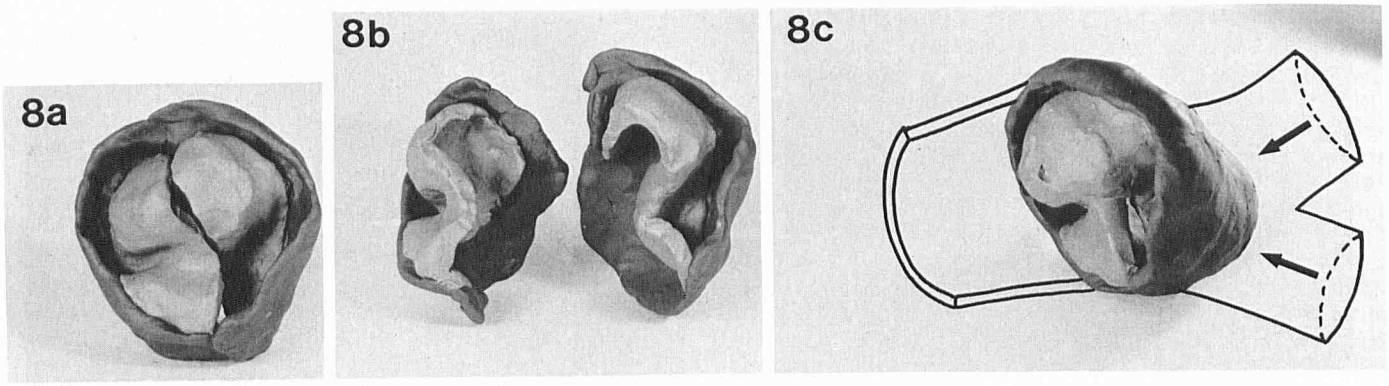

FIG 8. Model of valve at junction of 3 veins. *a*, View of free edges of valve cusps. *b*, Valve spread open to show cusps. *c*, Valve in situ at junction of 3 veins. *Arrows* indicate presumed direction of blood flow.

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Basal Perfusion of the Cutaneous Microcirculation: Measurements as a Function of Anatomic Position

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Noninvasive optical techniques of photopulse plethysmography (PPG) and laser Doppler velocimetry (LDV) have been used to identify regional variations in the basal skin blood flow of humans. The procedures assess either the volume (PPG) or the volume-velocity product (LDV) of cutaneous blood vessel perfusion. Fifty-two anatomic positions have been studied in 10 normal subjects resting horizontally. The mean perfusion levels were ranked to reveal the variations in cutaneous blood flow as a function of body site. Groups of data were collected into cohorts and average perfusion values for the subjects within each cohort were compared by the Newman-Keuls multiple comparison test. Most transparently, the results reveal a collection of regions (fingers, palms, face, ears) for which cutaneous perfusion is much higher than all other positions. More subtle differences and some unexpected similarities, however, are also apparent and, in some cases, agree or, in others, conflict, with previously published information. With some exceptions, good general agreement between the two techniques was observed.

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Regional variations in skin blood supply have been recognized for many years and numerous investigators have employed a variety of techniques to estimate skin perfusion [1]. This high level of study is understandable in terms of the physiologic importance of an efficient skin blood supply. For

of clinically significant situations (e.g., Raynaud's disease [5], chronic ulcers [6]). Apparent from the literature are clear differences in cutaneous blood supply to different anatomic regions and it is the further detailed probing of this dependence which this paper addresses.

Hertzman and associates [5,7,8] provided the earliest estimates of regional differences in skin blood flow. They used a photoelectric plethysmograph and concluded that flow to the skin of the trunk, arms, and legs was essentially equal, and much less than that to the palmar and plantar surfaces, and that in the skin of the face and head. In addition to these qualitative observations, an attempt was made to quantify the various perfusion levels in terms of a volume per unit area per unit time. Such a quantification has been the goal of much work, which has been well summarized [1]. Many different procedures have been employed, including plethysmography, venous occlusion methodology, radioactive tracer clearance techniques, and local heat loss [1,3]. Absolute comparisons among anatomic sites are awkward, however, because of the variety of detection means and the inconsistencies in the subject population and measurement conditions. Some studies, though, do allow certain relative regional skin blood flow assessments to be made. For example, Buchanan et al [9] used the clearance of $^{24}Na^{+}$ as an index of local circulatory efficiency and found (i) that skin blood flow was noticeably faster in the forehead than in the leg, and (ii) that symmetrical areas of pretibial skin in normal subjects at rest had equal blood flow. The latter conclusion has also been substantiated elsewhere [10] in a more complete study. Sejrsen [11] employed the washout of radioactive ^{133}Xe (delivered both by intracutaneous injection and by nontraumatic epicutaneous application) to measure skin blood flow in humans. Perfusion was estimated to be about 6 ml/100 g/min in the leg, 5 ml/100 g/min in the arm, slightly less in the abdomen, and 2–3 times greater in the cheek. Lundberg and Smedegard [2] have determined regional differences in skin blood flow using radioactive microspheres in rat and monkey animal models and have found that skin blood flows were significantly higher in the thoracic region than in the lumbar and sacral regions.

In this paper, relative assessments of basal regional skin blood flow in humans are presented. Data have been obtained at 52 different anatomic positions in 10 subjects using 2 techniques. The methods employed are photopulse plethysmography (PPG) [12,13] and laser Doppler velocimetry (LDV) [14–18]. Both these optical procedures are noninvasive and collect the perfusion information via small sensors positioned directly on the skin surface. The procedures do not quantitate skin blood perfusion (as a volume/weight of tissue/unit time) and it is questionable whether they can do so even with an independent "calibration." They do, however, produce outputs known to be related to fundamental skin perfusion characteristics, i.e., volume and flow rate (how much and how fast). They also generate this information in situ in humans with vanishingly small tissue perturbation. As such, it has been possible to perform some accurate, controlled comparisons of regional skin blood flow to a much larger number of sites on the human body than has been attempted before.

MATERIALS AND METHODS

Photopulse Plethysmography (PPG)

Descriptions of this procedure have appeared previously [12,13]. An infrared light emitting diode directs radiation into the skin. The wavelength range of the source (800–940 nm) spans a region for which the tissue is relatively transparent; on the other hand, hemoglobin absorbs strongly in this part of the spectrum and hence the backscattered radiation, which is measured with a phototransistor, contains information about the volume of blood in the skin site under observation.

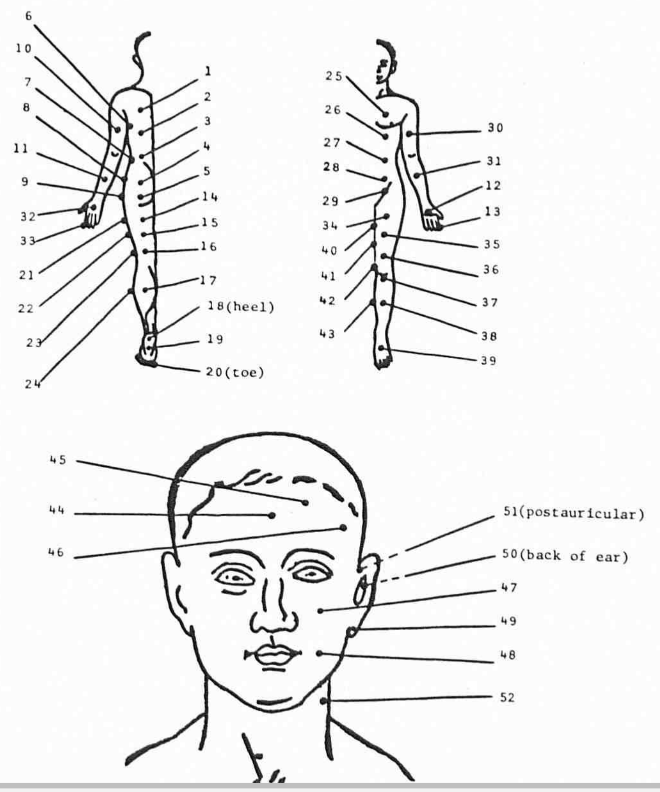
the blood volume fluctuations is performed by a photoplethysmograph (Medasonics, Mountain View, California). Increases in perfusion are registered by an enhancement of the amplitude of the output pulsations [8,12,13].

Laser Doppler Velocimetry (LDV)

A laser Doppler velocimeter [14–18] (LD5000, Medpacific Inc., Seattle, Washington) was used. Light at 632.8 nm from a 5 mW He-Ne laser is transmitted to the skin through an optical fiber. Doppler-shifted backscattered light from *mobile* red blood cells is collected by a similar optical fiber which guides the radiation back to the instrument. The detected signal is processed to produce an output which is a complicated function of the blood velocity and the effective blood volume within the field of view of the 2 fibers. Cardiac pulsations appear in the recorded waveform, but it is the envelope of these pulsations that is the quantity of interest. Physical support to the fibers at the point where they interface with the skin is provided by a small cylindrical probe which is attached to the application site using a double-sided adhesive perforated disc.

Experimental

Ten subjects were studied. The volunteers were healthy, young (20–30 years) men. Measurements were made in a single, well-ventilated room under reasonably constant temperature and humidity conditions (T = 23 ± 2°C, RH = 50–70%), to which the subjects were acclimatized for 15 min prior to the acquisition of PPG and LDV data. Measurements were taken from nude subjects in either a supine or prone position. Recordings from the 52 anatomic sites investigated (see Fig 1) were obtained consecutively over a 3- to 4-h period. Readings at any particular site were averaged over about 3 min by analyzing the recorded output. At each position, PPG and LDV measurements were made within 10 min of one another. Recordings were taken specifically from positions to the left of or on the midline. In a limited number of examples studied, bilateral measurements were indistinguishable. Before any perfusion readings were made by PPG, the plethysmograph was calibrated with an oscillating reflection device which provides a constant signal for equalization of the PPG sensor's sensitivity. Prior to the measurement of blood flow by LDV, the capillary perfusion monitor was zeroed using its internal circuitry.



RESULTS

The experimental data, as measured by the PPG and LDV techniques respectively, are summarized in Figs 2 and 3. These graphs show the ranked means, together with their respective SD, for the 52 anatomic sites studied. In Fig 4, a scatter plot of mean PPG measurement vs mean LDV determination is presented. The anatomic sites having high PPG and LDV assessed perfusion values are identified by number on the graph.

To statistically address the perfusion measurements, a simple first step is to compare the ranked means in pairs by a repeated measures test [19]. This is a dubious procedure, however, because, although the results may be used to compare perfusion at any pair of sites with the prescribed level of significance, comparisons among several different pairs are less significant [20]. Therefore, we have divided the various sites into groups and ranked up to 6 group means using the Newman-Keuls multiple comparison test [19]. The statistical results for the 3 groupings chosen are presented in Tables I–III. The point should be made that each set of comparisons (i.e., each individual Table) must be interpreted individually and that conclusions drawn by comparing statistical differences in 2 different Tables are less significant.

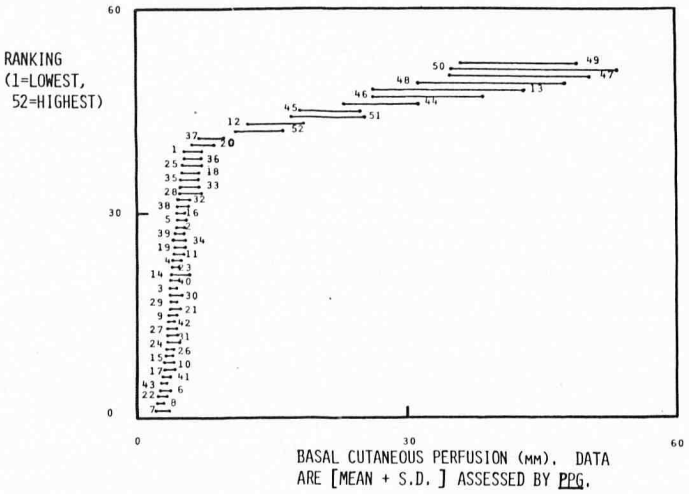
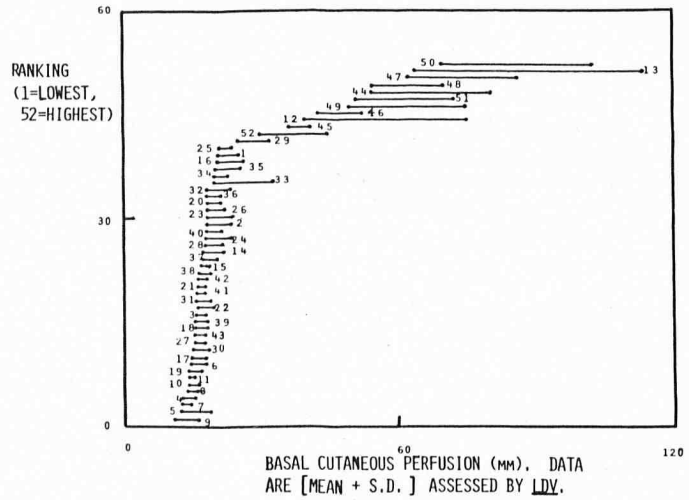


FIG 2. Basal cutaneous perfusion measurements assessed by PPG. The sites are ranked according to the mean values obtained and are presented with their respective SD. PPG units are signal amplitude magnitude in mm (1 mm is equivalent to 10 mV).



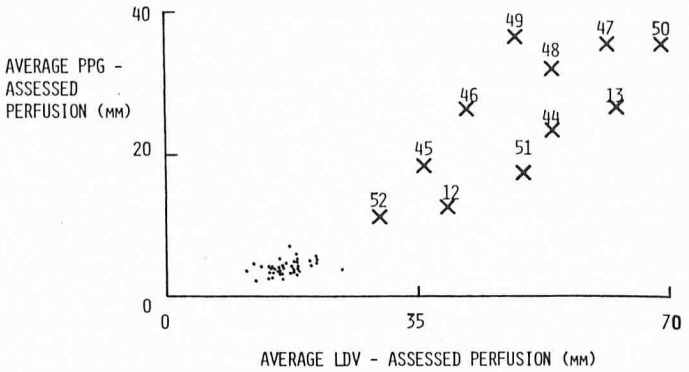


FIG 4. Plot of mean PPG perfusion measurement (1 mm = 10 mV) vs the corresponding LDV mean (1 mm = 20 mV) for the 52 anatomic positions studied. The sites of high PPG and LDV assessed perfusion values are indicated by number on the graph.

TABLE I. *Multiple comparisons of cutaneous perfusion measurements[a] for the anatomic position groups designated cohort A: trunk, upper limb, lower limb, foot, hand,[b] and face*

	Upper limb	Lower limb	Foot	Hand	Face
Trunk	N	N	N	**	**
Upper limb		N	N	**	**
Lower limb			N	**	**
Foot				**	**
Hand					*, N

[a] Where 2 entries appear in the Table, PPG assessment is given first, then LDV; otherwise, PPG and LDV agree.

[b] Palmar surface only.

The groups have been multiply compared using the Newman-Keuls statistical test [19] and differences have been assessed at the $p = 0.05$ and $p = 0.01$ levels of significance. The entry *N* in the Table means that perfusion of the 2 groups compared is not significantly different. The entry of 1 ($p = 0.05$) or 2 ($p = 0.01$) asterisks means that the group in the left-hand column has significantly lower perfusion than the paired group in the top row of the Table.

TABLE II. *Multiple comparisons of cutaneous perfusion measurements[a] for cohort B: side of the trunk, lower leg, upper leg, arm, lower trunk, upper trunk*

	Lower leg	Arm	Upper leg	Lower trunk	Upper trunk
Side	**	**	**	**	**
Lower leg		N	N	N	**, *
Arm			N	N	N, *
Upper leg				N	N
Lower trunk					N, *

[a] Where 2 entries appear in the Table, PPG assessment is given first, then LDV; otherwise, PPG and LDV agree.

The methods of comparison and Table entries are as described for Table I.

TABLE III. *Multiple comparisons of cutaneous perfusion measurements[a] for cohort C: hand,[b] finger, postauricular region (PAR), back of ear, ear lobe, and face*

	PAR	Finger	Face	Back of ear	Earlobe
Hand	N	*, N	N	**, N	**, N
PAR		N	N	**, N	**, N
Finger			N	N	N
Face				N	N
Back of ear					N

[a] Where 2 entries appear in the Table, PPG assessment is given first,

DISCUSSION

The extensive data gathered in this study can be used to compare the degree of perfusion at various anatomic sites over most surfaces of the body, as well as to investigate the correlation between the results of 2 measuring techniques, namely, PPG and LDV.

The means and SD at the various sites as obtained by the 2 methods appear in Figs 2 and 3, respectively. As a first approximation those figures identify 2 broad groups: (a) a large number of sites with "low" skin blood perfusion, and (b) a collection of positions with elevated microcirculation. We note that the variation in the latter (as measured by the SD) is much greater than the former.

This broad division can be observed also in Fig 4, where the results of the PPG and LDV correlate fairly well only for those sites with low readings. The body positions not associated with the low PPG–low LDV cluster are found on the head, face, ears, fingers, and palms. It is appropriate to note that these are the same anatomic positions associated with large and complex cutaneous arteriovenous shunts [21].

To facilitate a statistically significant comparison of the large number of experimental results that has been obtained, it was decided to group together parts of the data and then compare the mean perfusion levels of the chosen groups. The selection of the various groups is, by necessity, somewhat arbitrary, and, in the examples presented, has been performed anatomically. Multiple comparisons among groups have been performed by the Newman-Keuls statistical test [19] and differences have been assessed at both the $p = 0.05$ and $p = 0.01$ levels of significance.

The first set of groups (cohort A) considered was: trunk, upper limb, lower limb, feet, hands, and face. The multiple comparisons for the PPG results and LDV data are given in Table I. Cohort A contains regions of 2 distinct characteristics. The hands and the face represent anatomic regions of high cutaneous perfusion relative to all other sites on the body. Within this cohort, positions on the body excluding the hands and face are not distinguishable from one another. PPG and LDV are in complete agreement in comparing this cohort with the minor exception that PPG finds the face more highly perfused than the hands (at $p = 0.05$) whereas LDV suggests no difference.

Results for cohort B (side of the trunk, lower legs, upper legs, arms, lower trunk, and upper trunk) are statistically ranked in Table II. Once again, apart from a few discrepancies at the $p = 0.05$ level of significance, PPG and LDV are in good agreement. Within these groups, it is observed that the sides of the body are relatively poorly perfused compared to all other regions. Interestingly, it is found that the blood supply to the lower leg is significantly less than that to the upper trunk, whereas perfusion to the upper leg is not statistically different than that to the upper trunk. It may be suggested, therefore, that there is some indication in these comparisons (despite the statistical equivalence between upper and lower legs) of a contributory factor as to why wounds on the lower leg heal more slowly than elsewhere [22].

Cohort C (Table III) comprises 6 "high" blood flow groups: hand, finger, postauricular region, back of ear, ear lobe, and face. Multiple comparisons of the PPG information in this cohort are clearly different from those of the LDV data. LDV does not distinguish among any of the groups, and finds, at the levels of significance tested, that blood flow to all these regions is similar. It is possible that, because of the large SD associated with the LDV values for these sites, the subject group studied may not have been sufficiently large to allow any real differences to be found. PPG, however, identifies the back of the ear and the ear lobe as much more highly perfused regions than these results are consistent with known characteristics of human facial flushing [23].

When the results of this study are compared with those in the literature, there are areas of agreement and discrepancy. In the former case, the early, careful work of Hertzman and colleagues [5,7,8] is confirmed qualitatively and is statistically proved for a larger subject population. The identification of the facial region as a skin area much better perfused than the majority of the rest of the body is consistent with the half-lives for $^{24}Na^{+}$ clearance, forehead skin vs tibial skin, observed by Buchanan et al [9]. Fig 4, furthermore, provides more justification for this conclusion. The existence of a group of regions (face, ears, fingers, palms) with high LDV and PPG readings suggests that the residence time of a unit volume of cutaneous blood at these sites is short relative to the other anatomic positions. Consequently, the clearance of injected radiolabel into these highly perfused areas is expected (and is found) to be relatively rapid. [Of course, one may envisage clinical situations (e.g., full or partial venous occlusion) for which total volume can be increased and flow decreased thereby yielding discrepancy between PPG and LDV assessed perfusion.]

Disagreement between the investigation reported here and that performed by Lundberg and Smedegard [2] is apparent. Whereas these authors found that thoracic skin blood flow exceeded lumbar and sacral perfusion, no such differentiation was detected by LDV and PPG. However, this recent work was carried out in rats and monkeys, for which comparable noninvasive blood flow assessments are not currently available, and thus direct comparisons are somewhat tenuous.

In conclusion, the basal perfusion of the cutaneous microcirculation has been measured comprehensively as a function of anatomic position by 2 noninvasive optical techniques. Statistical assessment of the results has revealed important similarities and differences in resting skin blood flow. Because the detecting methodologies operate on different principles, there is potential in further experimentation to probe more closely the characteristics and origins of variable levels of regional cutaneous perfusion.

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Effect of a Skin Moisturizer on the Water Distribution in Human Stratum Corneum

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The effect of a skin moisturizer on the water content distribution in human stratum corneum was examined from the rate of water loss from the skin surface. An increase of 9% in the water content was calculated from the water loss data. This increase was not evenly distributed across the tissue. Most of the increase occurred near the skin surface. In the first one-tenth of the stratum corneum the increase was estimated to be about 100%.

Water is known to be a good plasticizer for stratum corneum [1]. The occlusive effect of a skin moisturizer on the water content in stratum corneum may be evaluated from the changes in the rate of transepidermal water loss (TEWL).

In this paper, we report the quantitative changes in the water concentration profile across the thickness of the stratum corneum calculated from the changes in the TEWL rates before and after the application of a skin moisturizer.

METHODS

Female subjects were recruited for the study. Prior to testing, the panelists washed their forearms with a mild detergent, rinsed with warm water, and patted dry. The washing procedure was followed by a 30-min equilibration period in a room that was maintained at a constant humidity (31% RH) and temperature (22°C). This period allowed the panelists to adjust to the conditions of the testing environment. One site was delineated on each forearm, and the rate of water loss was determined at each site. After the measurements were taken, one of the sites (randomly selected) was treated with 0.03 ml of a moisturizer on a 16 cm^2 area. The water loss measurements were repeated on both sites at 60, 90, and 120 min posttreatment.

The Evaporimeter EP 1 (Servomed, Sweden) was used to obtain the rate of water loss [2]. The output from the instrument was interfaced with an Apple II computer. The computer was programmed to acquire 1 data point per 4 s for 4 min and to perform a statistical analysis at the end of the measurement.

RESULTS AND DISCUSSION

It is known that the rate of water loss is affected by environmental factors. Therefore, the measurements were made in a room that was maintained at a constant humidity and temperature. The air current in the room was also minimized during the measurement. Another major factor influencing the rate of water loss is the physiologic state of the panelist. To alleviate the possibility of this interference, each panelist was asked to rest in the testing room for 30 min before actual testing began. The possible site-to-site variation was eliminated by the random selection of the treated sites.

The instrument used to obtain the TEWL rates measures the water vapor gradient on the skin surface. Therefore, theoretically, the measurements are instantaneous. However, the readings on the instrument can fluctuate very fast, making accurate readings difficult. By carefully controlling the environment during the measurements and by using a microcomputer to acquire the data, this difficulty may be eliminated. With each measurement, 2400 data points were collected from the Evaporimeter and analyzed statistically by the computer. It was found that the standard deviation in each measurement was about 15%.

The pretreatment value obtained here (7.95 ± 3.63 g/m^2 h) was in the same range as those reported by other investigators using different techniques [3,4]. Table I shows the effect of a moisturizer on the rate of water loss. It can be seen that the

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