0.02 °C • °C^{-1}at $r =$ 4.0 cm.

Table 2 presents the temperature profile data in addition to forearm heat loss, blood flow, arterial blood temperature and rectal temperature for every of the 30 immersions performed. Although linear tissue temperature profiles were observed in the forearm when the temperature data were averaged for the different groups according to the water temperature tested (see Fig.2), some individual variability regarding the shape of the temperature profile was observed. For 10 of the 15 subjects tested, the same shape of temperature profile was observed for left and right forearms although immersed at different temperatures. Intraindividual variability for the shape of the temperature profile was, therefore, observed for only 5 of the 15 subjects. For these five subjects, the average forearm circumference (26.6 ± 0.3 cm) was significantly smaller than for the 10 subjects showing no intraindividual variability (28.4 ± 0.4 cm). Furthermore, for the group of 10 subjects showing no intraindividual variability, a linear tissue temperature profile was observed in 50% of the subjects, a profile presenting a convex curvature in 30%, and a profile with a concave curvature was observed for the remaining 20% (see Fig. 3 for typical examples). For the subjects showing convex or concave curvatures, the r^2 values for the regression of T_t against r/r_{sk} were improved by an average of 5% by fitting the profiles with non-linear regressions compared to linear regressions. No significant relationship was observed between the rate of occurrence of a type of temperature profile and the water temperature, for all three shapes of profile observed. At T_w = 36°C, however, when all the immersions were pooled together, 5 of the 6 immersions showed a linear temperature profile. Furthermore, the forearm circumference of the subjects showing a linear profile was significantly larger (28.6 ± 0.6 cm) than for the subjects showing a non-linear profile (27.1 ± 0.3 cm).

Heat loss from the forearm. Figure 4 shows the inverse linear relationship between water temperature and the heat loss from the forearm at thermal steady-state (**r** = -0.94, $p < 0.001$). The forearm heat loss decreased almost fourfold, from 95.4 ± 1.6 W • m^{-2} at 15°C, to 26.0 ± 1.4 W • m^{-2} at 36°C.

Arterial blood temperature. The arterial blood temperature measured at the distal portion of the brachial artery before the immersion ($T_{bla(0)}$) averaged 36.62 ± 0.06°C, being 0.58 ± 0.03°C lower than the average rectal temperature of 37.20 ± 0.04°C measured simultaneously ($p < 0.001$). After 3 hours of immersion, the arterial blood temperature (T_{bla}) in the brachial artery (at the level of the proximal forearm), as calculated from Eq. 1 ranged from 35.20 ± 0.17°C at T_w = 15°C to 36.84 ± 0.12°C at T_w = 36°C (Table 2).

Forearm blood flow. The forearm blood flow ($\dot{Q}$) measured at thermal steady-state during immersion was minimal at temperatures ranging from 15°C (0.78 ± 0.15 ml • min^{-1} • 100 ml tissue^{-1}) to 30°C (1.33 ± 0.24 ml • min^{-1} • 100 ml tissue^{-1}). There was no significant difference between these blood flows. Forearm blood flow at 33°C (2.94 ± 0.17 ml • min^{-1} • 100 ml tissue^{-1}) was significantly greater ($p < 0.001$) than that measured at lower temperatures, while it was significantly lower ($p < 0.001$) than that measured at 36°C (6.20 ± 0.51 ml • min^{-1} • 100 ml $tissue^{-1}$). Forearm blood flow in water at 33°C was not significantly different from that measured in air at 25°C (measured at the end of the resting period) (3.55 ± 0.20 ml • min^{-1} • 100 ml $tissue^{-1}$).

DISCUSSION

Linear temperature profiles were observed in the forearm during water immersion at thermal steady-state when the temperature data were averaged across all conditions and subjects according to the water temperature tested. Three main shapes of temperature profile were observed, however, when the data were within individuals. Among individuals with equivalent left and right forearm profiles the highest occurrence rate was a linear profile (50%) followed by one with a convex curvature (30%). This is in agreement with other studies which have reported mainly linear (Bazett and McGlone, 1927; Reader and Whyte, 1951; Clarke et al., 1958; Saltin et al., 1968; Petrofsky and Lind, 1975; Sargeant, 1987) and parabolic profiles in limbs (Bazett and McGlone, 1927; Pennes, 1948; Reader and Whyte, 1951; Clarke et al., 1958; Kuehn et al., 1970; Williams and Karl, 1980). To our knowledge, however, no study has reported mean tissue temperature profiles in limbs.

It is noteworthy that the methods and techniques used in the present study were developed to optimize the accuracy of the tissue temperature measurements and the localization of the probe in the forearm. In opposition to the other studies, the probe withdrawal technique was not used in the present study which permitted a more accurate positioning of the sensor in the forearm, and the temperature data were corrected for the thermal conductivity along the wires of the multicouple probe. These considerations allowed us to obtain temperature measurements accurate to 0.1°C (Ducharme and Frim, 1988).

om the theoretical work of Burton (1934), the shape of the temperature profile inside a limb is dependent on the magnitude and uniformity of the heat generated or liberated in the tissue. According to this study, a non-uniform heat production or liberation inside the limb will produce a linear temperature profile, while a uniform heat production or liberation will produce a parabolic profile (Burton, 1934). In addition, Tikuisis and Ducharme (unpublished observations) have observed that the radial heat generated or liberated in a limb is non-uniform during cold stress (more heat is present at the longitudinal axis of the limb). A more uniform radial pattern is present at thermal neutrality. From these studies, it is expected that the temperature profile in a limb will present a progressive shift from a linear to a parabolic shape as the ambient temperature increases toward thermal neutrality. In the present study, however, no significant relationship was observed between the occurrence rate of a type of temperature profile and the water temperature. It seems, therefore, that other factors than the thermal stress could be responsible for the variability of the shape of the temperature profiles.

In the present study, the multicouple probe was implanted inside the muscle tissue of the forearm for all its length except for a few mm at the periphery of the limb where subcutaneous fat and skin were present. Ideally, the thermal probe should have been positionned away from major arteries, and bones. Practically, however, this is very difficult to achieve, particularly in the forearm where there is no large muscle mass. From Fig. 1, it is observed that on each side along the implanted multicouple probe, structures like the ulna bone (near r/r_{sk} = 0.5) and the ulnar artery (near r/r_{sk} = 0.2) are present. These anatomical structures have a rate of heat production or heat liberation different from the muscle tissue. The bone has little heat production, while the ulnar artery is an important source of convective heat liberation. Therefore, the muscle tissue surrounding the bone probably has a lower temperature, and the muscle tissue surrounding the artery a higher temperature than the muscle tissue away from those structures for the same relative depth. When the probe was implanted away from these anatomical structures, the temperature profile could have been linear. However, the temperature profile could have been influenced upward near the axis of the limb when the tip of the multicouple probe was close to the ulnar artery, producing a temperature profile with a convex curvature (see Fig. 3B). On the other hand, the temperature profile could have been influenced downward halfway through the forearm radius (r/r_{sk} = 0.5) when the multicouple probe was close to the ulna bone, producing a temperature profile with a concave curvature (see Fig. 3C). If this explanation is valid, then the rate of occurrence of the different type of temperature profiles should be independent of the water temperature, as observed in the present study, but should be dependent on the subject's anthropometric characteristics. It was observed that the subjects showing a linear profile had a significantly larger forearm circumference compared with those showing non-linear profile. This can be explained by the lower probability for artery and bone to affect the temperature profile in a large forearm because of the larger muscle mass free of bones and arteries, compared with a smaller forearm where the different structures are closer together, giving a greater probability for those anatomical structures to influence significantly the temperature profile. For the subject with the smallest forearm circumference, it is expected that a temperature profile having both the convex (near r/r_{sk} = 0.2) and the concave curvatures (near r/r_{sk} = 0.5) would be observed due to the influence of both the artery and the bone at the same time. Figure 5 presents the temperature profiles of the subjects having the largest and the smallest forearm circumferences. As expected, the subject with the largest forearm circumference (31.8 cm) showed a linear temperature profile, while the subject with the smallest forearm circumference (24.0 cm) showed a profile having both the convex and concave curvatures, probably due to the influence of both the ulnar artery near the axis, and the ulna bone near r/r_{sk} = 0.5.

Because of the similar anthropometric characteristics of both forearms for a given subject (see *Material and Methods*), similar temperature profiles are also expected for the two immersions performed by every subjects, whatever the water temperature tested. Indeed, 10 of the 15 subjects showed the same shape of temperature profile for the two water immersions. However, intraindividual variability was observed for 5 of the 15 subjects possibly because of their significantly smaller forearm circumference compared to the 10 other subjects. Small forearm circumferences will accentuate any small differences in the implantation pathway between the two forearms of a same subject, which can result in different shapes of temperature profile.

In conclusion, this study has shown that when the temperature data are averaged for the different groups according to the water temperature tested, the temperature profile inside the forearm is linear as a function of the radial distance from the forearm axis. When the data were taken individually, however, three shapes of temperature profiles were observed, with predominance for the linear profile observed in 50% of the subjects. No significant relationship was observed between the occurrence rate of the different types of temperature profile observed and the water temperature. It is suggested that anatomical structures like the ulna bone and the ulnar artery located at proximity to the multicouple probe pathway of implantation could have influenced significantly the shape of the temperature profile inside the forearm.

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REFERENCES

Aschoff, J. Der Anstieg der Rectaltemperatur bei Umshiebener Abkuehlung der Koerperoberflaeche. Pfluegers Archif. 248: 149-157, 1944.

Aschoff, J., H. Biebach, A. Heise, and T. Schmidt. Day-night variation in heat balance. In: Heat loss from animals and man. J.L. Monteith and L.E. Mount, eds., Butterworths, London, 1974, chap. 8, pp. 147-172.

Bazett, H.C., and B. McGlone. Temperature gradients in the tissues in man. Am. J. Physiol. 82: 415-451, 1927.

Bazett, H.C., L. Love, M. Newton, and L. Eisenberg. Temperature changes in blood flowing in arteries and veins in man. J. Appl. Physiol. 1: 3-19, 1948.

Brengelmann, G.L., and M. Savage. Influence of tissue compressibility on calibration for strain-gauge plethysmography. J. Appl. Physiol. 61(3): 1210-1216, 1986.

Brengelmann, G.L., C. Wyss, and L.B. Rowell. Control of forearm skin blood flow during periods of steadily increasing skin temperature. J. Appl. Physiol. 35(1): 77-84, 1973.

Buchthal, F., P. Honcke, and J. Lindhard. Temperature measurements in human muscles *in situ* at rest and during muscular work. Acta Physiol. Scand. 8: 230-258, 1944.

Burton, A.C. The application of the theory of heat flow to the study of energy metabolism. J. Nutr. 7: 497-533, 1934.

Clarke, R.S.J., R.F. Hellon, and A.R. Lind. The duration of sustained contractions of the human forearm at different muscle temperatures. J. Physiol. 143: 454-473, 1958.

Detry, J.-M.R., G.L. Brengelmann, L.B. Rowell, and C. Wyss. Skin and muscle components of forearm blood flow in directly heated resting man. J. Appl. Physiol. 32(4): 506-511, 1972.

Dubois, D., and E.F. Dubois. A formula to estimate the approximate surface area if height and weight be known. Arch. Int. Med. 17: 863-871, 1916.

Ducharme, M.B. Effective insulative properties of the human forearm tissuse. Ph.D. thesis, University of Toronto, Toronto, Ontario, 1990.

Ducharme, M.B., and J. Frim. A multicouple probe for temperature gradient measurements in biological materials. J. Appl. Physiol. 65(5): 2337-2342, 1988.

Ducharme, M.B., J. Frim, and P. Tikuisis. Errors in heat flux measurements due to the thermal resistance of heat flux disks. J. Appl. Physiol. 69(2): 776-784, 1990.

Drager, W.R., and H. Smith. Applied Regression Analysis. New York, John Wiley & sons, 1966.

Edwards, R.H.T., M.J. McDonnell, and D.K. Hill. A thermistor probe for myothermal measurements in man. J. Appl. Physiol. 36: 511-513, 1974.

Kuehn, L.A., S.D. Livingstone, and E.D.L. Topliff. Tissue temperature gradients in the African guinea hog. Can. J. Physiol. Pharmacol. 48(1): 28-34, 1970.

Pennes, H.P. Analysis of tissue and arterial blood temperatures in the resting human forearm. J. Appl. Physiol. 1(2): 93-122, 1948.

Petrofski, J.S., and A.R. Lind. The relationship of body fat content to deep muscle temperature and isometric endurance in man. Clin. Sci. Mol. Med. 48: 405-412, 1975.

Reader, S.R., and H.M. White. Tissue temperature gradients. J. Appl. Physiol. 4(5): 396-402, 1951.

Saltin, A., A.P. Gagge, and J.A.J. Stolwijk. Muscle temperature during submaximal exercise in man. J. Appl. Physiol. 25(6): 679-688, 1968.

Sargeant, A.J. Effect of muscle temperature on leg extention force and short-term power output in humans. Eur. J. Appl. Physiol. 56: 693-698, 1987.

Stoll, A.M., and J.D. Hardy. Direct experimental comparison of several surface temperature measuring devices. Rev. Sci. Instr. 20(9): 678-686, 1949.

Tikuisis, P., and M.B. Ducharme. Finite-element solution of thermal conductivity of muscle during cold water immersion. J. Appl. Physiol. (submitted).

Whitney, R.J. The measurement of volume changes in human limbs. J. Physiol. (London), *121:* 1-27, *1953.*

Williams, D.B., and R.C. Karl. Measurement of deep muscle temperature in ischemic limbs. Am. J. Surg., 139: 503-507, 1980.

Table 1. Anthropometric characteristics of the subjects. The anthropometric measurements were performed on both forearms and pooled for each subject. SA_D, calculated from the Dubois and Dubois equation.

subject #	age (y)	height (cm)	weight (kg)	SA_D (m^2)	forearm circumference (cm)	forearm radius (cm)	skin+fat thickness (cm)	muscle thickness (cm)	proportion by volume muscle (%)	skin+fat (%)	bone (%)
1	25	172	89.5	2.0	30.7	4.3	0.5	3.8	71.6	21.5	7.0
2	18	180	65.0	1.8	24.1	3.9	0.3	3.6	80.6	10.4	9.0
3	19	185	78.2	2.0	29.1	4.4	0.4	4.0	79.5	10.9	9.6
4	30	176	71.0	1.9	27.0	4.1	0.3	3.8	78.0	15.1	6.9
5	21	176	83.8	2.0	30.5	4.3	0.5	3.8	70.1	22.5	7.5
6	20	183	74.3	2.0	28.6	4.1	0.4	3.7	77.6	15.0	7.5
7	18	173	71.4	1.9	26.6	4.1	0.3	3.8	78.7	11.4	9.9
8	20	176	59.2	1.7	25.4	3.6	0.3	3.2	73.8	16.4	9.9
9	29	177	88.5	2.1	31.5	4.7	0.2	4.4	82.6	10.7	6.8
10	20	176	66.2	1.8	24.1	3.7	0.3	3.4	83.9	8.2	8.0
11	22	187	77.5	2.0	27.5	4.2	0.2	4.0	84.6	7.6	7.9
12	26	173	75.2	1.9	27.5	4.3	0.3	4.0	73.1	16.8	10.2
13	29	185	70.0	1.9	26.9	4.1	0.2	3.9	78.4	14.5	7.2
14	22	185	81.6	2.1	27.8	4.0	0.3	3.6	75.6	14.6	9.7
15	18	182	62.1	1.8	25.0	3.8	0.2	3.6	82.2	11.2	6.6
Mean	22.5	180	74.2	1.9	27.5	4.1	0.3	3.8	78.0	13.8	8.2
±SE	1.1	1	2.4	0.03	0.6	0.1	0.02	0.1	1.2	1.1	0.3

Table 2. Data for thermal variables at thermal steady-state during immersion of the forearm at water temperatures ranging between 15 and 36°C. MD(13) is the subject's initials and number, $\dot{H}$ is the heat flux from the forearm ($W \cdot m^{-2}$), $\dot{Q}$ is the forearm blood flow ($ml \cdot min^{-1} \cdot 100\ ml\ tissue^{-1}$), r is the radius (cm), r_{sk} is the radius of the forearm (cm), r/r_{sk} is the relative radius, T_{bla} is the blood temperature at the brachial artery (°C), T_{re} is the rectal temperature (°C), T_t is the tissue temperature (°C), and T_w is the water temperature (°C).

MD(13) T_w: 19.92

r	r/r_{sk}	T_t
0.0	0.00	27.15
0.5	0.12	26.28
1.0	0.24	25.84
1.5	0.37	25.71
2.0	0.49	25.12
2.5	0.61	23.84
3.0	0.73	23.43
3.5	0.85	22.40
4.1	1.00	20.18
T_{re}	37.80	
T_{bla}	36.09	
$\dot{H}$	69.60	
$\dot{Q}$	1.05	

MD(13) T_w: 29.89

r	r/r_{sk}	T_t
0.0	0.00	33.89
0.5	0.12	33.42
1.0	0.24	33.38
1.5	0.37	33.27
2.0	0.49	32.80
2.5	0.61	32.07
3.0	0.73	31.75
3.5	0.85	31.03
4.1	1.00	30.10
T_{re}	37.80	
T_{bla}	36.85	
$\dot{H}$	40.28	
$\dot{Q}$	1.49	

MI(4) T_w: 35.98

r	r/r_{sk}	T_t
0.0	0.00	36.64
0.5	0.13	36.57
1.0	0.25	36.55
1.5	0.38	36.52
2.0	0.50	36.51
2.5	0.63	36.45
3.0	0.75	36.45
3.5	0.88	36.39
4.0	1.00	36.11
T_{re}	37.70	
T_{bla}	37.32	
$\dot{H}$	22.91	
$\dot{Q}$	7.14	

MI(4) T_w: 15.01

r	r/r_{sk}	T_t
0.3	0.08	23.99
0.8	0.20	23.55
1.3	0.33	23.12
1.8	0.45	21.78
2.3	0.58	20.45
2.8	0.70	19.23
3.3	0.83	18.01
3.8	0.95	16.49
4.0	1.00	15.33
T_{re}	37.75	
T_{bla}	35.75	
$\dot{H}$	92.99	
$\dot{Q}$	1.03	

DB(2) T_w: 32.93

r	r/r_{sk}	T_t
0.0	0.00	35.21
0.5	0.14	34.82
1.0	0.27	34.34
1.5	0.41	33.94
2.0	0.54	33.70
2.5	0.68	33.42
3.0	0.81	33.22
3.5	0.95	33.05
3.7	1.00	33.04
T_{re}	37.5	
T_{bla}	36.40	
$\dot{H}$	3.24	
$\dot{Q}$	3.2	

DB(2) T_w: 19.99

r	r/r_{sk}	T_t
0.0	0.00	27.17
0.5	0.13	26.93
1.0	0.26	26.69
1.5	0.40	25.28
2.0	0.53	23.75
2.5	0.66	22.41
3.0	0.79	21.79
3.5	0.92	21.00
3.8	1.00	20.27
T_{re}	37.5	
Tbla	35.42	
$\dot{H}$	78.75	
$\dot{Q}$	1.72	

MC(1) T_w: 35.93

r	r/r_{sk}	T_t
0.0	0.00	36.74
1.5	0.11	36.69
1.0	0.23	36.64
1.5	0.34	36.57
2.0	0.46	36.53
2.5	0.57	36.48
3.0	0.68	36.39
3.5	0.80	36.29
4.0	0.91	36.22
4.4	1.00	36.04
T_{re}	37.2	
T_{bla}	36.76	
$\dot{H}$	24.94	
$\dot{Q}$	6.20	

MC(1) T_w: 19.89

r	r/r_{sk}	T_t
0.0	0.00	30.69
0.5	0.12	30.17
1.0	0.23	28.38
1.5	0.35	26.75
2.0	0.47	25.50
2.5	0.58	24.11
3.0	0.70	22.89
3.5	0.81	22.04
4.0	0.93	21.07
4.3	1.00	19.96
T_{re}	37.2	
T_{bla}	35.58	
$\dot{H}$	88.03	
$\dot{Q}$	1.18	

LG(3) T_w: 32.98

r	r/r_{sk}	T_t
0.0	0.00	36.33
0.5	0.11	36.04
1.0	0.22	35.58
1.5	0.33	35.15
2.0	0.44	34.71
2.5	0.56	34.19
3.0	0.67	33.74
3.5	0.78	33.56
4.0	0.89	33.29
4.5	1.00	33.05
T_{re}	37.60	
T_{bla}	36.58	
$\dot{H}$	39.26	
$\dot{Q}$	3.08	

LG(3) T_w: 20.01

r	r/r_{sk}	T_t
0.0	0.00	28.29
0.5	0.11	27.91
1.0	0.23	26.81
1.5	0.34	25.45
2.0	0.46	24.48
2.5	0.57	23.50
3.0	0.68	22.45
3.5	0.80	21.80
4.0	0.91	21.19
4.4	1.00	20.25
T_{re}	37.30	
T_{bla}	35.53	
$\dot{H}$	59.35	
$\dot{Q}$	0.86	

BD(5) T_w: 32.9

r	r/r_{sk}	T_t
0.0	0.00	35.79
0.5	0.12	35.48
1.0	0.23	35.07
1.5	0.35	34.62
2.0	0.47	34.42
2.5	0.58	34.09
3.0	0.70	33.78
3.5	0.81	33.52
4.0	0.93	33.34
4.3	1.00	33.08
T_{re}	37.20	
T_{bla}	36.08	
$\dot{H}$	40.65	
$\dot{Q}$	2.60	

BD(5) T_w: 14.98

r	r/r_{sk}	T_t
0.0	0.00	27.69
0.5	0.12	26.19
1.0	0.23	24.73
1.5	0.35	23.03
2.0	0.47	21.54
2.5	0.58	19.96
3.0	0.70	18.78
3.5	0.81	17.63
4.0	0.93	16.77
4.3	1.00	15.15
T_{re}	37.00	
T_{bla}	34.50	
$\dot{H}$	93.79	
$\dot{Q}$	0.98	

MB(15) T_w: 20.03

r	r/r_{sk}	T_t
0.2	0.05	26.76
0.7	0.17	26.43
1.2	0.29	26.10
1.7	0.41	25.00
2.2	0.52	23.90
2.7	0.64	23.00
3.2	0.76	22.11
3.7	0.88	20.92
4.2	1.00	20.22
T_{re}	37.70	
T_{bla}	36.15	
$\dot{H}$	74.46	
$\dot{Q}$	1.07	

MB(15) T_w: 33.01

r	r/r_{sk}	T_t
0.2	0.05	35.72
0.7	0.17	35.62
1.2	0.29	35.51
1.7	0.41	35.12
2.2	0.52	34.73
2.8	0.64	34.36
3.3	0.76	33.98
3.8	0.88	33.47
4.2	1.00	33.18
T_{re}	37.60	
T_{bla}	37.03	
$\dot{H}$	54.21	
$\dot{Q}$	3.38	

CS(6) T_w: 35.98

r	r/r_{sk}	T_t
0.0	0.00	36.94
0.5	0.12	36.84
1.0	0.24	36.78
1.5	0.36	36.68
2.0	0.48	36.61
2.5	0.60	36.57
3.0	0.71	36.46
3.5	0.83	36.34
4.0	0.95	36.31
4.2	1.00	36.15
T_{re}	37.20	
T_{bla}	36.61	
$\dot{H}$	26.03	
$\dot{Q}$	7.46	

CS(6) T_w: 32.98

r	r/r_{sk}	T_t
0.0	0.00	35.67
0.5	0.13	35.37
1.0	0.26	35.12
1.5	0.40	34.83
2.0	0.53	34.64
2.5	0.66	34.31
3.0	0.79	34.14
3.5	0.92	33.59
3.8	1.00	33.09
T_{re}	37.40	
T_{bla}	36.45	
$\dot{H}$	55.04	
$\dot{Q}$	2.41	

LF(7) T_w: 32.95

r	r/r_{sk}	T_t
0.0	0.00	35.96
0.5	0.13	35.51
1.0	0.25	35.03
1.5	0.38	34.53
2.0	0.50	34.24
2.5	0.63	33.78
3.0	0.75	33.50
3.5	0.88	33.22
4.0	1.00	33.17
T_{re}	37.30	
T_{bla}	36.44	
$\dot{H}$	37.54	
$\dot{Q}$	2.90	

LF(7) T_w: 15.04

r	r/r_{sk}	T_t
0.1	0.02	21.44
0.6	0.15	21.30
1.1	0.27	20.63
1.6	0.39	19.64
2.1	0.51	18.67
2.6	0.63	17.75
3.1	0.76	17.16
3.6	0.88	16.46
4.1	1.00	15.27
T_{re}	37.40	
T_{bla}	35.15	
$\dot{H}$	94.04	
$\dot{Q}$	1.10	

JH(8) T_w: 35.96

r	r/r_{sk}	T_t
0.0	0.00	36.99
0.5	0.14	36.84
1.0	0.29	36.70
1.5	0.43	36.53
2.0	0.57	36.46
2.5	0.71	36.31
3.0	0.86	36.19
3.5	1.00	36.06
T_{re}	37.40	
T_{bla}	36.44	
$\dot{H}$	29.23	
$\dot{Q}$	6.16	

JH(8) T_w: 30.03

r	r/r_{sk}	T_t
0.0	0.00	34.73
0.5	0.14	33.88
1.0	0.28	33.12
1.5	0.42	32.46
2.0	0.56	32.01
2.5	0.69	31.42
3.0	0.83	31.02
3.5	0.97	30.58
3.6	1.00	30.21
T_{re}	37.20	
T_{bla}	36.23	
$\dot{H}$	46.36	
$\dot{Q}$	0.87	

JB(9) T_w: 29.97

r	r/r_{sk}	T_t
0.0	0.00	35.12
0.5	0.12	34.74
1.0	0.24	34.08
1.5	0.36	33.45
2.0	0.48	32.94
2.5	0.60	32.27
3.0	0.71	31.49
3.5	0.83	30.89
4.0	0.95	30.40
4.2	1.00	30.19
T_{re}	37.20	
T_{bla}	36.48	
$\dot{H}$	41.58	
$\dot{Q}$	0.73	

JB(9) T_w: 15.04

r	r/r_{sk}	T_t
0.0	0.00	27.53
0.5	0.10	26.87
1.0	0.21	25.56
1.5	0.31	23.99
2.0	0.42	22.61
2.5	0.52	21.25
3.0	0.63	19.79
3.5	0.73	18.48
4.0	0.83	17.44
4.5	0.94	16.52
4.8	1.00	15.33
T_{re}	37.10	
T_{bla}	35.01	
$\dot{H}$	102.27	
$\dot{Q}$	0.80	

RB(10) T_w: 14.97

r	r/r_{sk}	T_t
0.2	0.06	22.98
0.7	0.19	22.08
1.2	0.33	21.59
1.7	0.47	19.22
2.2	0.61	18.03
2.7	0.75	17.26
3.2	0.89	16.44
3.6	1.00	15.22
T_{re}	37.60	
T_{bla}	35.55	
$\dot{H}$	94.02	
$\dot{Q}$	0.53	

RB(10) T_w: 30.03

r	r/r_{sk}	T_t
0.1	0.03	34.16
0.6	0.16	33.38
1.1	0.30	32.71
1.6	0.43	32.16
2.1	0.57	31.62
2.6	0.70	31.03
3.1	0.84	30.66
3.6	0.97	30.33
3.7	1.00	30.16
T_{re}	37.40	
T_{bla}	36.50	
$\dot{H}$	45.01	
$\dot{Q}$	0.73	

DBD(11) T_w: 35.9

r	r/r_{sk}	T_t
0.0	0.00	37.03
0.5	0.11	36.97
1.0	0.23	36.93
1.5	0.34	36.87
2.0	0.46	36.81
2.5	0.57	36.77
3.0	0.68	36.66
3.5	0.80	36.55
4.0	0.91	36.49
4.3	1.00	36.29
T_{re}	37.50	
T_{bla}	36.92	
$\dot{H}$	29.95	
$\dot{Q}$	5.93	

DBD(11) T_w: 29.99

r	r/r_{sk}	T_t
0.0	0.00	34.52
0.5	0.12	34.33
1.0	0.24	34.16
1.5	0.37	33.52
2.0	0.49	33.01
2.5	0.61	32.40
3.0	0.73	31.59
3.5	0.85	31.14
4.0	0.98	30.71
4.1	1.00	30.20
T_{re}	37.70	
T_{bla}	36.94	
$\dot{H}$	56.84	
$\dot{Q}$	1.35	

JD(12) T_w: 35.9

r	r/r_{sk}	T_t
0.0	0.00	37.17
0.5	0.12	37.05
1.0	0.24	36.94
1.5	0.36	36.81
2.0	0.48	36.77
2.5	0.60	36.59
3.0	0.71	36.44
3.5	0.83	36.30
4.0	0.95	36.26
4.2	1.00	36.13
T_{re}	37.50	
T_{bla}	37.02	
$\dot{H}$	22.91	
$\dot{Q}$	7.14	

JD(12) T_w: 20.05

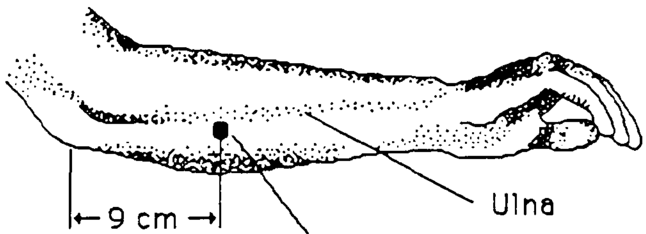
r	r/r_{sk}	T_t
0.0	0.00	28.66
0.5	0.11	28.20
1.0	0.22	26.76
1.5	0.33	25.22
2.0	0.44	24.01
2.5	0.56	23.64
3.0	0.67	23.25
3.5	0.78	22.66
4.0	0.89	22.13
4.5	1.00	20.47
T_{re}	37.40	
T_{bla}	35.72	
$\dot{H}$	58.25	
$\dot{Q}$	1.25	

PQ(14) T_w: 29.96

r	r/r_{sk}	T_t
0.0	0.00	33.83
0.5	0.13	33.32
1.0	0.26	32.65
1.5	0.39	32.04
2.0	0.51	31.56
2.5	0.64	30.97
3.0	0.77	30.68
3.5	0.90	30.35
3.9	1.00	30.07
T_{re}	37.50	
T_{bla}	36.61	
$\dot{H}$	42.00	
$\dot{Q}$	1.38	

PQ(14) T_w: 14.97

r	r/r_{sk}	T_t
0.0	0.00	21.06
0.5	0.13	19.83
1.0	0.25	18.78
1.5	0.38	17.77
2.0	0.50	17.14
2.5	0.63	16.38
3.0	0.75	15.98
3.5	0.88	15.59
4.0	1.00	15.18
T_{re}	37.30	
T_{bla}	35.26	
$\dot{H}$	95.42	
$\dot{Q}$	0.25	



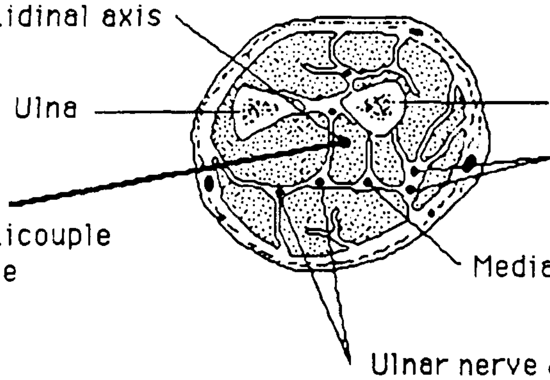


Fig. 1. Diagrams showing the site of implantation of the multicouple probe into the forearm.

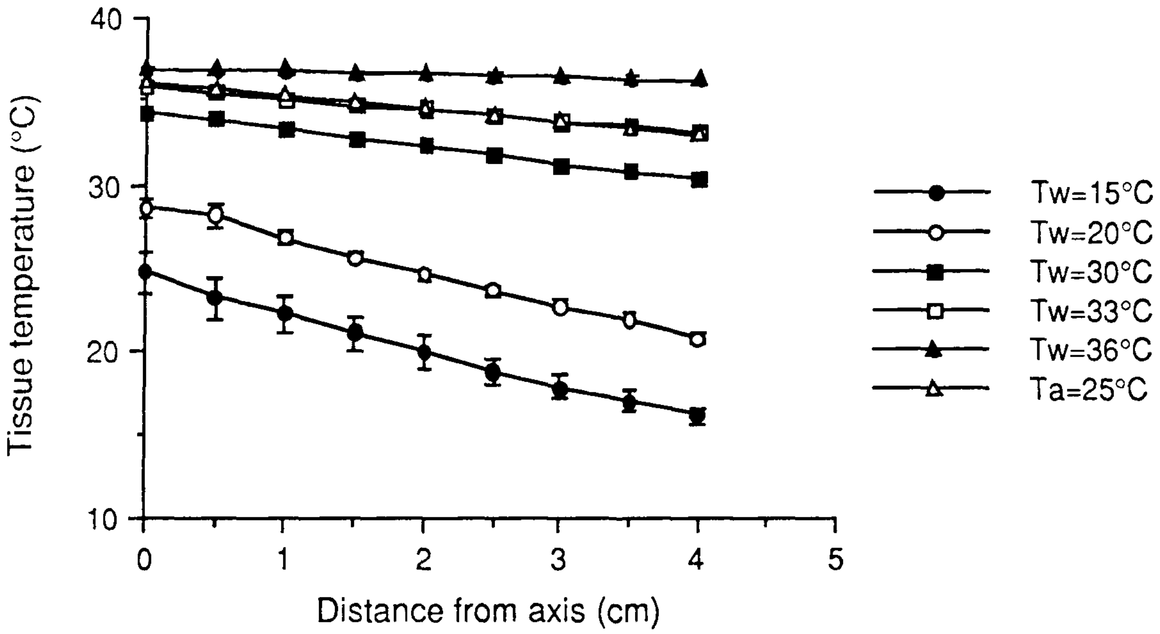


Fig. 2. Tissue temperature profiles inside the forearm at thermal steady-state for all temperature conditions tested. Data are expressed as means ± SE. n = 6 for each temperature condition. Tw, water temperature; Ta, air temperature.

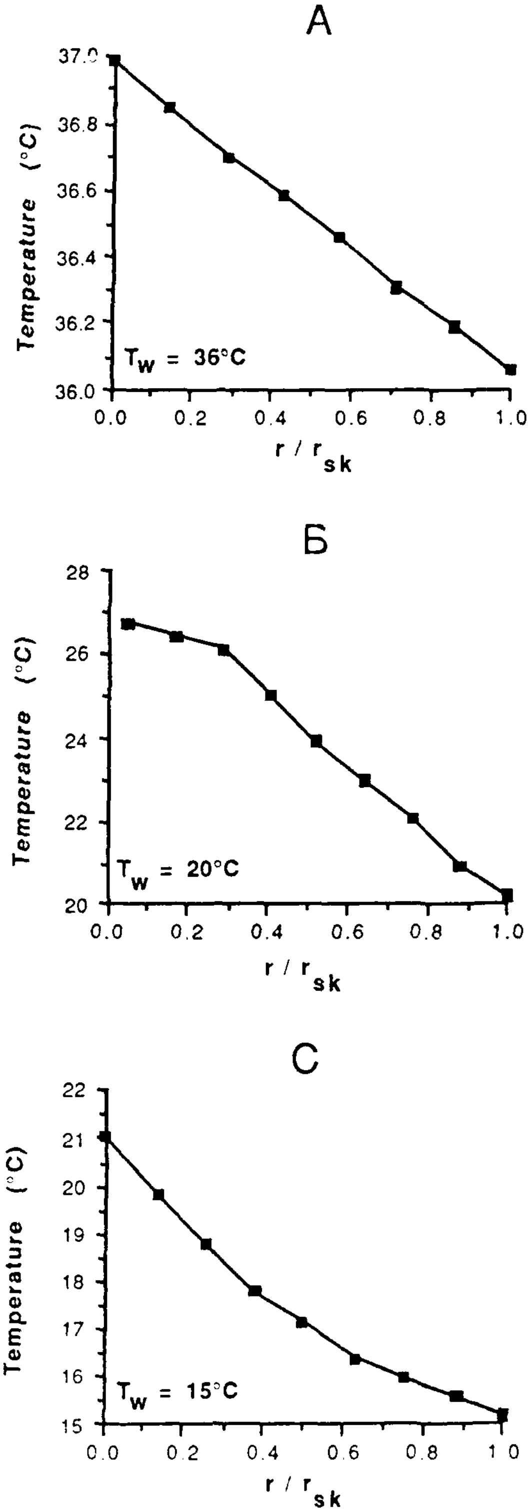


Fig. 3. Typical examples of the different types of tissue temperature profiles observed in the forearm during immersion at water temperatures ranging beween 15 and 36°C, which illustrate the interindividual variability. A) linear profile, B) profile with convex curvature, C) profile with concave curvature.

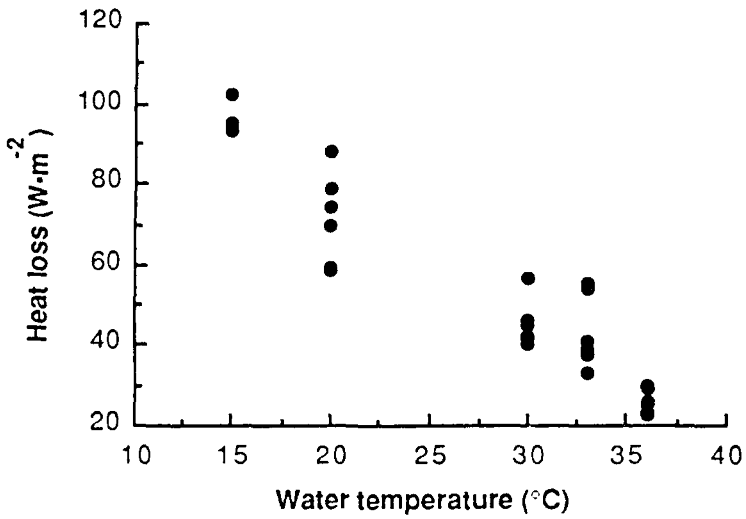


Fig. 4. Heat loss from the forearm at thermal steady-state for all temperature conditions tested.

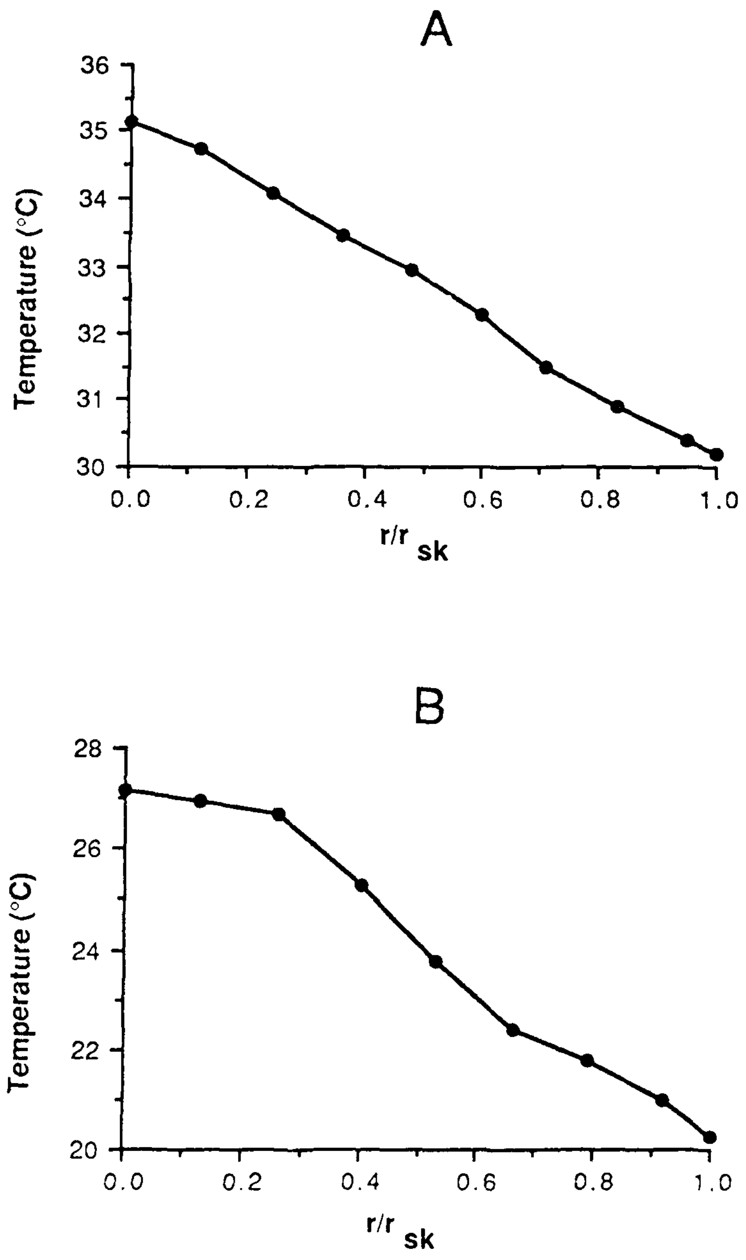


Fig. 5. Temperature profiles in the forearm at thermal neutrality. A) for the subject having the largest forearm circumference (31.8 cm) during immersion at T_w = 30°C, B) for the subject having the smallest forearm circumference (24.0 cm) during immersion at T_w = 20°C.

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The purpose of the present study was to investigate the effect of a range of water temperatures (Tw from 15 to 36°C) on the shape of the tissue temperature profile of the resting human forearm at thermal stability. Tissue temperature (Tt) was continuously monitored by a calibrated multicouple probe during 3 hours immersion of the forearm. The probe was implanted approximately 9 cm distal from the olecranon process along the ulnar ridge. Tt was measured every 5 mm, from the longitudinal axis of the forearm (determined from computed tomography scanning) to the skin surface. For all temperature conditions, the temperature profile inside the limb was linear as a function of the radial distance from the forearm axis (p 0.01) when the temperature data were averaged for the different groups at each water temperature tested. However, interindividual variability regarding the shape of the temperature profile was observed. A linear profile was observed in 50% of the experiments, a profile with convex curvature in 30%, and a profile with concave curvature in the remaining 20%. No significant relationship was observed between the occurrence rate of the different shapes of temperature profile and the water temperature. Reproducibility of the shape of the temperature profile was observed for 10 of the 15 subjects tested. These data suggest that anatomical structures like bone and artery located at proximity of the pathway of the thermal probe implantation could have influenced the shape of the individual temperature profile inside the forearm.

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Cold stress, cold water immersion, intramuscular temperature, thermal stress