Anesthesiology
73:541–545, 1990

Skin-surface Temperature Gradients Correlate with Fingertip Blood Flow in Humans

Eduardo H. Rubinstein, M.D., Ph.D., Daniel I. Sessler, M.D.†*

Skin-surface temperature gradients (forearm temperature − fingertip temperature) have been used as an index of thermoregulatory peripheral vasoconstriction. However, they have not been specifically compared with total finger blood flow, nor is it known how long it takes fingertip temperature to fully reflect an abrupt change in finger blood flow. Steady-state skin-temperature gradients were compared with total fingertip blood flow in 19 healthy volunteers. There was an excellent correlation between steady-state skin-surface temperature gradients and total fingertip blood flow measured with venous-occlusion volume plethysmography: gradient = 0.2 − 5.7 · log(flow), r = 0.98. The half-time for fingertip cooling after complete arterial obstruction (in 8 volunteers) was 6.6 ± 1.2 min. The authors conclude that skin-temperature gradients are an accurate measure of thermoregulatory peripheral vasoconstriction. (Key words: Measurement techniques, blood flow: volume plethysmography. Brain, hypothalamus. Hypothermia. Temperature, measurement: skin.)

SKIN-SURFACE temperature gradients (forearm temperature − fingertip temperature) have been used as an index of thermoregulatory peripheral vasoconstriction.[1–7] This indirect measure of total finger blood is inexpensive, easy to use, and functional even in cases of patient movement (*e.g.*, perianesthetic tremor). However, the validity of this flow measurement technique has been questioned.[8]

Cutaneous circulation in the finger has two components: capillary flow (which is partially nutritional) and arteriovenous shunts (which are mostly thermoregulatory). Blood flow through the shunts ranges from negligible to 80% of the total.[9] Skin-surface temperature gradients correlate reasonably well with capillary blood flow,[7,10–13] but their correlation with total finger blood flow has not been confirmed.

We therefore tested the hypothesis that steady-state forearm–fingertip temperature gradients accurately reflect total fingertip blood flow, which was measured with venous-occlusion volume plethysmography. In addition, we determined the time required for fingertip temperature to reflect an acute decrease in peripheral blood flow by calculating the rate constant for finger cooling after complete arterial occlusion.

* Professor of Physiology and Anesthesiology, Departments of Physiology and Anesthesiology, University of California, Los Angeles.

† Assistant Professor of Anesthesia, Department of Anesthesia, University of California, San Francisco.

Received from the Departments of Physiology and Anesthesiology, University of California, Los Angeles, California, and the Department of Anesthesia, University of California, San Francisco, California. Accepted for publication March 29, 1990. Supported by National Institute of Health grant R29 GM39723 and Augustine Medical, Inc.

Address reprint requests to Dr. Sessler: Department of Anesthesia, University of California School of Medicine, Room C-450, 513 Parnassus Avenue, San Francisco, California 94143-0648.

Materials and Methods

With approval from the Human Subject Protection Committee, we compared skin-temperature gradients with total fingertip blood flow in 19 healthy volunteers. None was obese, taking medication, or had a history of thyroid disease, dysautonomia, Raynaud's syndrome, or hypertension. Volunteers ranged in age from 26 to 56 yr, and 15 were male. Ambient temperatures were maintained near 22° C.

During the study, volunteers wore surgical scrub clothes and rested supine with the left arm supported at the level of the sternum. This position improved venous drainage from the hand, facilitating recording of digital blood flow. Volunteers were placed between two circulating water blankets, with the left arm exposed. Blanket temperatures were set randomly between 30 and 40° C to produce a wide range of centrally mediated (thermoregulatory) finger blood flows. Steady thermoregulatory state was defined as a skin-temperature gradient changing less than 0.2° C per 5 min over 30 min.

Total fingertip blood flow was measured at the end of the 30-min equilibration period; three recordings at 1-min intervals were averaged. The skin temperature gradient also was recorded at that time. Afterward, a tourniquet placed around the base of the middle finger in eight volunteers, was inflated to 30 mmHg above systolic blood pressure (producing complete digital ischemia) to determine the rate constant for fingertip cooling. Fingertip temperatures then were measured at 2.5, 5, 10, 15, 20, 25, and 30 min after occlusion.

Total finger blood flows were quantified in the left hand with the use of venous-occlusion volume plethysmography.[14] Changes in index fingertip volume were measured with a sensor constructed from the barrel of a 20- or 30-ml syringe (as appropriate for the volunteer's finger size). The syringe barrel was cut approximately 3 cm from the Luer connector and the tip of a latex glove finger was fit inside (fig. 1). Because the glove tip was sealed to the syringe, it was not necessary to make an airtight connection between the finger and the syringe. We distended the glove tip by applying a small negative pressure to the Luer connector before inserting the distal phalanx of the second finger; this minimized air-trapping between the finger and the glove.

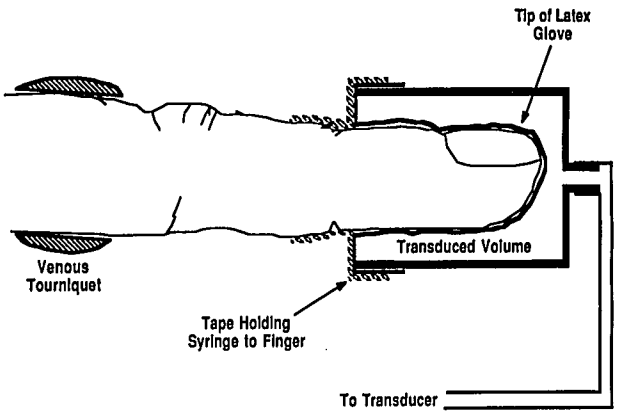

FIG. 1. A cut-off syringe barrel lined with the tip of a latex glove. The test fingertip is positioned snugly inside the latex, and volume changes between the latex and syringe barrel are recorded from an air volume transducer connected to a preamplifier and strip chart recorder.

A short length of low-compliance tubing connected the syringe barrel to an air volume transducer (Statham Gould, Cleveland, OH) that was connected to a preamplifier and strip chart (Gould Brush 220) that recorded volume changes during each pulse cycle.

Blood flow measurements were made by rapidly inflating a 3.2-cm-wide (Critikon, Tampa, FL) venous tourniquet around the base of the finger to approximately 40–50 mmHg for 5–15 s. The tourniquet allowed arterial blood to enter the finger, but prevented venous blood from leaving. This resulted in an increasing finger volume; the rate of increase (*e.g.*, the volume *vs.* time slope) was considered to be blood flow in milliliters per minute. Typical low- and high-flow records are shown in figure 2.

Peripheral vasoconstriction also was quantified by calculating skin-surface temperature gradients (forearm temperature − middle fingertip temperature) on the same arm used for volume plethysmography.[1,7] Skin-surface temperatures were measured with a Mon-a-Therm® model 6500 thermometer and disposable thermocouples (St. Louis, MO). The thermocouples were incorporated into self-sticking 1-cm-diameter disks.

The rate constant β (min^{-1}) for finger cooling was calculated with an equation derived from Newton's law of cooling (see appendix):

$$\beta = \{\ln (T_i - T_f) - \ln [T(t) - T_f]\}/t$$

where T(t) (° C) is finger temperature at time t (min), T_f (° C) is the final steady-state finger temperature (at time = 30 min), and T_i = initial finger temperature in ° C (at time = 0). The half-time for finger cooling ($t_{1/2}$) was calculated as $\ln(2)/\beta$.

The six values of β for each subject were averaged, and from these the average and standard deviation for the entire group were calculated. Extrapolation from fingertip temperatures to skin-surface temperature gradients is valid because gradients result from a decrease in finger temperature (forearm temperature remains essentially unchanged).[7] Conversely, the heat loss equation can be rearranged to predict gradient changes, rather than finger temperature. However, the rate constant will be similar when forearm temperature does not change appreciably during the study period.

Pearson's product-moment correlation was used to determine the relation between skin-temperature gradients and the log of finger blood flow. Data are expressed as means ± standard deviations.

Results

The three flow recordings that were averaged at the end of the 30-min equilibration period never differed by more than 10%. There was an excellent correlation between steady state skin-temperature gradients and total fingertip blood flow over a more than 30-fold range of flows: gradient = 0.2 − 5.7 · log(flow), r = 0.98 (fig. 3).

After 30 min of arterial occlusion, fingertip temperature exceeded ambient temperature (22.2 ± 0.5° C) by

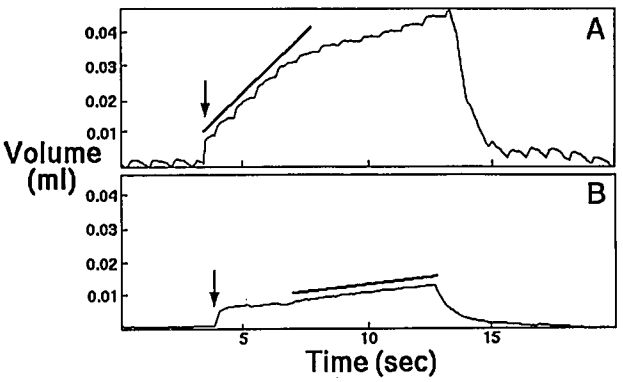

FIG. 2. Typical volume plethysmographic traces quantifying fingertip blood flow: trace *A* is a record showing high flow (≈0.42 ml/min), and trace *B* is a typical low-flow recording (≈0.056 ml/min). The baseline pulsations are evident only during high flow and result from blood entering and leaving the finger with each heartbeat. Arrows indicate venous tourniquet inflation that prevents blood from leaving the finger. Rapid inflation pushes a small amount of venous blood from under the tourniquet into the fingertip causing an artifact on the tracing. The increase in fingertip volume (slope of the volume *vs.* time curve) equals fingertip blood flow. The slope decreases (plateau phase) when sufficient blood has entered the finger to increase its venous pressure to cuff pressure (*e.g.*, the finger is "full"); this occurs in trace *A* ≈5 sec after tourniquet inflation. Volume inside the plethysmograph does not increase immediately after tourniquet inflation in trace *B* because flow is so low that ≈4 sec are required to fill the finger between the tourniquet and the plethysmograph.

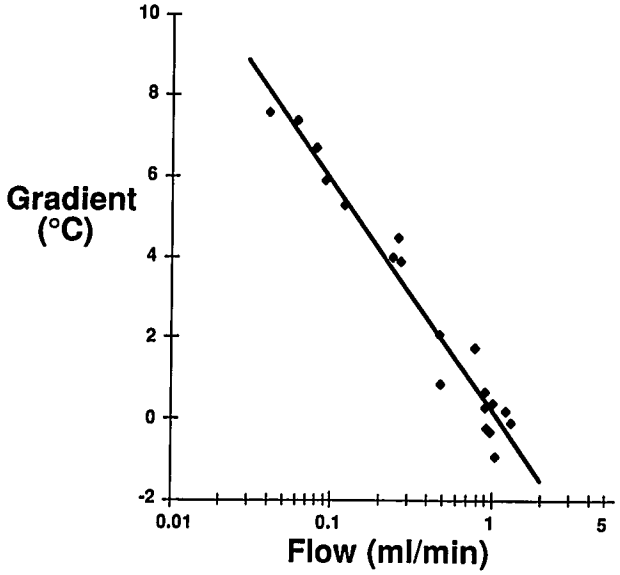

FIG. 3. Total fingertip blood flow correlated well with skin-temperature gradients (forearm temperature − fingertip temperature). Gradient = 0.2 − 5.7 · log (flow), r = 0.98.

only 0.30 ± 0.17° C (fig. 4). Forearm skin temperatures changed an average of only 0.1° C during the study, indicating that increasing skin-temperature gradients resulted entirely from fingertip temperature decreasing to near-ambient temperature. The rate constant (β) equaled

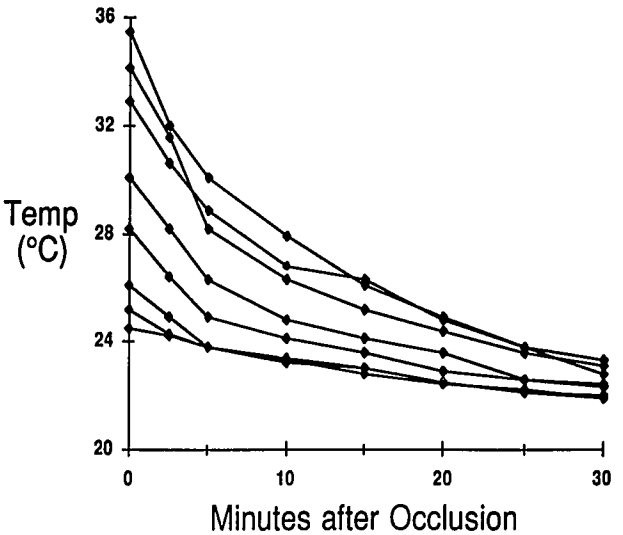

FIG. 4. Finger skin temperature following total arterial occlusion by a tourniquet around the base of the finger. Fingertip temperatures were fit to a heat loss equation: $T(t) = (T_i - T_f)e^{-\beta t} + T_f$, for which T(t) (°C) is finger temperature at time t (min), T_i (°C) = initial finger temperature (at time = 0), T_f (°C) = final steady-state finger temperature (at time = 30), and β (min^{-1}) is a function of finger mass and surface area. $\beta = 0.11 \pm 0.02$ min^{-1}, which corresponds to a half time of 6.6 min.

TABLE 1. Average Value of β and the Half Time ($t_{1/2}$) in Eight Volunteers Between 2.5 and 25 min after a Tourniquet Was Inflated Around the Base of One Finger

Volunteer	β (min^{-1})	$t_{1/2}$ (min)
1	0.10 ± 0.02	6.8 ± 1.0
2	0.12 ± 0.02	5.8 ± 0.8
3	0.10 ± 0.01	6.9 ± 1.1
4	0.11 ± 0.02	6.1 ± 1.0
5	0.13 ± 0.02	5.2 ± 0.9
6	0.12 ± 0.03	5.8 ± 1.3
7	0.11 ± .003	6.5 ± 1.7
8	0.07 ± 0.01	10.1 ± 1.1
Total	0.11 ± 0.02	6.6 ± 1.2

"Total" indicates the average for the entire study group.

0.11 ± 0.02 min^{-1}, which corresponds to a half-time ($t_{1/2}$) of 6.6 ± 1.2 min (table 1).

Discussion

Thermoregulatory vasoconstriction occurs most notably in skin covering the hands, feet, nose, *etc.* which contain both capillaries and an array of arteriovenous shunts.[15–17] Because these shunts are approximately 100 μm in diameter, they permit passage of 10,000 times as much blood as a comparable length of 10-μm capillary.[9] However, the arteriovenous shunts are located in a deeper layer of the skin,[18] so that a given volume of blood traversing these shunts dissipates only one third as much heat as it does passing through superficial capillaries.[19]

Our results demonstrate that steady-state skin-surface temperature gradients correlate extremely well with total finger blood flow measured with volume plethysmography. The correlation was much better than that obtained previously between skin-temperature gradients and the laser Doppler flow index.[7] Since laser Doppler flowmetry measures mostly capillary flow, mixed with a variable amount of shunt flow,[9] it is not surprising that this technique results in a lower degree of correlation with total flow.

Finger temperature depends largely on the finger's supply of warm arterial blood, because heat production in the finger is modest (finger blood flow usually far exceeds metabolic needs). In fact, finger temperature and the difference between finger temperature and central temperature have long been considered indices of peripheral flow.[20–22] However, neither of these measures can be used in a changing environment, because finger temperature depends also on ambient temperature. A potential advantage of forearm–fingertip gradients is that the reference temperature is a skin site exposed to the same ambient temperature as the fingertip. Therefore, a change in ambient temperature similarly affects forearm and fingertip temperature (in the absence of thermoreg-

ulatory changes in blood flow), producing little change in the gradient.

In our previous studies,[1-3,5-7] we prospectively defined a 4° C skin-temperature gradient as significant thermoregulatory vasoconstriction. A 4° C gradient was empirically chosen because it is the approximate midpoint in the range of clinically observed gradients. It is apparent from figure 3 that a 4° C gradient was an appropriate choice, corresponding to a fingertip blood flow ≈0.2 ml/min. This is an approximately five-fold decrease from a typical high-flow (vasodilated) state, and is likely to indicate physiologic regulation. It is also apparent from figure 3 that finger flow can easily decrease another ten-fold in a typical operating room environment.

Our data indicate that finger cooling, in the absence of arterial flow, has a half-time of 6.6 ± 1.2 min. (A similar lag time does *not* occur during vasodilation; increased blood flow decreases the gradient almost immediately *via* internal warming.) β is a function of finger size, but not of ambient or initial finger temperature. Absolute cooling rates depend strongly on ambient temperature, and can be predicted from β and equation 4 (see appendix). Although β was calculated using a zero-blood flow model, equation 4 remains valid for physiologic changes in vascular tone that result in greater steady-state blood flows. Skin-temperature gradients thus reflect nearly all the decrease in finger blood flow if three to four half-times are allowed to elapse between the flow change and gradient measurement.

In our previous studies of intraoperative thermoregulatory thresholds, we recorded skin-temperature gradients at 10-min intervals. In many cases, gradients increased from ≈ −2° C (a typical intraoperative gradient) to well above 4° C in ≈30 min. These data suggest that thermoregulatory vasoconstriction rapidly decreases finger blood flow to minimal values. However, the intraoperative thermoregulatory threshold is not determined by the *time* at which vasoconstriction occurs, but by the *central temperature* at which it occurs. Central temperatures in anesthetized patients rarely decrease more than 0.1° C in the 30 min preceding development of a 4° C skin-temperature gradient. Published thermoregulatory threshold values during halothane,[1] nitrous oxide/fentanyl,[7] and isoflurane[3] anesthesia therefore remain valid, even if thermoregulatory responses actually occurred before our prospectively defined "significant" gradient.

In summary, there was an excellent correlation between steady-state skin-surface temperature gradients (forearm temperature − fingertip temperature) and total fingertip blood flow measured with venous-occlusion volume plethysmography. The half-time for fingertip cooling after complete arterial obstruction (a zero-blood flow test) was 6.6 min, indicating that gradients measured 15–20 min after acute vasoconstriction accurately reflect finger blood flow. We conclude that skin-temperature gradients are an inexpensive, easy-to-use, and accurate measure of thermoregulatory peripheral vasoconstriction.

The authors appreciate many helpful discussions with Andrew M. Sessler, Ph.D., Senior Scientist, Lawrence Berkeley Laboratory. They thank Mon-a-Therm® for donating the thermometer and thermocouples used in this study.

References

1. Sessler DI, Olofsson CI, Rubinstein EH, Beebe JJ: The thermoregulatory threshold in humans during halothane anesthesia. ANESTHESIOLOGY 68:836–842, 1988
2. Sessler DI, Moayeri A, Glosten B, Støen R, McGuire J: Thermoregulatory vasoconstriction minimally decreases cutaneous heat loss. ANESTHESIOLOGY, in press
3. Støen R, Sessler DI: The thermoregulatory threshold is inversely proportional to isoflurane concentration. ANESTHESIOLOGY 72: 822-827, 1990
4. Kelleher JF, Ruff RH: The penumbra effect: Vasomotion-dependent pulse oximeter artifact due to probe malposition. ANESTHESIOLOGY 71:787–790, 1989
5. Bissonnette B, Sessler DI: Passive or active inspired gas humidification increases thermal steady-state temperatures in anesthetized infants. Anesth Analg 69:783–787, 1989
6. Sessler DI, Støen R, Glosten B: Validation of skin-surface temperature gradients as measure of centrally-mediated peripheral vasoconstriction (abstract). Anesth Analg 70:S363, 1990
7. Sessler DI, Olofsson CI, Rubinstein EH: The thermoregulatory threshold in humans during nitrous oxide-fentanyl anesthesia. ANESTHESIOLOGY 69:357–364, 1988
8. Loubser PG: Skin circulation and the thermoregulatory threshold. ANESTHESIOLOGY 70:370, 1989
9. Hales JRS: Skin arteriovenous anastomoses, their control and role in thermoregulation, Cardiovascular Shunts: Phylogenetic, Ontogenetic and Clinical Aspects. Edited by Johansen K, Burggren W. Copenhagen, Munksgaard, 1984, pp 433–448
10. Hirata K, Nagasaka T, Noda Y: Partitional measurement of capillary and arteriovenous anastomotic blood flow in the human finger by laser-Doppler-flowmeter. Eur J Appl Physiol 57:616–621, 1988
11. Holloway Jr GA, Watkins DW: Laser Doppler measurement of cutaneous blood flow. J Invest Dermatol 69:306–309, 1977
12. Carpenter RL, Kopacz DJ, Mackey DC: Accuracy of laser Doppler capillary flow measurements for predicting blood loss from skin incisions in pigs. Anesth Analg 68:308–311, 1989
13. Fagrell B: Dynamics of skin microcirculation in humans. J Cardiovasc Pharmacol 7(suppl 3):S53–S58, 1985
14. Burch GE, Cohn AE, Neumann C: A study by quantitative methods of the spontaneous variations in volume of the finger tip, toe tip, and postero-superior portion of the pinna of resting normal white adults. Am J Physiol 136:433–447, 1942
15. Brück K: Thermoregulation: Control mechanisms and neural processes, Temperature Regulation and Energy Metabolism in the Newborn. Edited by Sinclair JC. New York, Grune & Stratton, 1978, pp 157–185
16. Grant RT, Bland EF: Observations on arteriovenous anastomoses in human skin and in bird's foot with special reference to the reaction to cold. Heart 15:385–407, 1931
17. Coffman JD: Total and nutritional blood flow in the finger. Clin Sci 42:243–250, 1972
18. Higgins JC, Eady RAJ: Human dermal microvasculature: I. Its segmental differentiation: Light and electron microscopic study. Br J Dermatol 104:117–129, 1981

19. Rübsamen K, Hales JRS: Role of arteriovenous anastomoses in determining heat transfer across the hindleg skin of sheep, Thermal Physiology. Edited by Hales JRS. New York, Raven Press, 1984, pp 259–262
20. Hertzman AB, Randall WC: Regional differences in the basal and maximal rates of blood flow in the skin. J Appl Physiol 1:234–241, 1948
21. Smith RR: Thermal factors controlling rabbit skin thermoregulatory processes. Fed Proc 28:1011–1016, 1969
22. Goetz RH: The rate and control of the blood flow through the skin of the lower extremities. Am Heart J 31:146–182, 1946

Appendix

The rate constant for finger cooling was calculated at each measurement interval after occlusion using a heat loss equation. Newton's law of cooling is

$$dQ/dt = KA[T(t) - T_f], \quad (1)$$

for which dQ/dt (cal/min) is heat flux K ($cal \cdot cm^{-2} \cdot °C^{-1} \cdot min^{-1}$) is a constant, A ($cm^2$) is the area, T(t) (°C) is finger temperature at time t (min), and T_f (°C) is the final steady-state finger temperature (at time = 30 min). Following tourniquet inflation (zero finger blood flow), $T_f \approx$ ambient temperature. However, this equation remains valid when physiological alterations in blood flow produces steady-state T_f above ambient temperature. From the heat content of the finger

$$dQ/dt = -C_v V(dT/dt), \quad (2)$$

for which C_v ($cal \cdot °C^{-1} \cdot cm^{-3}$) is the specific heat, V (cm^3) is fingertip volume, and dT/dt (°C) is the change in fingertip temperature at time t (min).

$$dT/dt = -\beta[T(t) - T_f], \quad (3)$$

for which β (min^{-1}) = KA/C_vV. This equation was integrated to solve for T(t):

$$T(t) = (T_i - T_f)e^{-\beta t} + T_f, \quad (4)$$

for which T_i = initial finger temperature in °C (at time = 0). This equation was rearranged to solve for β:

$$\beta = \{\ln (T_i - T_f) - \ln [T(t) - T_f]\}/t. \quad (5)$$