EXTENT OF RADIAL COUNTER-CURRENT HEAT EXCHANGE IN THE FOREARM MUSCLE DURING COLD EXPOSURE

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INTRODUCTION

Counter-current heat exchange in the limbs is usually considered as an exchange of heat between major counter-current vessels in the axial direction. However, attention has been recently given to counter-current heat exchange between the microvessels of the vasculature away from the major axial vessels. Weinbaum et al. (1) have demontrated that such heat exchange is 100% complete three generations before the capillary level. Heat recovery by this mechanism is considered in the radial, as opposed to the axial, direction. In this study, the extent of net heat recovery by this mechanism is estimated for the human foreann during cold exposure.

METHOD

1. ***Experimental.*** Data were obtained from steady-state temperatures measured in the foreann (2) after 3 h of immersion in water at temperatures (Tw) of 15 (N = 6), 20 (N = 5), and 30°C (N = 5). Temperatures were measured every 0.5 cm from the longitudinal axis of the foreann to the skin approximately 9 cm distal from the elbow, and from these values a volume-weighted mean was obtained. These means (± SE) were 18.74 (0.52), 23.41 (0.21), and 31.78 (0.17) °C with increasing Tw. Arterial blood temperatures entering the forearm were measured Once before immersion and corrected for axial counter-current heat exchange; mean (± SE) values at steady-state were 35.23 (0.17), 35.68 (0.12), and 36.51 (0.17)°C with increasing Tw. Heat flux was measured at two sites on the skin adjacent to the temperature probe; mean values (± SE) were 87.7 (7.9), 71.8 (5.7), and 46.4 (2.8) W/m^2 with increasing Tw. Blood flows (± SE) entering the forearm and measured by plethysmograhy were 467 (82), 727 (86), and 779 (136) l/h/m^3 with increasing Tw.

2. ***Analysis.*** The approach taken herein to determine the net recovery of radial convective heat exchange was based on a simple heat balance. First, the convective heat exchange was obtained from the measured amount of heat lost through the skin after subtraction of the metabolic contribution assuming the Q_{10} rule. Second, the potential convective heat loss (i.e., maximum possible) was determined by the difference between the average muscle temperature and the arterial blood temperature. One minus the ratio of these two quantities yields the fraction of heat recovery. All heat quantities are expressed as W/m^3 and apply to the muscle tissue only.

The convective heat exchange per unit volume (bc) was determined by

$$bc = q_v - m$$

where q_v is the heat lost and m is the metabolic heat produced per unit volume. These quantities were determined by (3)

$$q_v = 2 \cdot hf / r$$

where hf and r are the heat flux and the radius at the muscle-fat boundary, and (4)

$$m = 684 \cdot 2^{(\bar{T} - 35)/10}$$

where $\bar{T}$ is the average muscle temperature.

The potential convective heat loss (i.e. assuming no counter-current heat exchange) was determined by (4)

$$bc_{max} = 1.13 \cdot bf \cdot (T_a - \overline{T})$$

where bf is the blood flow ($l/h/m^3$) and T_a is the arterial blood temperature entering the forearm. Heat flux and blood flow at the muscle level were determined by assuming negligible metabolic heat production and blood flow at the skin+fat level.

RESULTS

Values were calculated for each individual and means of these are reported below.

Table of mean calculated ***values for*** *forearm muscle* ***tissue.***

T_w	q_v	m	bc	bf	bc_{max}	$1 - bc/bc_{max}$
15	**5016**	**222**	**4794**	**467**	**9995**	**0.460**
20	**4076**	**306**	**3769**	**727**	**12032**	**0.678**
30	**2744**	**547**	**2197**	**779**	**5004**	**0.470**

Convective hear exchange between blood and tissue accounts for most **of** the total heat produced (i.e., $bc + m$); the metabolic contribution **is** approximately **4, 7,** and 20% of the total €or T_w of **15, 20, and** 30°C, respectively. Radial counter-current heat exchange returns about **53% of** the potential convective heat available.

CONCLUSION

Through the simple approach of comparing measured heat loss to the predicted potential hear loss using average values of tissue temperature and blood flow, the results suggest that radial counter-current heat exchange does not return all the heat brought in by the blood. This **can** be explained by noting that while heat recovery between counter-current vessels **may** be **100%** efficient in the tissue space between the vessels, recovery is reduced in the much larger **tissue** space outside the conduction path between the vessels.

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