

MODELS TO DESCRIBE FINGER BEHAVIOR UNDER COLD-STRESS

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INTRODUCTION

The fingers and toes act, thermally, as heat exchange mechanisms. In comfortable and warm environments their function is to dissipate heat. This is achieved, primarily, by vasodilatation which enhances blood flow to the extremities by up to 30 - 100 fold above the required (nutritional) level [1]. In cold environments, the strategy of the body is to conserve heat. This is effected by almost completely shutting off blood supply to the extremities. Termed vasoconstriction, this causes an abrupt and drastic reduction in the blood supply to the extremities. Consequently and as the main heat source is removed, the temperature of the extremities starts to fall off.

At some time, typically 12 - 30 min. after the onset of the cold exposure, the temperature of the extremity may begin to rise. This phenomenon is termed "cold introduced vasodilatation", (CIVD) or "Lewis waves" [2]. It involves short periods of opening-closing of the cold-constricted blood vessels. The nature of CIVD is well documented, whereas the underlying mechanisms and precise sequence of events are not completely understood.

This paper describes a series of studies in which finger behavior is modeled under cold-stress. In the first of these models the finger is depicted as a thermally insulated cylinder with internal heat sources. The second is a lumped parameter model of the finger tip. The third model of the entire finger is quite detailed and includes blood perfusion to the capillary bed, counter-current heat exchange between major blood vessels.

CYLINDER WITH INTERNAL HEAT SOURCES

The finger is depicted as a cylinder with internal heat sources which account, primarily, for the thermal effects of blood perfusion. A time-dependent energy balance is formulated for longitudinal conduction and heat exchange with the environment [3]. The model is solved for axial finger temperatures. Finger endurance times for cold exposure are also calculated. These times quantify the effects of finger length, diameter, extent of thermal insulation applied and environmental temperatures on the endurance times.

LUMPED-PARAMETER FINGER TIP MODEL

The most noticeable effects of CIVD are in the tip of the finger as shown in Fig. 1. This suggests the separate modeling of this area. Consideration of the anatomy and geometry of the tip of the finger would point out to the modeling of the tip as a lumped-parameter semi-sphere supplied by one artery and drained by a single vein [4]. Blood arriving at the tip is distributed to the capillaries where it is assumed to equilibrate with the temperature of the tissue.

Observation of Fig. 1, yields a certain characteristic of CIVD waves, i.e., temperature increases are faster than the following temperature decreases. No indication is given, however, to the nature of change of blood supply. This is left out to be determined by a comparison of the model results with the measured record for assumed blood flow change patterns. We have assumed 3 plausible blood flow patterns, namely: sinusoidal, rectangular and triangular. Of these the latter turned out to be the most suitable.

Figure 2 shows a comparison of measured and calculated finger-tip temperatures for on assumed series of triangular waves of blood perfusion. The similarity of the two records is quite good but one should bear in mind that the input function, i.e., blood perfusion, was estimated and adjusted but was not measured. We have measured simultaneously blood perfusion and temperatures of the finger-tip [5] and compared the results with those predicted by the lumped parameter model, Fig. 3. The data in this figure support the assumption of the triangular wave form.

NUMERICAL MODEL OF THE ENTIRE FINGER

This model [6] treats the finger as a cylinder wrapped around by thermal insulation. Four concentric tissues make up the finger model: core, muscle, fat and skin, each having separate thermophysical and anatomic properties. In addition, the model assumes two major blood vessels in the finger - an artery and a vein. These vessels supply and drain the tissues and exchange heat both with the tissue and between them.

The model was solved by a numerical finite differences scheme. Figure 4 shows variations of finger-tip temperatures for bare and gloved fingers and still and windy (15 km/hr) environments for low (nutritional) blood flow without CIVD. It is noted that the effect of the wind on the finger is quite pronounced and a bare finger in still air would be more protected than a gloved one in moderate wind.

Another result of counter-current heat exchange is shown in Fig. 5. Accordingly, as the finger cools off, the diminished blood flow is shunted away from the superficial to the internal regions of the finger. This provides a thermal "coupling" between the major blood vessels and results in a further reduction in heat loss to the environment. The effect of counter-current heat exchange is demonstrated in that the arterial and venous temperatures approach each other closer as this heat conserving

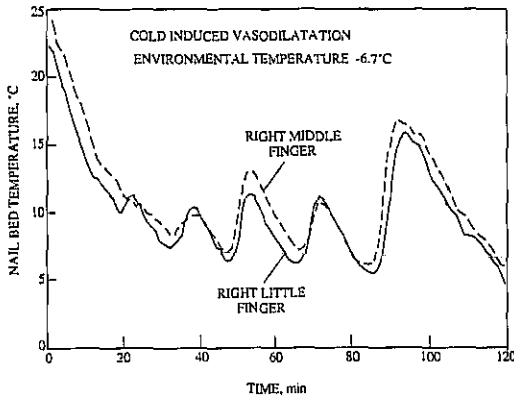


Fig. 1: Temperature variations in two fingertips due to cold-induced vasodilatation.

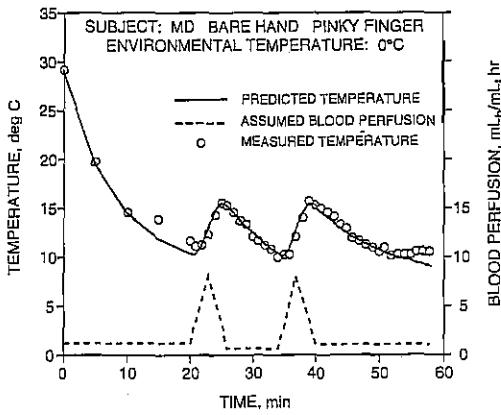


Fig. 2: Comparison of measured and predicted bare pinky fingertip temperatures in a 0°C environment.

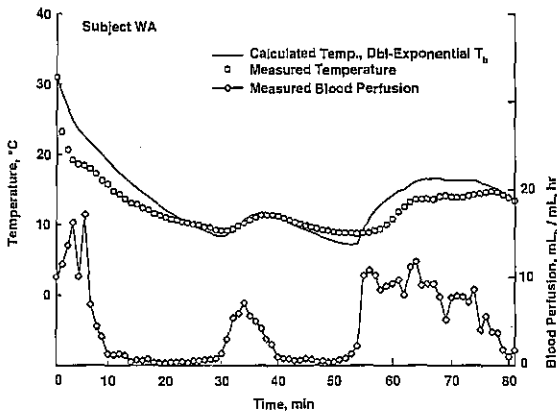


Fig. 3: Measured blood perfusion rates and compared left middle finger temperatures for a subject in a 0°C environment.

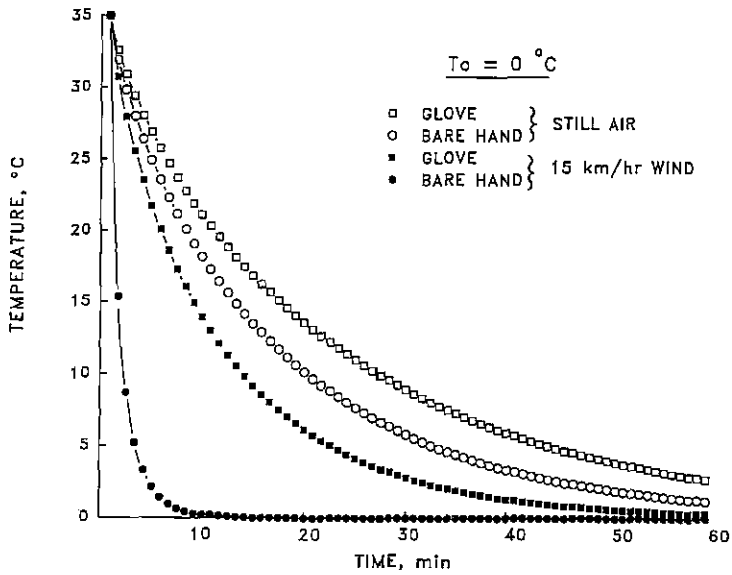


Fig. 4: Calculated temperature variations of the tip of bare and gloved fingers for still and windy air at 0°C .

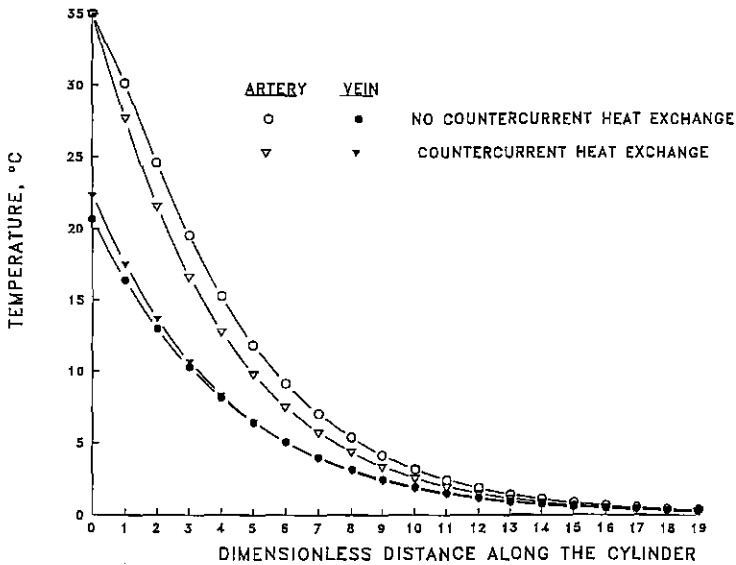


Fig. 5: Effect of counter-current heat exchange on arterial and venous blood temperature distributions in the finger model.

mechanism is activated. The net amount of heat saved in the present case, due to the counter-current effect, is about 14%.

CONCLUSION

This paper presents, briefly, 3 models which describe the energy balance of an extremity exposed to cold weather. All models lack, at this stage of their development, any intrinsic physiological mechanisms. However, under certain plausible assumptions, they are shown to have the capabilities to follow changes induced by exposure to external stimuli. Following experimental validation these models may become useful in predicting blood perfusion rates from measured temperature records.

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