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QUANTITATIVE VALUES OF BLOOD FLOW THROUGH THE HUMAN FOREARM, HAND, AND FINGER AS FUNCTIONS OF TEMPERATURE

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I. Introduction

A literature search was made to obtain values of human forearm, hand and finger blood flow as functions of environmental temperature. The sources used include both government and laboratory reports and the research presented in the open literature. An attempt was made to review many of the more quantitative noninvasive determinations and to collate the results in such a way as to yield blood flow values for each body segment as continuous functions of temperature. It is hoped that this data will be useful to physiologists, biothermal modelers and others interested in the study of man's circulatory and thermoregulatory systems.

Noninvasive methods of measuring blood flow are diverse. They generally depend upon either knowing the amount of heat rejected or the amount of displacement produced in a secondary medium by the body segment at the environmental condition being studied. A basic understanding of these techniques is essential in order to gain an insight into the data averaging procedure used in this report. The compendium, therefore, includes a brief review of the various ways used to measure blood flow.

The compendium includes an abstract or summary of each work from which data was taken. These citations are drawn from the various reports and presented with little or no modification.

Also given is a separate list of all works that were reviewed during the course of this literature search. Blood flow values from many of these reports were not included in the data analysis for the three body segments. Blood flow values were used only if the ambient air and local segment temperatures were well controlled within narrow limits during each experiment and if the subjects were in thermal equilibrium in the resting state. However, much useful qualitative information may be obtained from the numerous reports listed.

In addition to the above, a table is presented which describes a number of the important aspects of each quantitative experiment used in this investigation. These are as follows:

1. Author and date of each experiment,
2. Body segment used in blood flow study,
3. Room or ambient air temperature,
4. Local segment temperature (plethysmograph water bath temperature, air temperature or local skin temperature, depending upon measurement technique used),
5. Local temperature converted to segment skin temperature,
6. Measured blood flow values in units of ml/100 ml (segment volume) - min.,
7. Number of subjects used in each experiment.

This information is also given in graphical form as a function of skin temperature for various ranges of ambient temperature for each body segment.

II. Blood Flow Measurement Techniques

A number of detailed reviews or comparisons of noninvasive blood flow measurement techniques have been published.[1,2,5,6,7] A brief description of each type will be presented here to enable the reader to better understand the basic principles, application and possible limitation of their use.

Three types of methods have been used for quantitative blood flow measurement in the forearms, hands and fingers of man. The first depends on the change in the volume of the segment after obstruction of the venous return blood, the second measures the pulsatile volume in the given segment and the third is based on thermal measurements such as skin temperature, heat loss, tissue conductance and tissue thermal conductivity.

A. Venous Occlusion Plethysmography

This technique may be more easily described as displacement plethysmography. Essentially these devices enclose the body segment within a rigid or fixed volume container. They employ either air or water as the working fluid which surrounds the body segment. An increase in the volume of the enclosed segment displaces fluid from the rigid container to a system for measuring volume.

A venous occlusion cuff is applied to the body segment proximally to the volume container. After inflation of the cuff, venous return blood is obstructed causing blood pooling in the segment distal to the cuff. It is assumed that the volume increase as measured by the displaced air or water immediately following cuff inflation is indicative of continued normal arterial blood inflow to the segment enclosed in the container.

As pointed out by Hyman and Winsor[5] each of the working fluids used in displacement plethysmographs has certain inherent disadvantages. Water imposes hydrostatis forces on the tissues which tend to impede arterial flow into the enclosed segment. In addition, water because of its high heat capacity and intimate body contact introduces thermal problems which may alter the responses being studied. The high thermal expansion coefficient of an air-filled system introduces problems of drift.

Other problem areas of concern with the displacement plethysmograph are motion artifacts; occluding cuff configuration and placement; body orientation and the affects of both cuff and volume container upon the internal hemodynamics of the segment being studied.

B. Volume Pulse Measurement Techniques

These methods measure the transient effects or dimensional changes occurring in a body segment with each pulsation of blood flowing through the segment. Included in this category are the impedance, capacitance, mercury-in-rubber strain gauge and photoelectric plethysmographs.

The impedance plethysmograph measures the electrical impedance changes which vary with the blood content of the segment during each blood pulse. With a tetra-polar arrangement four electrodes are placed on or around the given segment separated by various axial distances. A high frequency low amperage electrical current is input between the outer two electrodes. Simultaneously, the impedance produced by the electrically conductive tissue and blood is measured between the two inner electrodes. Additional blood placed between the two inner electrodes during a pulse has the effect of placing a second resistor in parallel with the tissue resistance lying between the two recording electrodes. This in turn decreases the total segmental resistance between the recording electrodes proportionally to the pulse blood flow.

In using the capacitance plethysmograph the segment being studied is placed within a wire mesh capsule which serves as one plate of a condenser. The skin of the enclosed segment serves as the second plate. When connected to the proper circuitry changes in the capacity of this condenser reflect the changes in the skin to wire mesh distance occurring during a pulsatile flow of blood.

The mercury-in-rubber strain gauge plethysmograph employs a mercury filled elastic rubber tube as the expansion transducer. When the tube is stretched, the column of mercury is narrowed changing its electrical resistance in proportion to its increase in length. If the filled tube is placed circumferentially around a given body segment it is possible to measure the increase in segment girth produced by the blood pulse passing through the circumscribed tissue. This circumferential length change is then a measure of the pulse volume of the blood flowing through the segment being studied.

In using the photoelectric plethysmograph a light source is used to transilluminate the body tissue. The light which has passed through the skin is recorded by a photocell. The intensity of the photocell current will vary as a function of the blood content of the illuminated tissue during each blood pulse.

The impedance, capacitance and mercury-in-rubber strain gauge plethysmographs measure both the tissue changes with each pulsation and show a progressive increase in segment blood pooling after venous occlusion.

These methods have the advantage that they may be applied to the skin of the trunk and head as well as to the extremities. However, the extent of correlation between the blood flow as measured by these techniques and that actually occurring in the tissue has not been firmly established.

C. Thermal Measurements

The thermal measurement technique of determining blood flow may also be called the calorimetric method. The body segment to be studied is enclosed within a well insulated thermal calorimeter and the heat loss from the segment is measured under steady state conditions. This heat loss may be related to blood flow within the segment by determining the tissue conductance which depends upon the convective heat transfer occurring within the segment.

As stated by Landowne and Katz[6] the thermal or enclosed calorimetric method presents the following disadvantages:

1. The assumption that the venous blood is at skin temperature after equilibration is not valid,
2. The calorimeter insulation is not complete and a variable gain or loss of heat may occur,
3. Conduction and radiation cannot be evaluated, and
4. A rapid succession of events cannot be studied.

In addition, the temperature of the body segment being measured will be strongly influenced by the application of either an enclosing calorimeter or a gradient calorimeter. Therefore the blood flow within the segment will be altered by the measuring device .

Due to the limitations of the thermal techniques the quantitative data presented herein have largely been obtained by the venous occlusion plethysmography or volume pulse measurement techniques. The local segmental temperatures given in Table I refer to the air or water bath temperatures if displacement plethysmographs were used or to ambient air temperatures if the pulse volume measurement techniques were used.

III. Comparison of Various Blood Flow Experiments

The investigations cited in this compendium have measured segmental blood flow at various values of local temperature (air or water temperature of the plethysmograph). While the methods used have been similar, it is difficult to compare the data from different experiments. According to Thauer[7] there are three main reasons for these difficulties: a) A steady state is achieved only at temperatures below 32 to 35°C or above 44 to 45°C. Between these limits the blood flow changes with time, increasing at first and later declining almost to its original value. b) Even at lower temperatures, when this phenomenon is absent, spontaneous fluctuations in blood flow occur. c) Although in most experiments the room temperature was kept constant, the temperatures used have rarely been the same, and both room temperature and clothing would have to be identical if results were to be strictly comparable.

Various experimental results could be compared if the room and local temperatures were well controlled and if the subjects were similarly clothed. All of the works reviewed during this literature search are listed in Appendix A. Of these reports, twenty-three experiments list the local and room temperatures which were held fairly constant.

Abstracts or authors' summaries are given in Appendix B for each of the twenty-three works from which quantitative blood flow values were obtained. The blood flow values taken from these reports are listed in Table I alphabetically by author.

Table I may also be used as a brief summary of each experiment. The author, date and type of measurement are given for each experiment. Three blood flow measurement techniques were used in these reports; venous occlusion plethysmography with both air and water as the displacement fluid and photoelectric plethysmography. Also given for each experiment are the body segment considered, room and local temperature, the measured blood flow, and the number of subjects used.

Since the local temperatures given in Table I represent either the plethysmograph water bath or air temperature the relations shown in Figures 1 and 2 were used to convert the local temperatures to corresponding skin temperatures. Figure 1[4] illustrates the average skin temperature as a function of plethysmograph water bath temperatures. Figure 2[3] shows the average skin temperature vs.

TABLE I. FOREARM, HAND, AND FINGER BLOOD FLOW VALUES VERSUS LOCAL AND AMBIENT TEMPERATURES

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Abramson & Fierst - 1942	Forearm	26.0	32.0	33.3	1.77	56
Water bath, V.O.P.*	Hand	26.0	32.0	33.3	9.32	61
Abramson et al. - 1971	Forearm	26.0	45.0	41.3	8.7	19
Water bath, V.O.P.		26.0	34.0	34.7	3.3	35
		26.0	23.0	26.3	1.0	16
		26.0	6.0	10.6	1.3	29
	Hand	26.0	41.0	39.3	20.5	8
		26.0	34.0	34.7	8.3	14
		26.0	23.0	26.3	1.4	8
		26.0	6.0	10.6	2.0	9
Abramson, Zazeela & Marrus - 1939	Forearm	26.0	32.0	33.3	2.26	6
Water bath, V.O.P.		26.0	45.0	41.3	8.91	6
	Hand	26.0	32.0	33.3	14.12	17
		26.0	45.0	41.3	35.26	15
Bader & Macht - 1948	Hand	23.5	23.5	30.8	0.6	1
Air bath, V.O.P.		23.5	23.5	30.8	0.8	1
Bader & Mead - 1949	Finger	15.0	15.0	35.0	0.79	2
Water bath, V.O.P.		32.0	32.0	24.5	76.1	2
Barcroft & Edholm - 1946	Forearm	18.5	N.A.	37.0	5.9	7
Water bath, V.O.P.		18.5	N.A.	35.0	4.25	7
		18.5	N.A.	34.0	3.4	7
		18.5	N.A.	33.0	2.7	7
		18.5	N.A.	32.0	2.3	7
		18.5	N.A.	30.0	1.6	7

*V.O.P. = venous occlusion plethysmograph

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Barcroft & Edholm - 1943	Forearm	17.0	10.0	13.5	0.5	5
Water bath, V.O.P.		17.0	15.0	18.0	0.5	5
		17.0	20.0	23.5	0.5	5
		17.0	25.0	28.0	0.7	5
		17.0	30.0	32.0	1.6	5
		17.0	32.0	33.3	2.3	5
		17.0	35.0	35.5	4.3	5
		17.0	37.0	36.8	5.9	5
		17.0	45.0	41.3	17.6	5
Bargeton et al. - 1959	Hand	24.86	10.0	13.5	3.6	3
Water bath, V.O.P.		24.86	11.0	14.2	2.5	3
		24.86	13.0	16.0	1.7	3
		24.86	15.0	18.0	1.1	3
		24.86	17.0	20.1	1.3	3
		24.86	19.0	22.5	1.4	3
		24.86	21.0	24.5	1.7	3
		24.86	23.0	26.2	2.1	3
		24.86	25.0	28.0	2.2	3
		24.86	27.0	29.6	2.2	3
		24.86	29.0	31.2	2.6	3
		24.86	31.0	32.6	3.0	3
		24.86	33.0	34.0	3.5	3
		24.86	35.0	35.5	4.2	3
		24.86	37.0	36.8	6.4	3
		24.86	39.0	38.0	8.8	3
		24.86	41.0	39.1	17.7	3
		24.86	43.0	40.2	21.1	3
		24.86	45.0	41.3	29.6	3
Brown, Hatcher & Page - 1953	Forearm	20.0	5.0	10.1	1.5	37
Water bath, V.O.P.		20.0	10.0	13.5	1.4	37
		20.0	20.0	23.5	1.7	37

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Brown, Hatcher & Page - 1953 (Concluded)	Forearm	20.0	30.0	32.0	2.8	37
		20.0	33.0	34.0	3.0	37
		20.0	34.0	34.8	3.2	37
		20.0	35.0	35.5	3.1	37
		20.0	38.0	37.5	5.3	37
		20.0	42.5	40.0	8.1	37
		20.0	45.0	41.3	10.3	37
Brown & Page - 1952 Water bath, V.O.P.	Hand	20.0	5.0	10.1	3.0	37
		20.0	10.0	13.5	1.0	37
		20.0	20.0	23.5	0.8	37
		20.0	30.0	32.0	[illegible].8	37
		20.0	32.0	33.3	4.5	37
		20.0	35.0	35.5	6.1	37
		20.0	38.0	37.5	9.2	37
		20.0	42.5	40.0	16.7	37
		20.0	45.0	41.3	19.7	37
Catchpole & Jepson - 1955 Water bath, V.O.P.	Hand	21.0	15.0	18.0	0.8	4
		21.0	20.0	23.5	0.4	4
		21.0	25.0	28.0	2.5	4
		21.0	30.0	32.0	4.6	4
	Finger	21.0	15.0	18.0	1.3	4
		21.0	20.0	23.5	1.25	4
		21.0	25.0	28.0	3.8	4
		21.0	30.0	32.0	11.2	4
Coffman & Cohen - 1971 Water bath, V.O.P.	Finger	28.3	28.3	33.5	59.7	10
		20.0	20.0	28.4	32.7	10

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Cooper, Edholm & Mottram - 1955 Air bath, V.O.P.	Forearm	23.5	30.5	32.3	1.45	1
		24.5	30.0	32.0	1.60	1
		23.5	34.0	34.8	1.90	1
		23.5	30.0	32.0	2.02	1
		24.5	30.5	32.3	2.05	1
		23.5	34.0	34.8	2.10	1
		23.5	34.0	34.8	2.12	1
		19.5	34.0	34.8	2.20	1
		23.5	34.0	34.8	2.27	1
		22.5	34.0	34.8	2.30	1
		23.5	34.0	34.8	2.39	1
		25.5	34.0	34.8	2.45	1
		24.5	34.0	34.8	2.60	1
		25.5	34.0	34.8	2.61	1
		23.5	34.0	34.8	2.70	1
		22.5	34.0	34.8	2.90	1
		23.5	34.0	34.8	3.03	1
		23.5	34.0	34.8	3.18	1
		23.5	34.0	34.8	3.20	1
		25.5	35.0	35.5	3.20	1
		23.5	34.0	34.8	3.60	1
		26.5	34.0	34.8	3.80	1
		24.5	34.0	34.8	4.0	1
		22.5	34.0	34.8	4.30	1
		22.5	30.5	32.3	4.50	1
		25.5	34.0	34.8	5.30	1
		24.5	34.0	34.8	5.60	1
		25.5	34.0	34.8	6.00	1
		23.5	34.0	34.8	6.17	1
		24.5	34.0	34.8	7.64	1
Ferris et al. - 1947 Air bath, V.O.P.	Hand	17.9	N.A.	18.0	0.4	1
		21.2	N.A.	22.2	0.7	1

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Ferris et al. - 1947 (Concluded)	Hand	22.5	N.A.	28.4	1.3	1
		24.4	N.A.	30.4	2.8	1
		29.6	N.A.	35.8	17.0	1
		30.2	N.A.	36.3	19.5	1
		17.2	N.A.	18.4	0.4	1
		22.2	N.A.	22.8	0.7	1
		23.7	N.A.	28.9	2.7	1
		24.8	N.A.	32.6	6.0	1
		30.2	N.A.	35.7	17.2	1
Forester II, Ferris, & Day - 1946 Air bath, V.O.P.	Hand	15.2	N.A.	15.7	0.75	1
		16.0	N.A.	16.6	0.46	1
		17.2	N.A.	18.2	0.50	1
		17.9	N.A.	17.8	0.21	1
		19.1	N.A.	19.4	0.26	1
		19.9	N.A.	23.6	1.00	1
		20.2	N.A.	19.6	0.31	1
		20.3	N.A.	20.2	0.35	1
		21.2	N.A.	20.6	0.61	1
		21.2	N.A.	20.8	0.51	1
		21.4	N.A.	27.7	2.50	1
		21.8	N.A.	24.6	3.40	1
		22.3	N.A.	26.1	1.60	1
		25.0	N.A.	32.8	8.72	1
		25.1	N.A.	31.6	9.48	1
		25.1	N.A.	34.4	6.72	1
		25.3	N.A.	32.9	5.85	1
		25.3	N.A.	34.6	16.50	1
		29.6	N.A.	35.4	11.30	1
		29.9	N.A.	35.7	16.08	1
		34.3	N.A.	36.0	10.85	1
		34.5	N.A.	36.0	11.00	1
		36.0	N.A.	36.7	8.98	1

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Forester II, Ferris, & Day - 1946 (Concluded)	Hand	36.3	N.A.	36.8	11.40	1
		37.4	N.A.	36.9	12.10	1
		15.3	N.A.	16.0	0.15	1
		15.4	N.A.	16.0	0.44	1
		18.9	N.A.	20.8	0.65	1
		19.8	N.A.	20.8	0.57	1
		22.8	N.A.	23.4	0.72	1
		23.4	N.A.	26.3	0.77	1
		24.4	N.A.	28.9	6.40	1
		25.0	N.A.	31.2	6.75	1
		29.4	N.A.	35.8	8.27	1
		29.6	N.A.	35.5	21.70	1
		33.2	N.A.	36.4	23.60	1
		33.4	N.A.	36.3	13.20	1
		38.0	N.A.	36.8	23.40	1
		38.0	N.A.	36.6	31.70	1
Grayson - 1949 Water bath, V.O.P.	Forearm	23.0	31.0	32.6	2.23	3
		30.0	31.0	32.6	2.40	3
		36.0	31.0	32.6	2.33	3
		38.0	31.0	32.6	2.66	3
		41.0	31.0	32.6	3.86	3
		45.0	31.0	32.6	7.66	3
	Finger	25.0	31.0	32.6	4.82	9
		30.0	31.0	32.6	5.82	9
		36.0	31.0	32.6	9.10	9
		38.0	31.0	32.6	6.07	9
		41.0	31.0	32.6	7.02	9
		45.0	31.0	32.6	9.88	9

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Hertzman & Randall -	Forearm	26.0	26.0	32.3	1.2	1
1948		26.0	26.0	32.3	3.4	1
Photoelectric	Hand	26.0	26.0	32.3	3.6	1
plethysmograph		26.0	26.0	32.3	9.4	1
	Finger	26.0	26.0	32.3	7.2	1
		26.0	26.0	32.3	27.0	1
Hillestad - 1962	Hand	25.0	32.0	33.3	6.0	5
Water bath, V.O.P.		25.0	40.0	38.5	9.0	5
Hillestad - 1970	Hand	23.0	32.0	33.3	4.5	5
Water bath, V.O.P.		23.0	40.0	38.6	7.5	5
Killian & Oclassen -	Hand	20.0	25.0	28.0	2.0	1
1938		20.0	30.1	32.0	3.7	1
Water bath, V.O.P.		20.0	34.9	35.3	8.6	1
		20.0	39.7	38.5	15.5	1
		20.0	44.8	41.0	17.1	1
Ludbrook - 1971	Forearm	21.4	19.6	23.0	0.9	4
Water bath, V.O.P.		21.4	19.6	23.0	0.9	4
		21.4	19.9	23.4	0.8	4
		21.4	39.8	38.5	3.5	4
		30.6	39.0	38.0	10.3	4
		30.6	39.1	38.1	9.5	4
	Hand	23.0	19.4	22.7	0.6	4
		23.0	19.7	23.0	0.4	4
		23.0	19.2	22.5	1.3	4
		23.0	39.6	38.5	4.0	4
		28.6	39.4	38.4	17.6	4
		28.6	39.9	38.6	26.0	4

Table I (Continued)

Source and Type of Experiment	Body Segment	Room Temperature, °C	Local Temperature, °C	Local Temperature Converted to Segment Skin Temperature, °C	Blood Flow ml/100 ml-min.	Number of Subjects
Roddie & Shepherd - 1955	Hand	19.0	32.0	33.3	9.0	5
Water bath, V.O.P.		19.0	32.0	33.3	6.0	5
		19.0	32.0	33.3	7.0	5
		22.5	42.5	40.7	26.0	5
		22.5	44.0	40.0	34.0	5
Spealman - 1945	Hand	15.0	10.0	13.5	1.9	3
Water bath, V.O.P.		15.0	15.0	18.0	0.3	3
		15.0	25.0	28.0	0.6	3
		15.0	35.0	35.5	1.9	3
		21.0	5.0	10.1	4.3	6
		21.0	10.0	13.5	2.5	6
		21.0	15.0	18.0	0.9	6
		21.0	20.0	23.5	1.3	6
		21.0	25.0	28.0	2.7	6
		21.0	35.0	35.5	5.9	6
		30.0	2.0	8.7	6.4	3
		30.0	5.0	10.1	6.8	3
		30.0	15.0	18.0	5.5	3
		30.0	20.0	23.5	8.1	3
		30.0	35.0	35.5	20.6	3

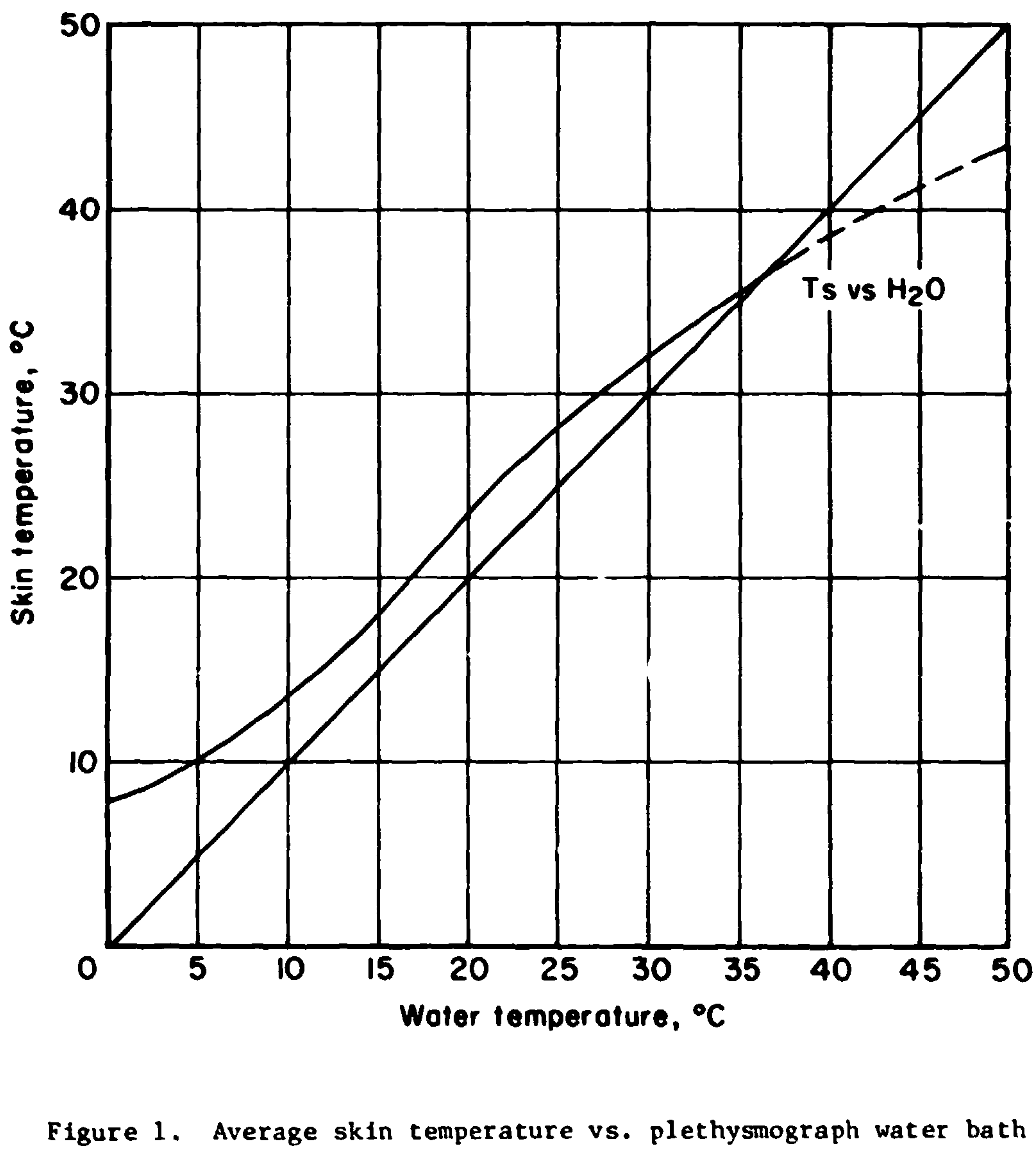

Figure 1. Average skin temperature vs. plethysmograph water bath temperature.

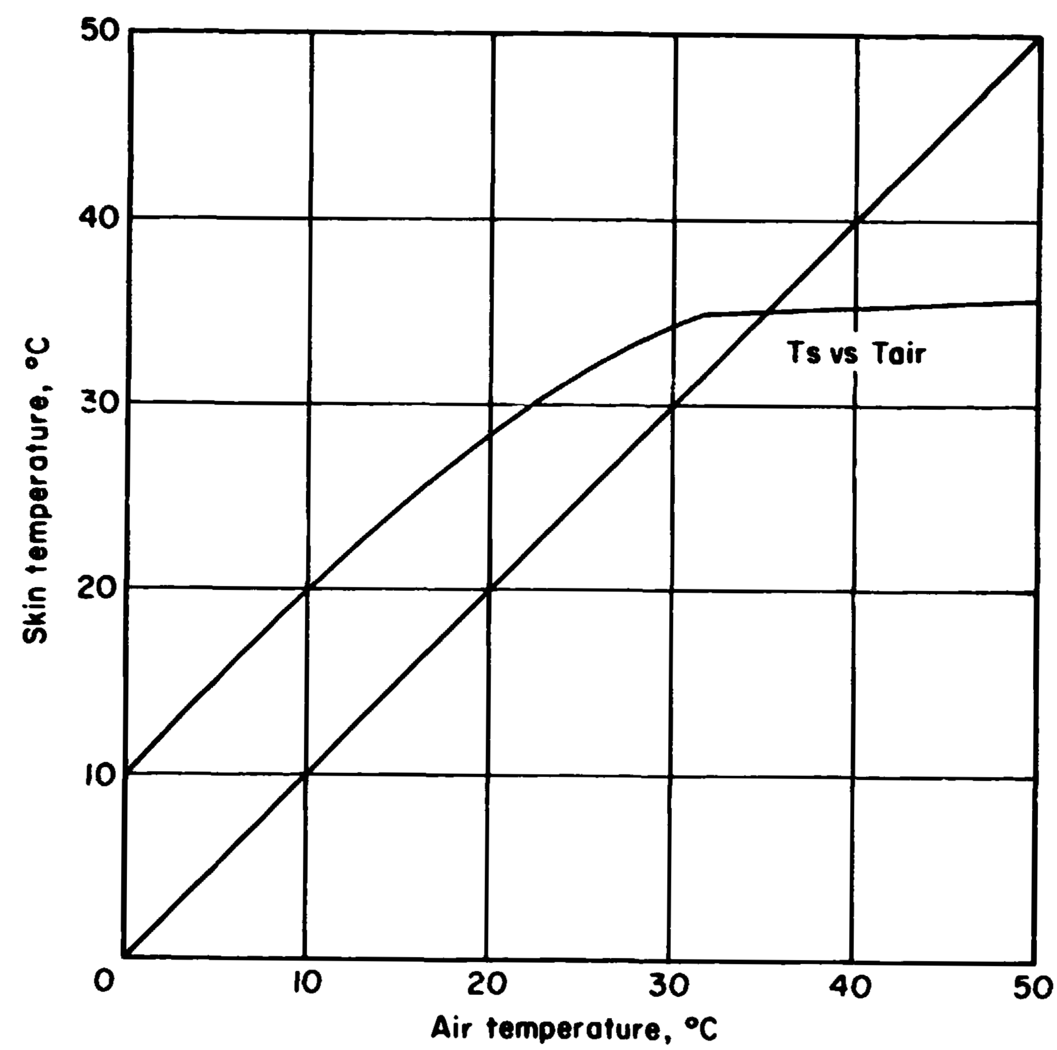

Figure 2. Average skin temperature vs. plethysmograph air temperature.

plethysmograph air temperature. By using these two figures it was possible to establish the local segmental skin temperature as a basis of comparison for all of the blood flow values obtained from the literature for each body segment.

Figures 3, 10 and 17 show the blood flow values for the forearm, hand and finger, pectively, as functions of the converted skin temperatures. All of the blood flow values obtained from the literature are plotted in these three figures independent of the room temperature used. In an attempt to establish the effect of room temperature upon blood flow the overall data for each segment was averaged in 5°C room temperature ranges. By this process the forearm data shown in Figure 3 which were measured in room temperatures between 15.1 and 20.0°C were averaged as a function of skin temperature as shown in Figure 4. Similarly the forearm blood flow values from room temperatures between 20.1 and 25.0°C are plotted vs. skin temperature in Figure 5. This averaging technique was repeated for increasing 5°C increments of room temperature for each of the three body segments over the complete range of room temperatures given in Table I. Figures 4 through 9 show the averaged values of forearm blood flow. Figures 11 through 16 present the averaged blood flow data for the hand while Figures 18 through 24 give the averaged finger blood flow values.

Several of the average blood flow figures have only one data point. This means that only one experimental determination was made for the given body segment at room temperatures falling within the 5°C range in question.

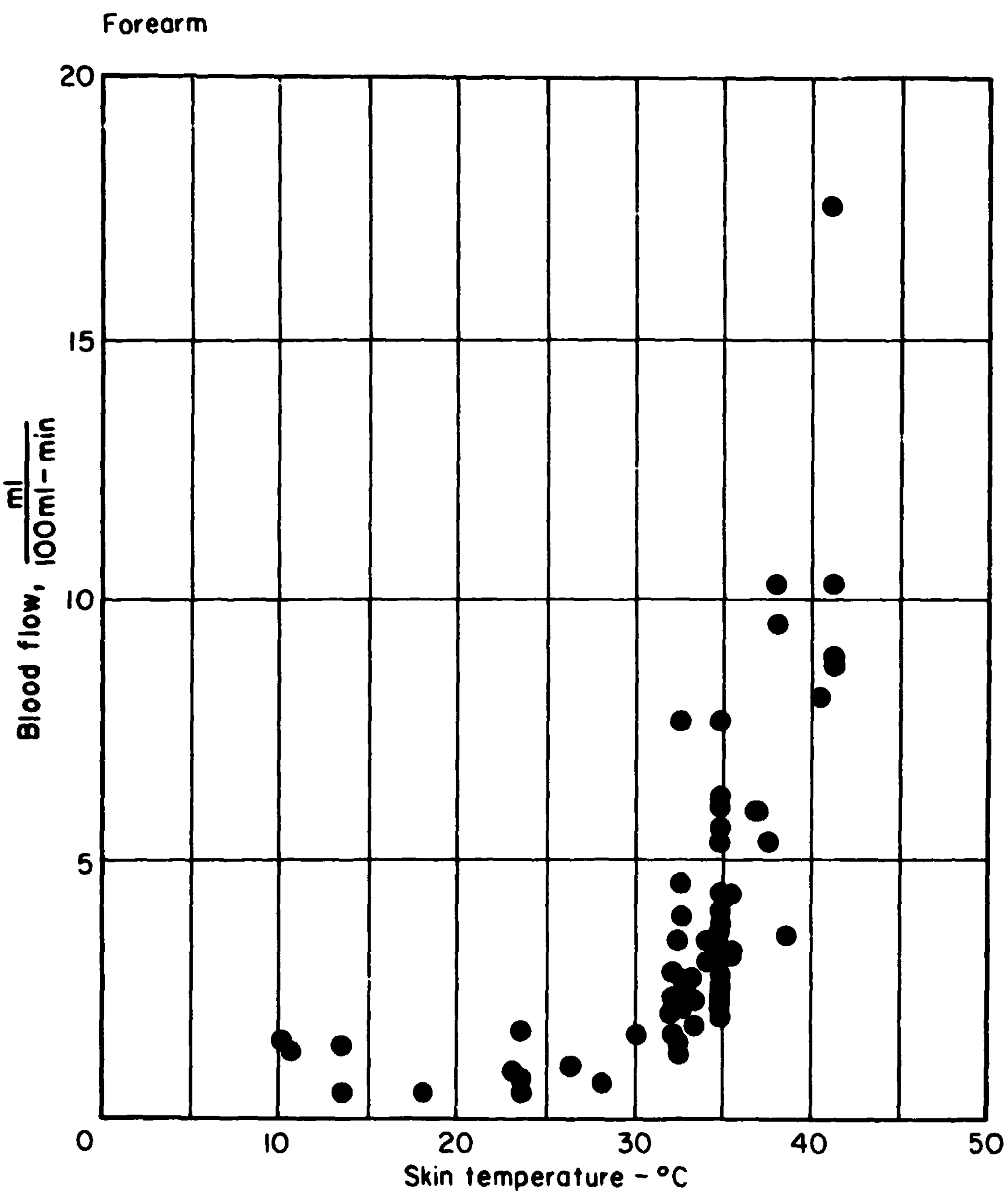

Figure 3. Forearm blood flow vs. skin temperature, room temperature = 15 to 45°C.

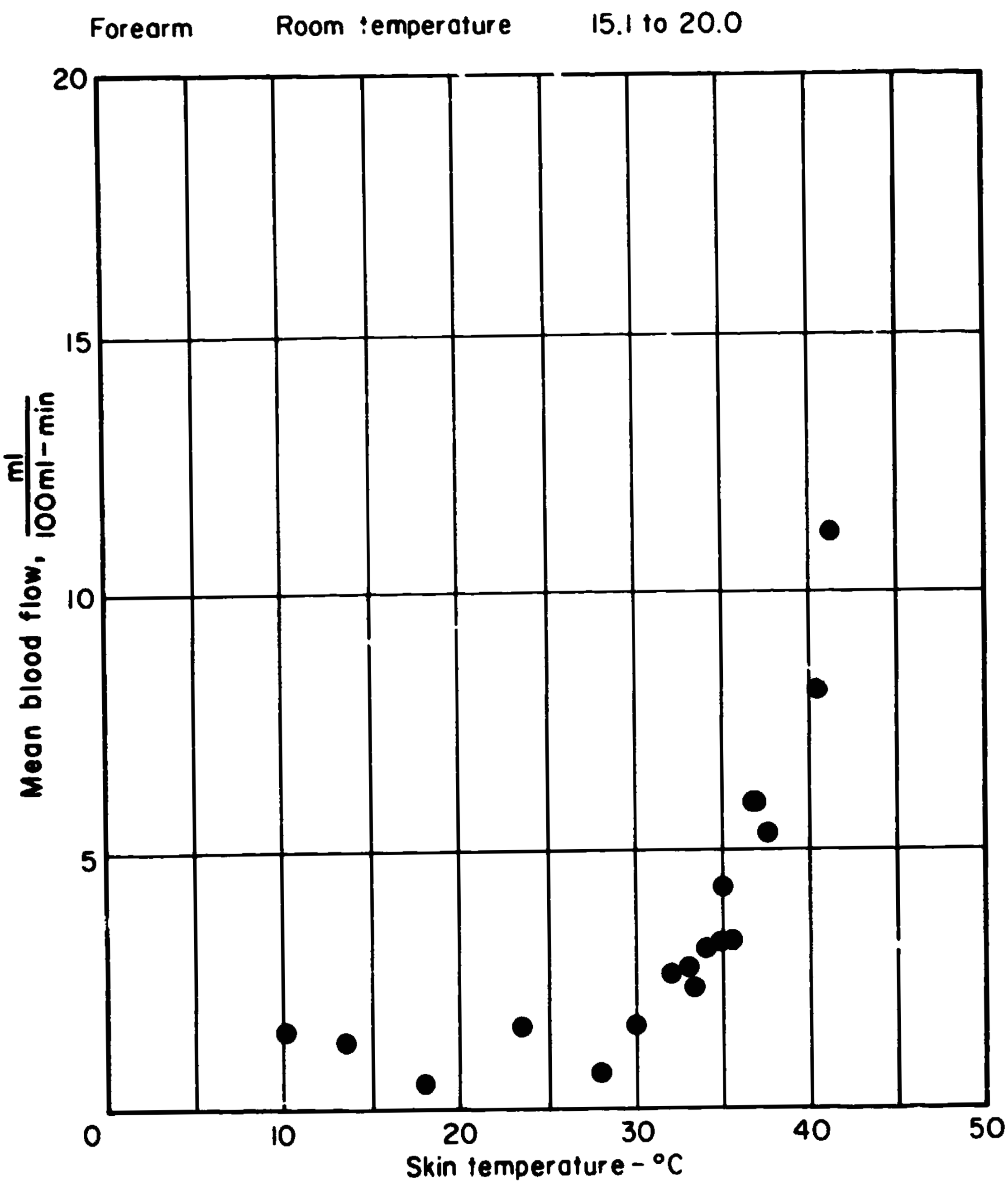

Figure 4. Forearm blood flow vs. skin temperature, room temperature = 15.1 to 20.0°C.

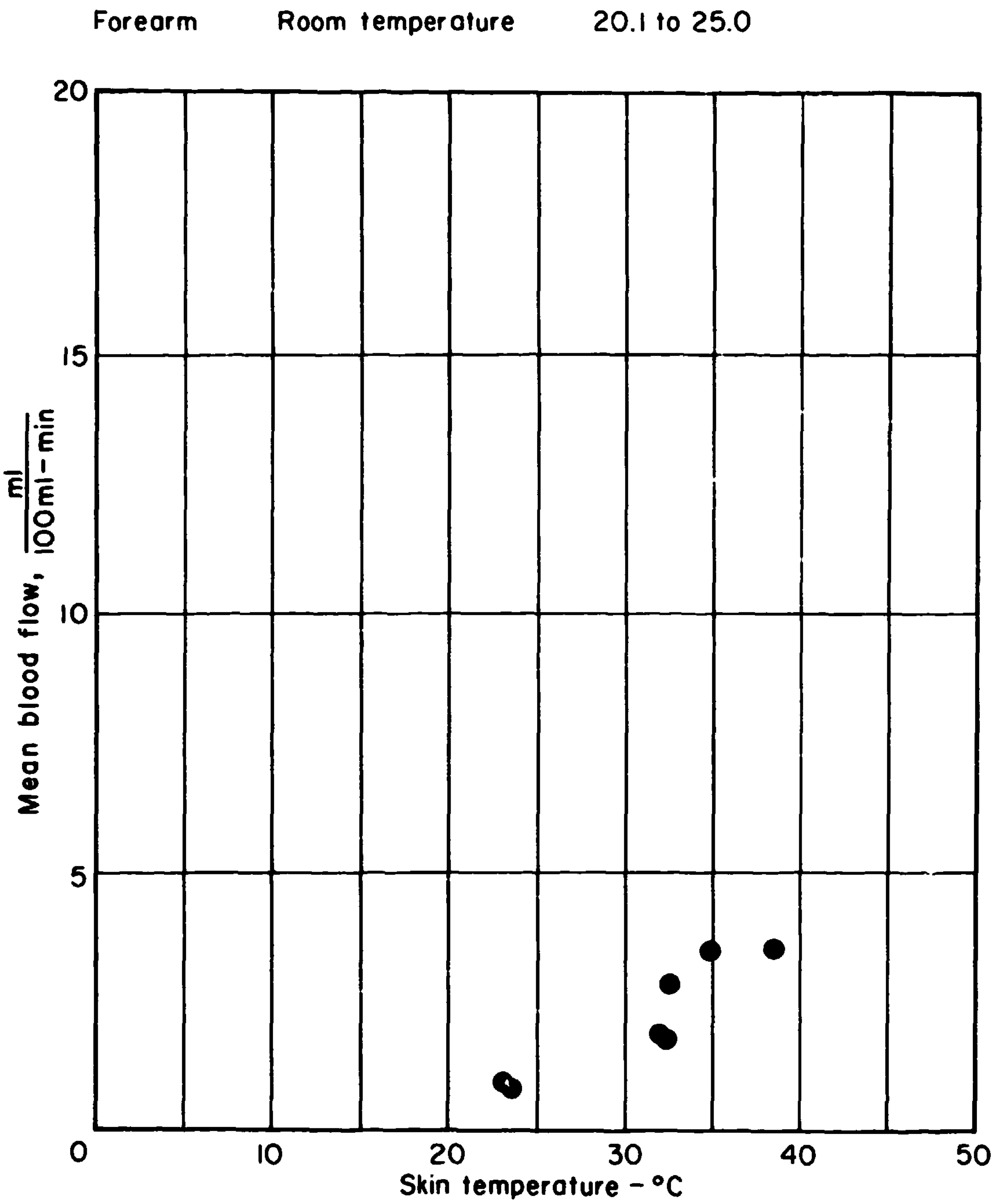

Figure 5. Forearm blood flow vs. skin temperature, room temperature 20.1 to 25.0°C.

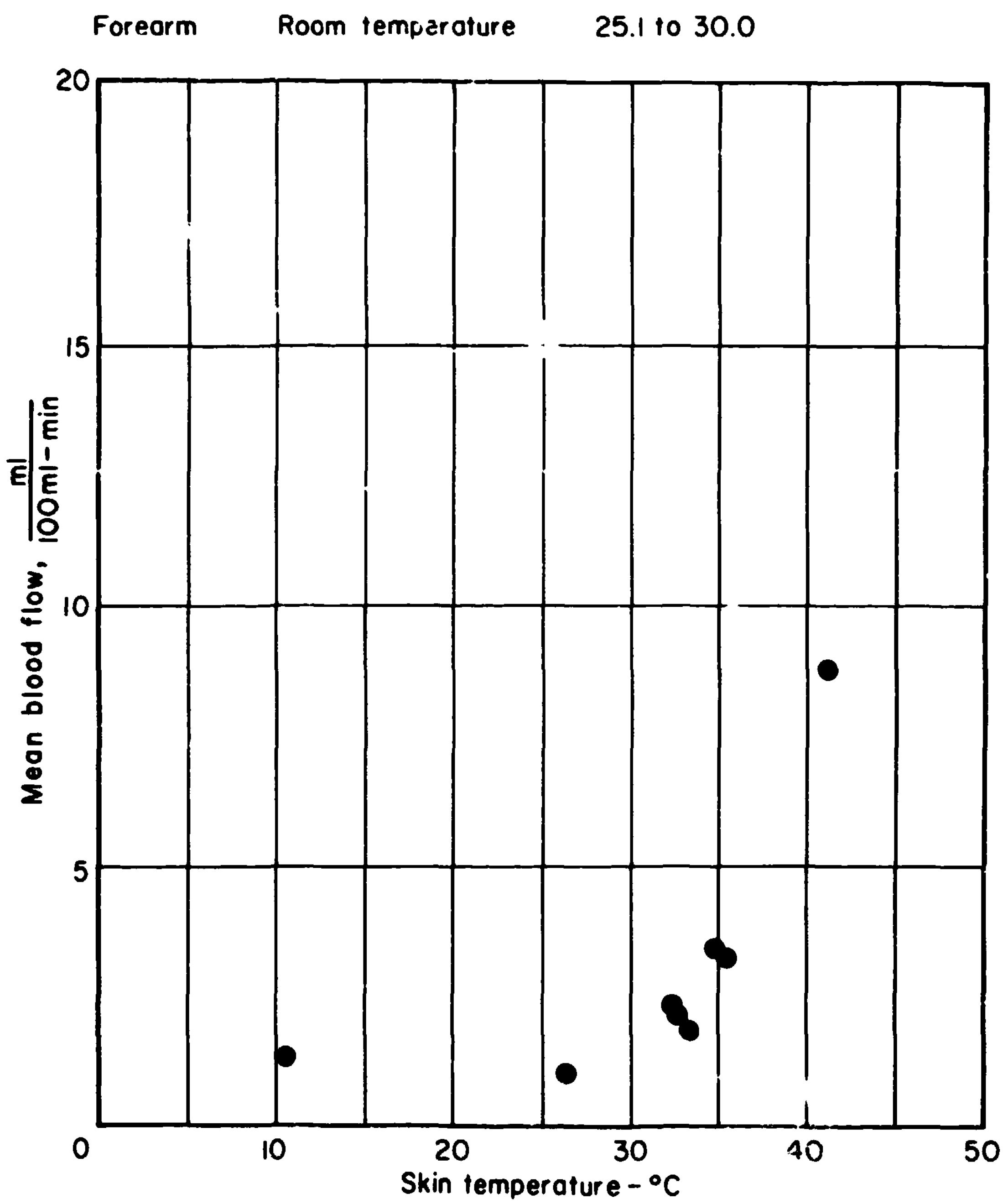

Figure 6. Forearm blood flow vs. skin temperature, room temperature = 25.1 to 30.0°C.

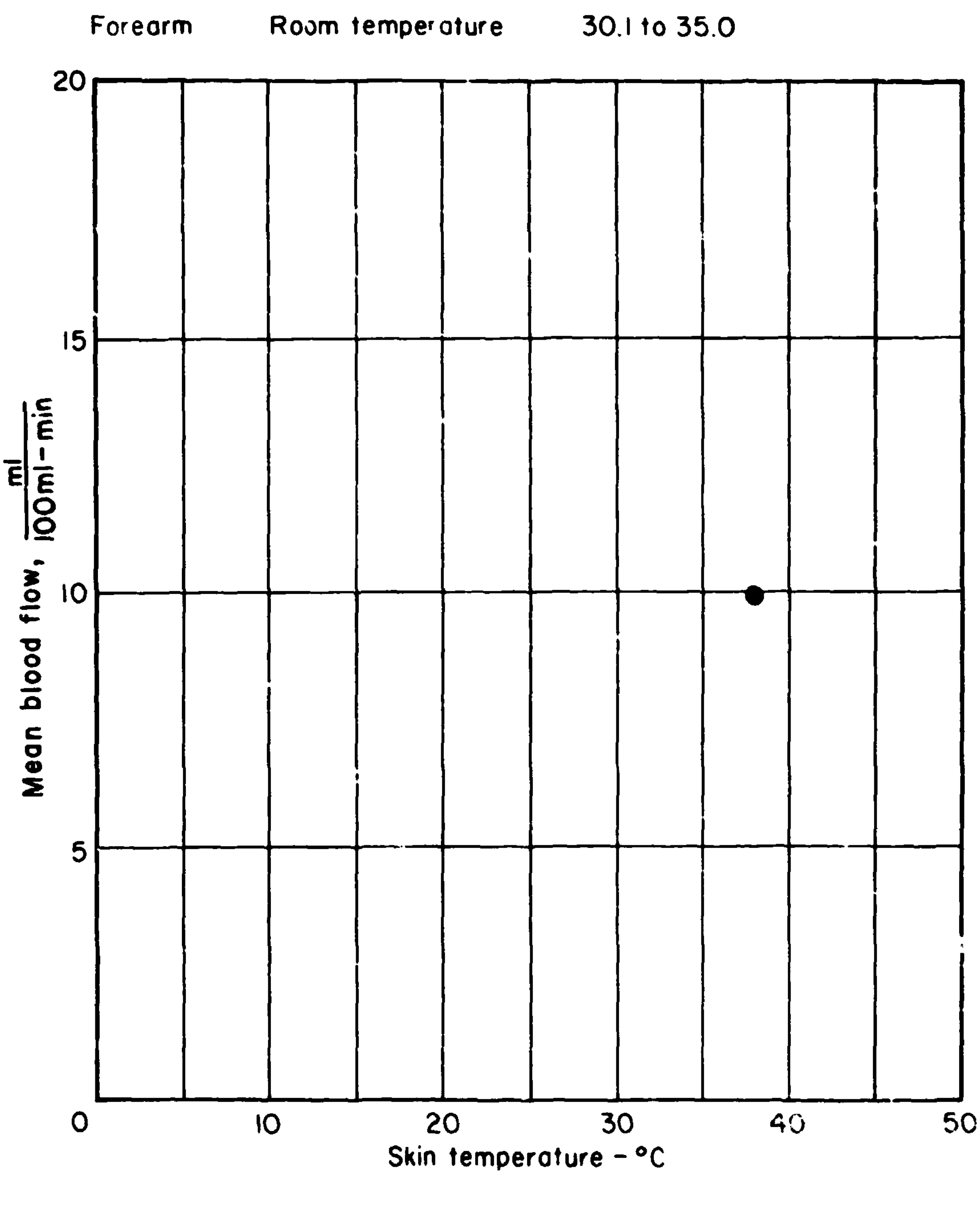

Figure 7. Forearm blood flow vs. skin temperature, room temperature = 30.1 to 35.0°C.

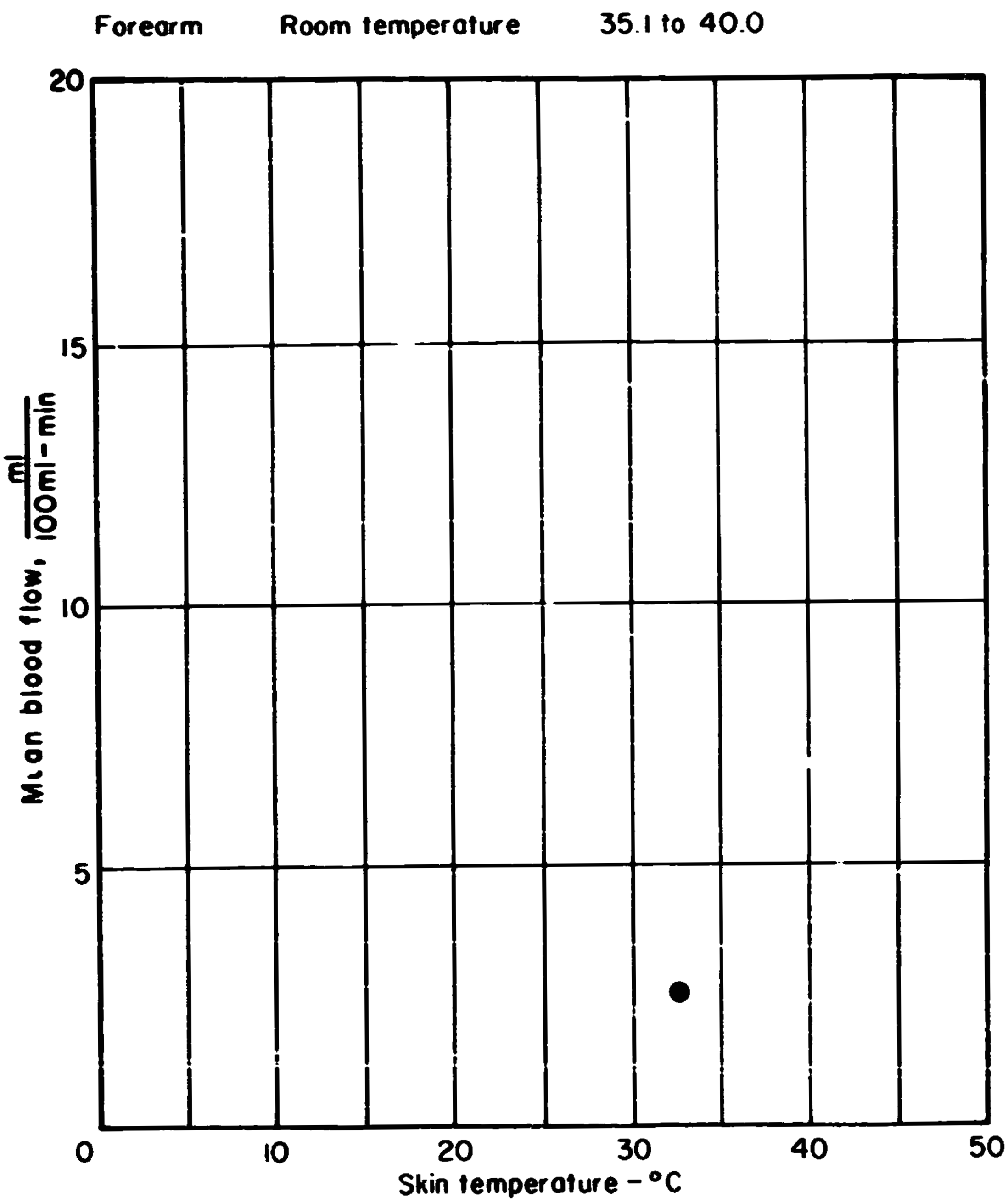

Figure 8. Forearm blood flow vs skin temperature, room temperature = 35.1 to 40.0°C.

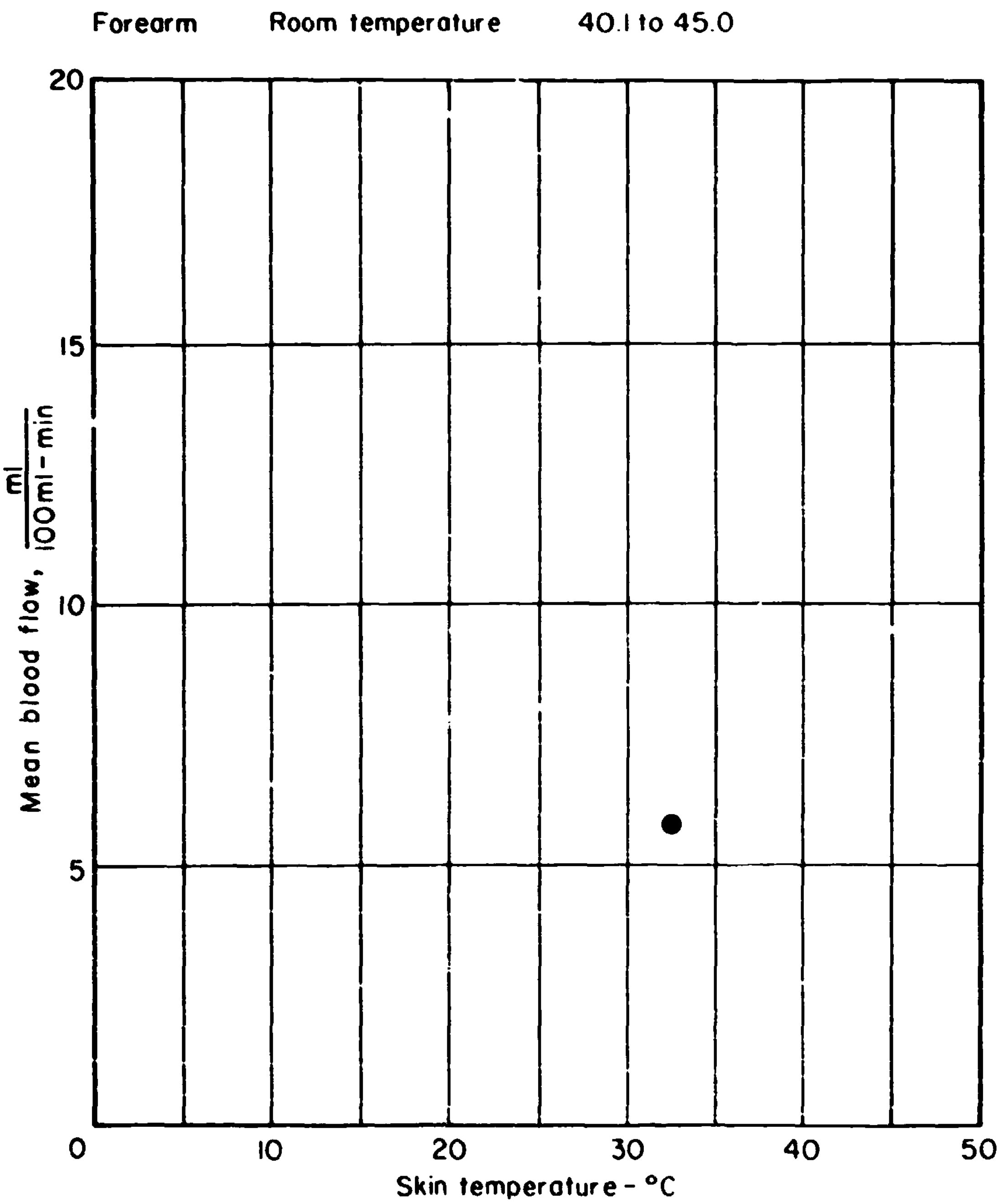

Figure 9. Forearm blood flow vs. skin temperature, room temperature = above 40.1°C.

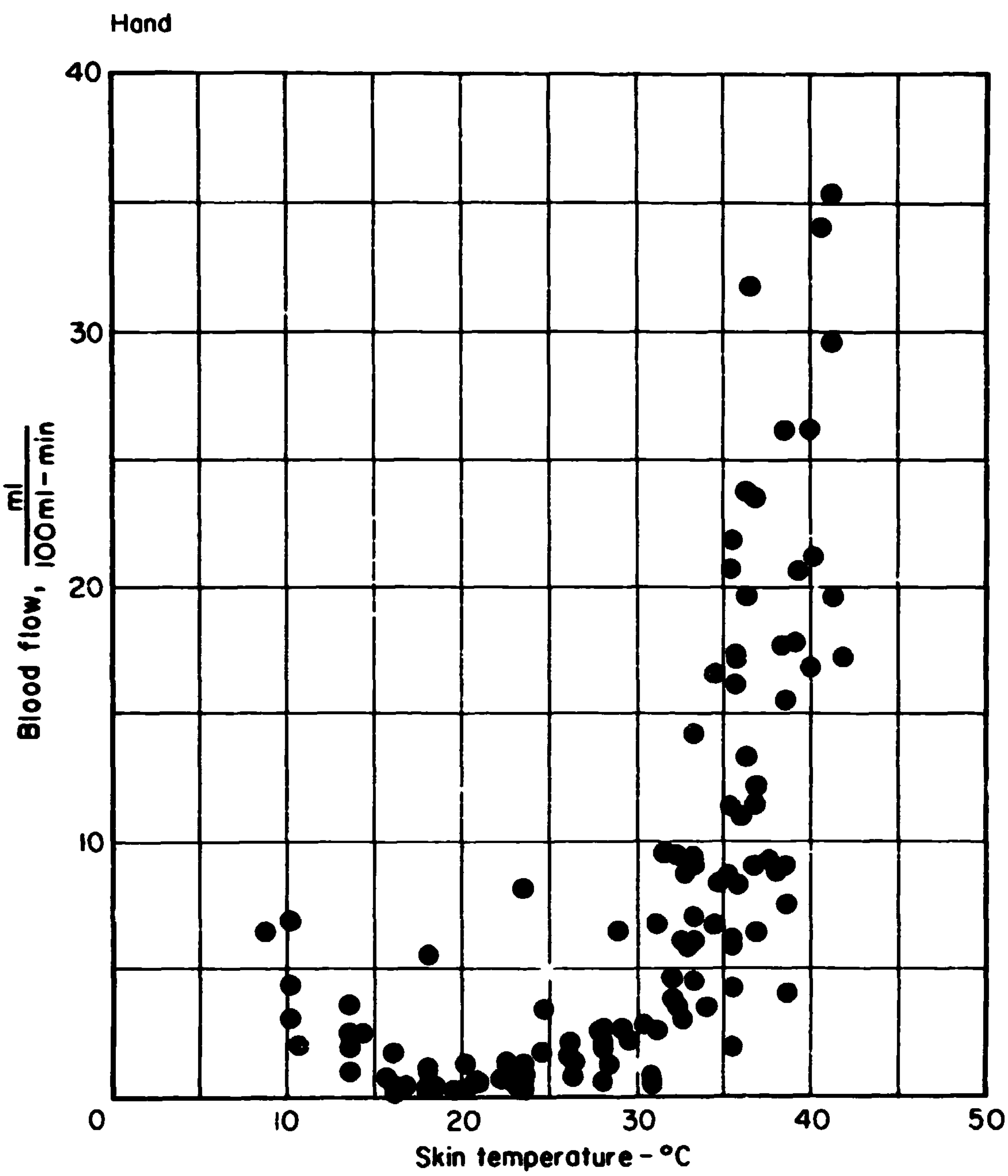

Figure 10. Hand blood flow vs. skin temperature, room temperature = 15 to 40°C.

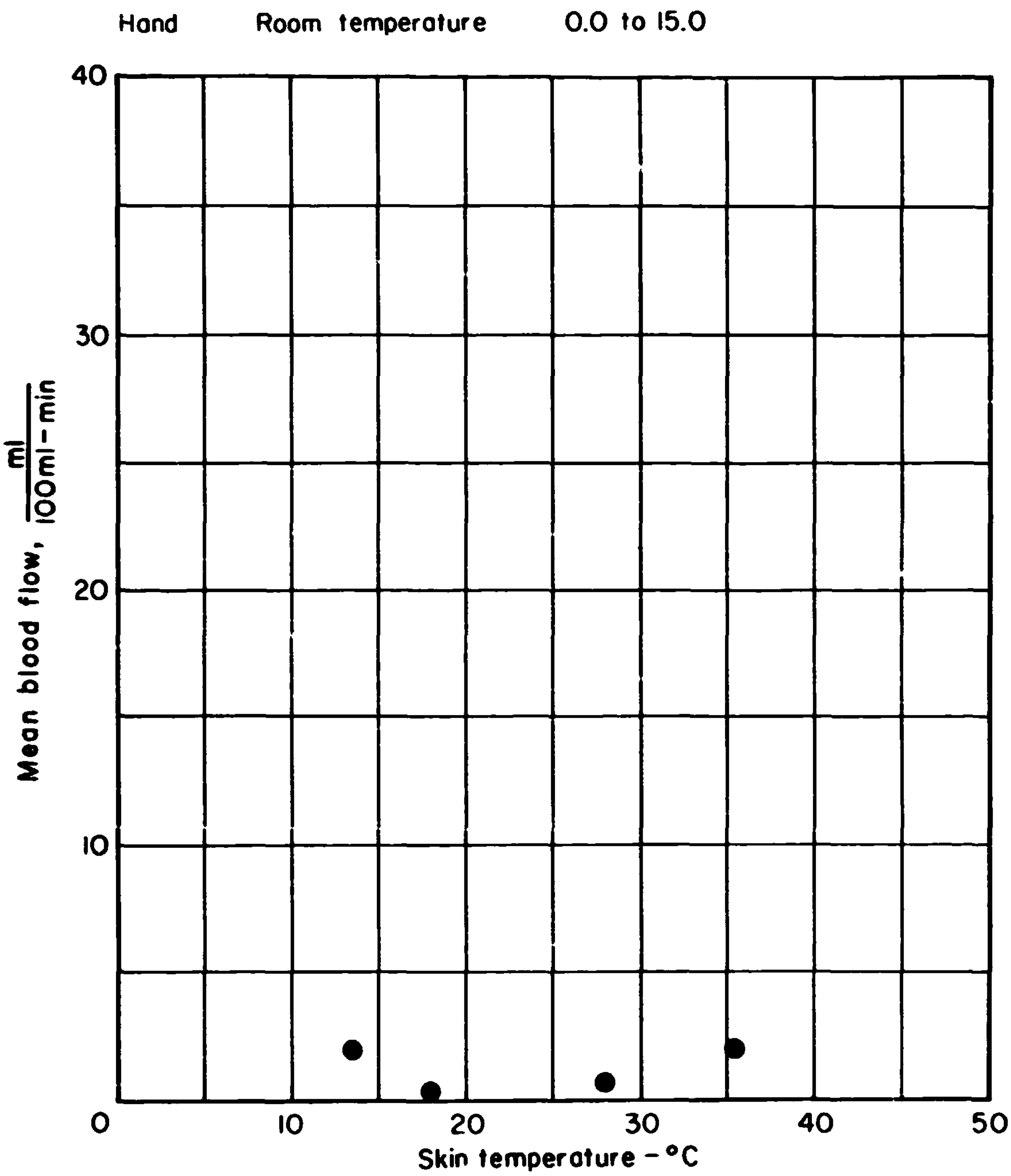

Figure 11. Hand blood flow vs. skin temperature, room temperature = 0.0 to 15.0°C.

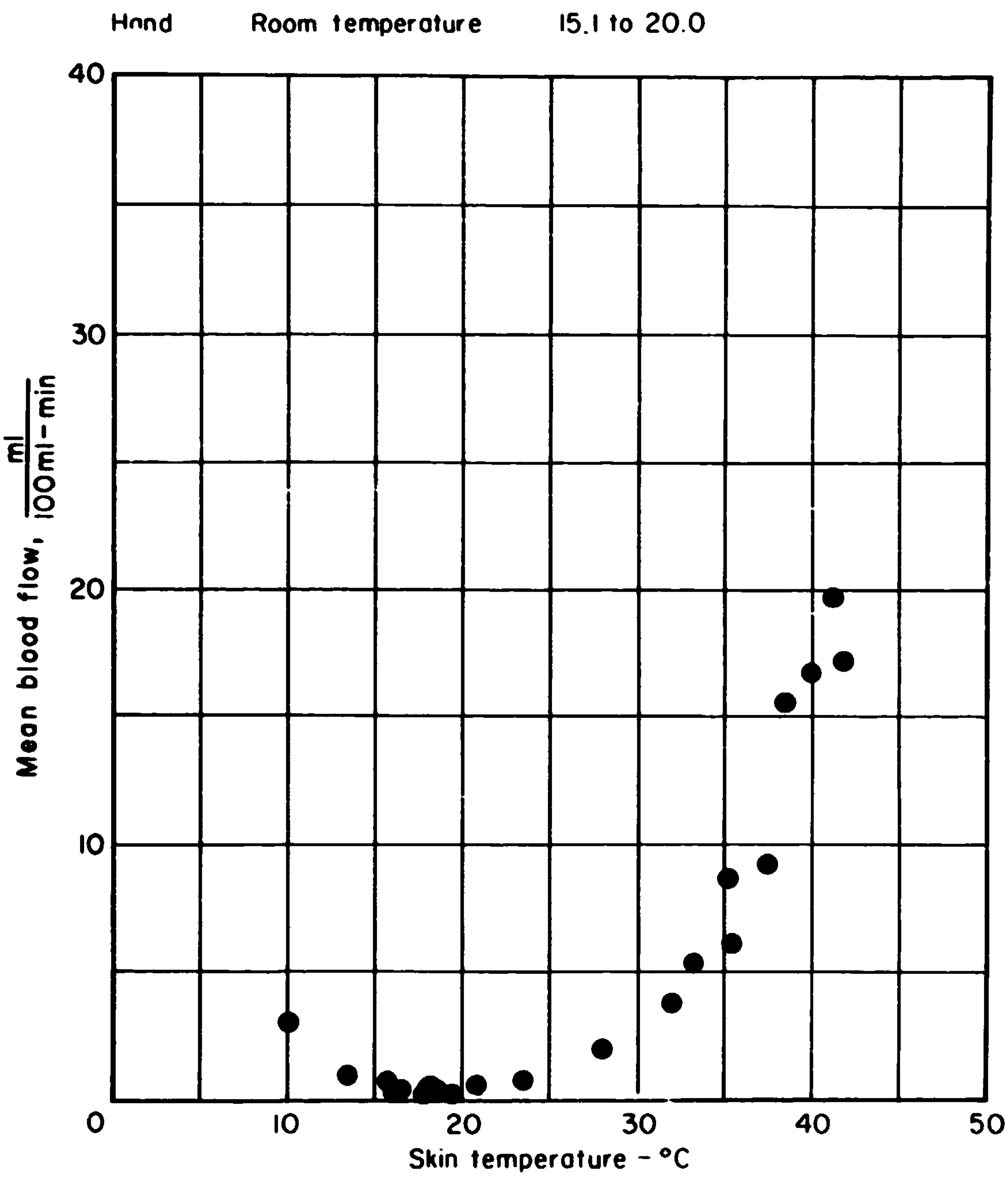

Figure 12. Hand blood flow vs. skin temperature, room temperature = 15.1 to 20.0°C.

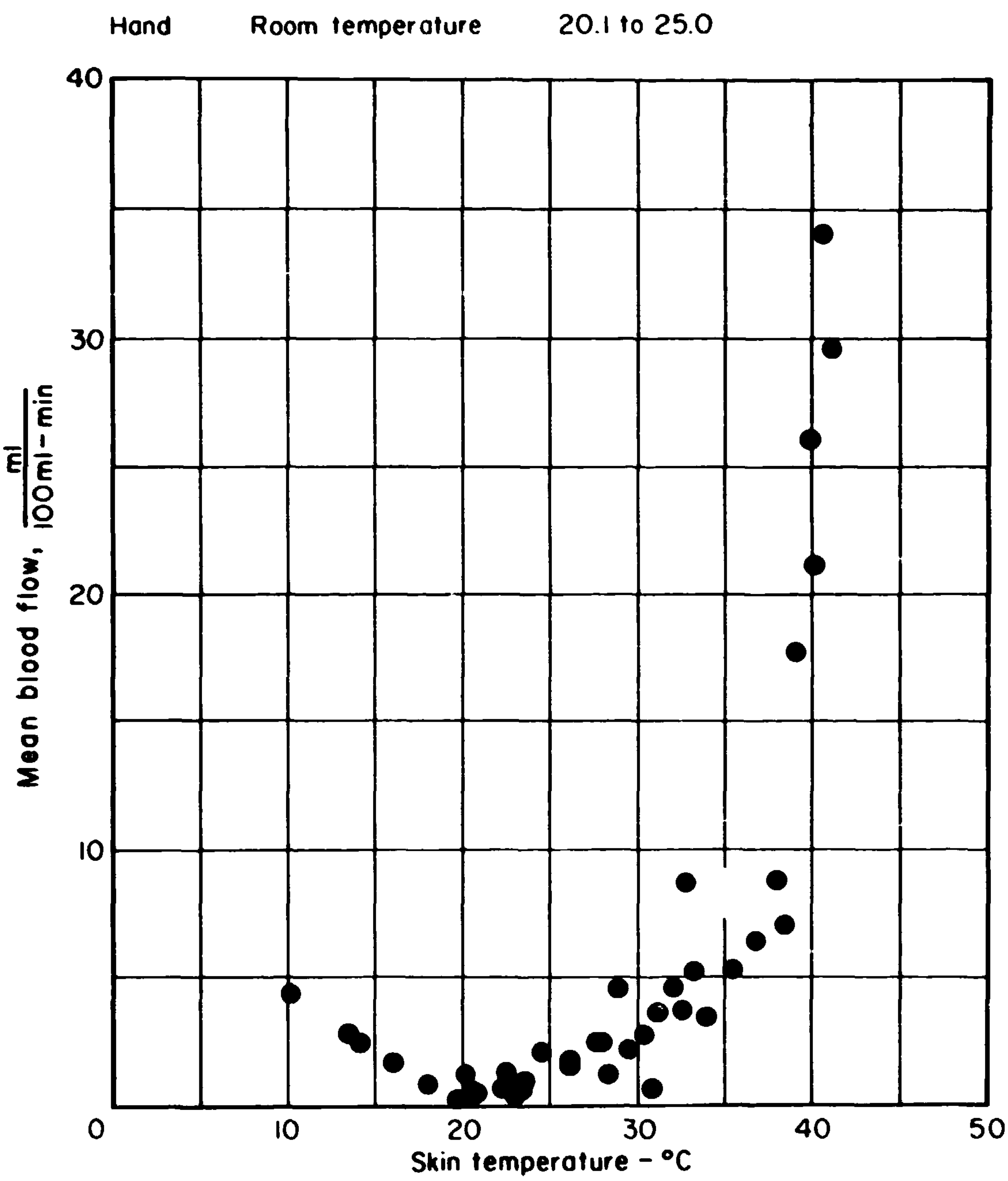

Figure 13. Hand blood flow vs. skin temperature, room temperature = 20.1 to 25.0°C.

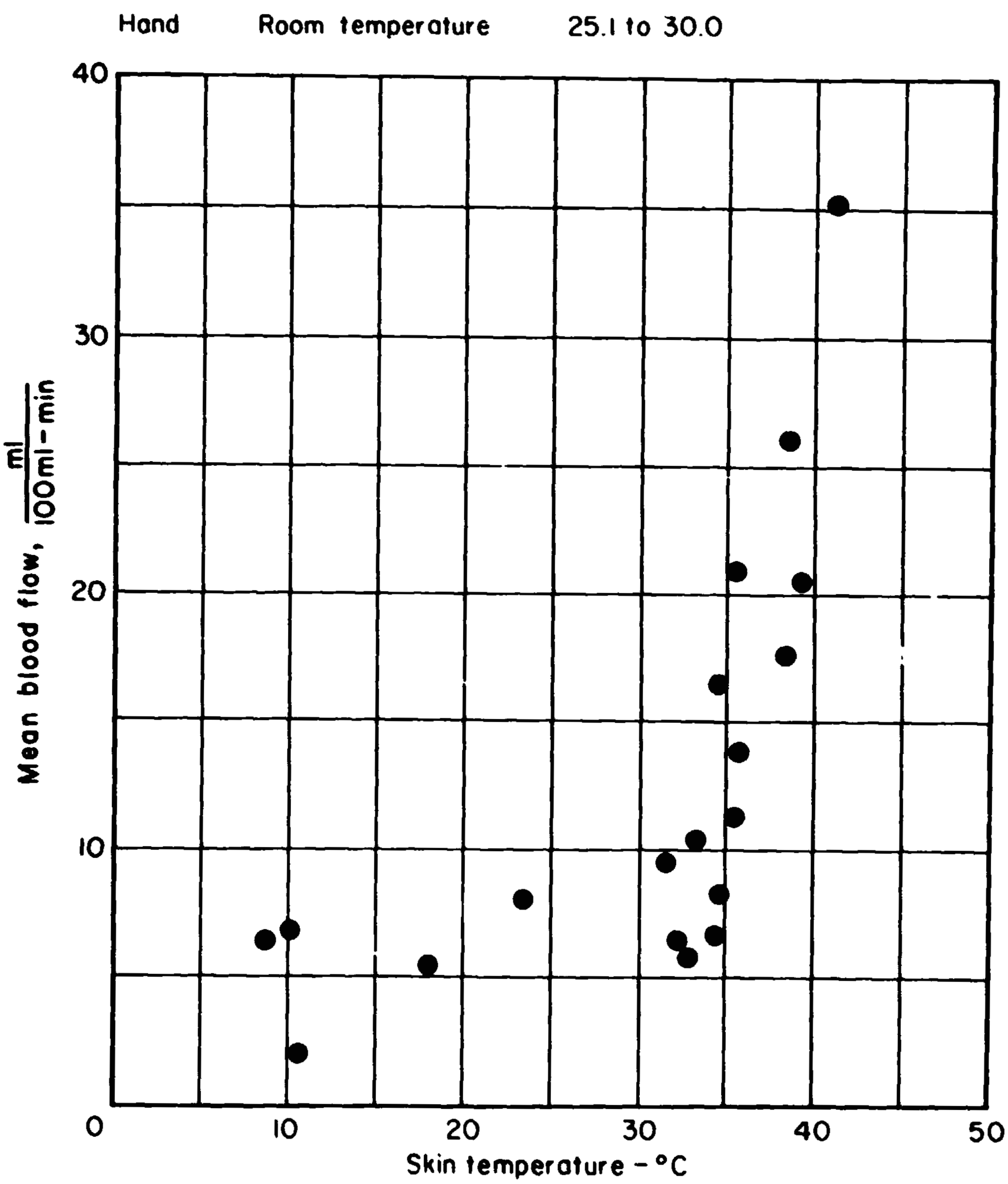

Figure 14. Hand bl od flow vs. skin temperature, room temperature = 25.1 to 30.0°C.

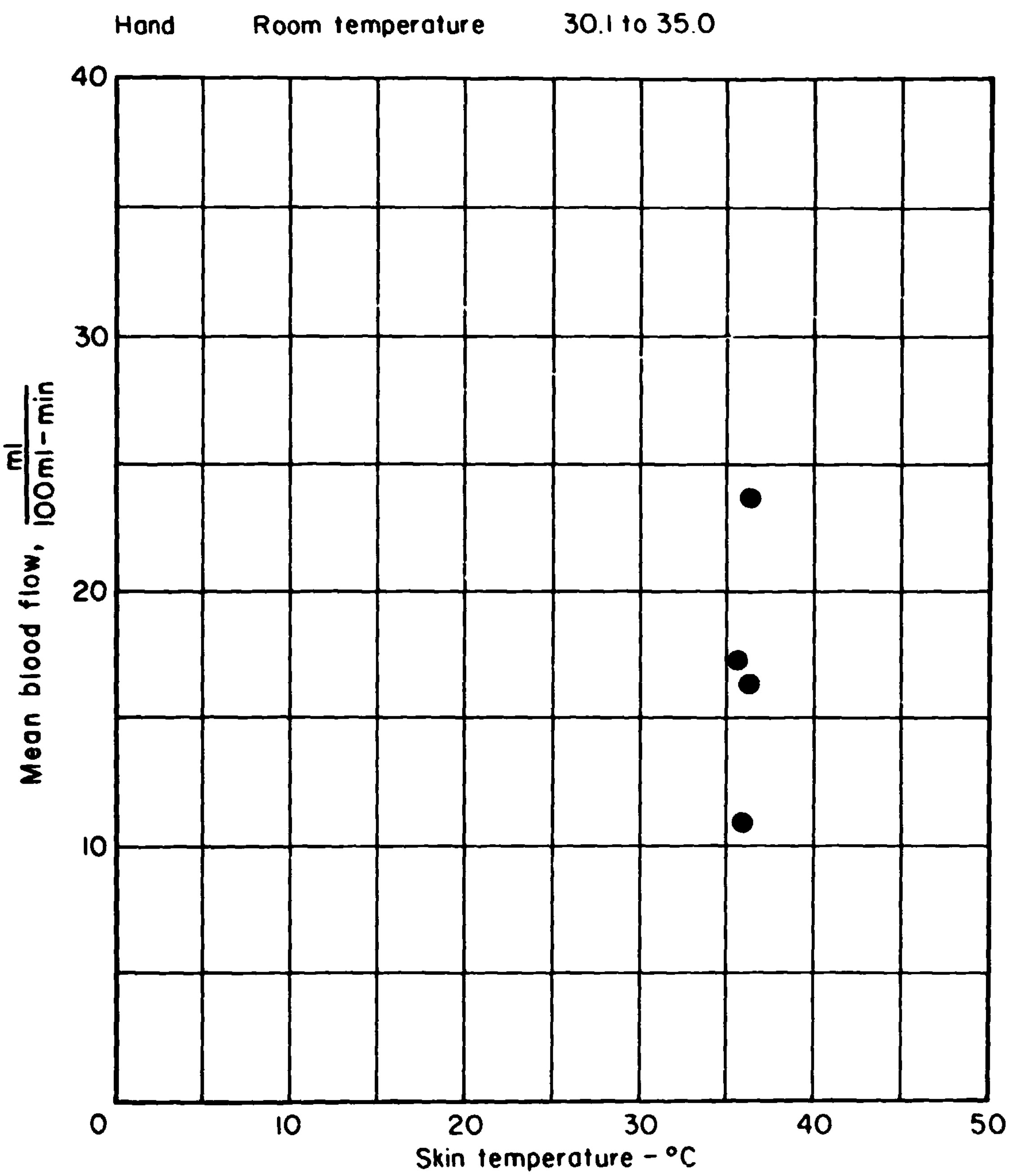

Figure 15. Hand blood flow vs. skin temperature, room temperature = 30.1 to 35.0°C.

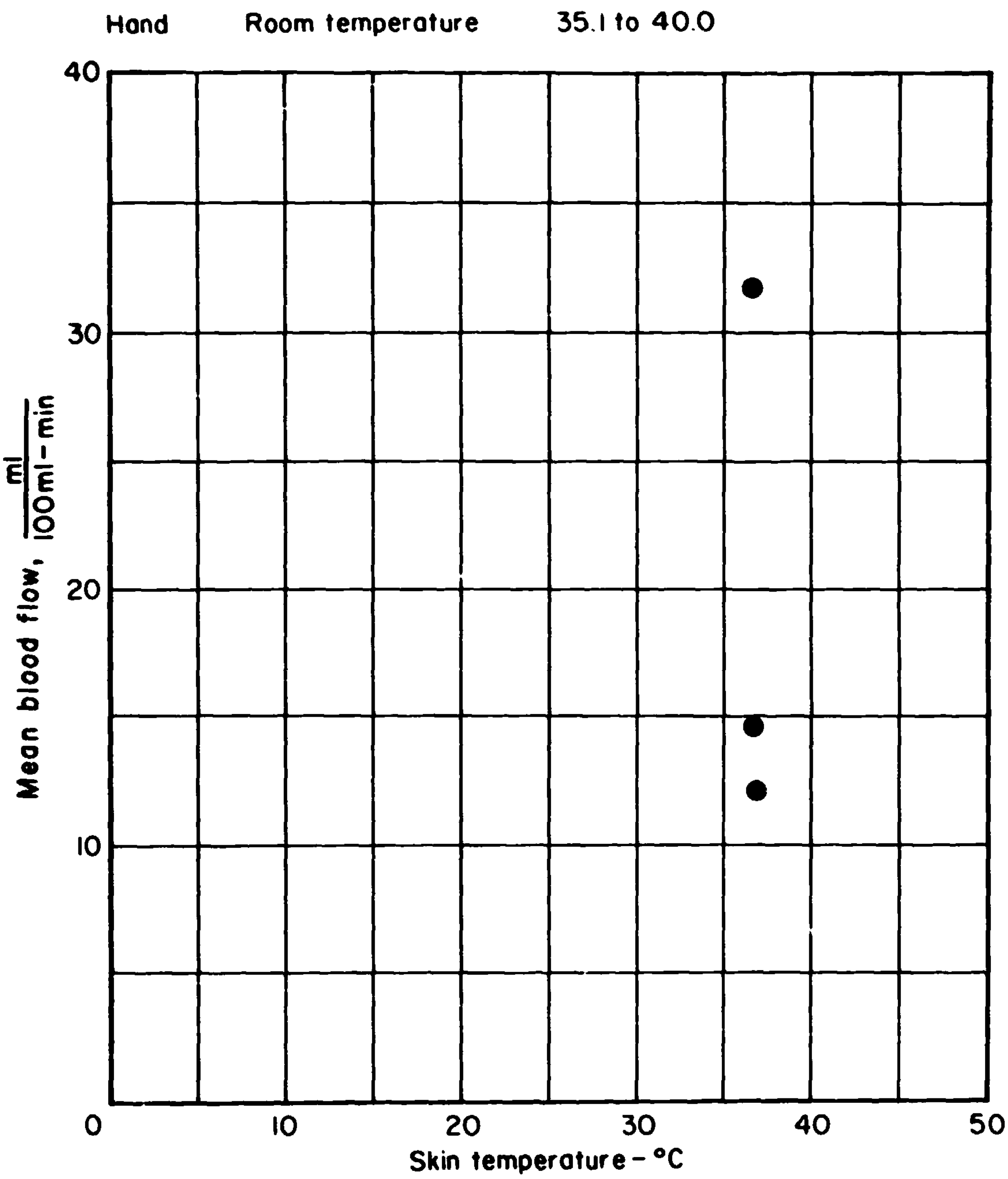

Figure 16. Hand blood flow vs. skin temperature, room temperature = 30.1 to 40.0°C.

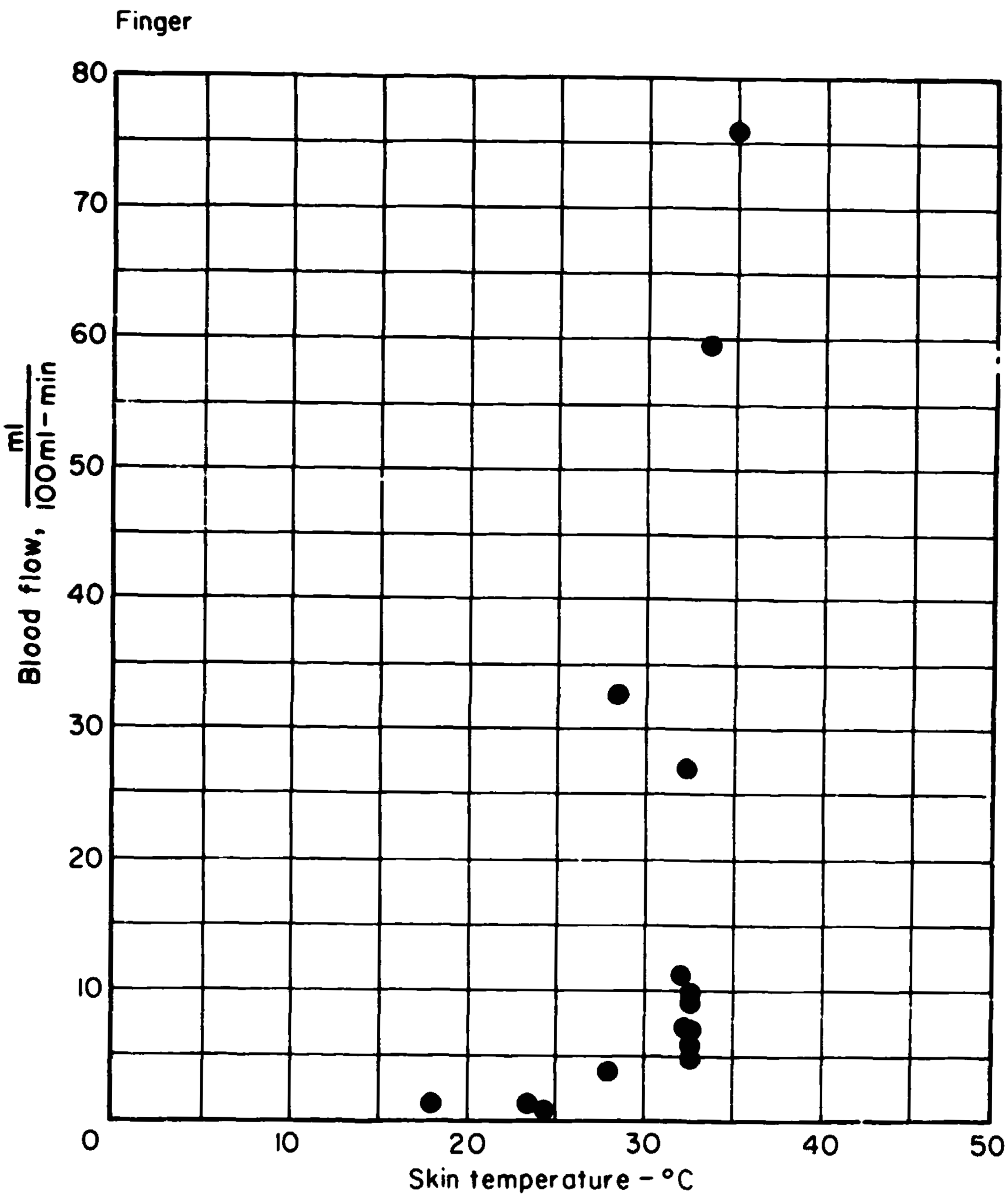

Figure 17. Finger blood flow vs. skin temperature, room temperature = 15 to 45°C.

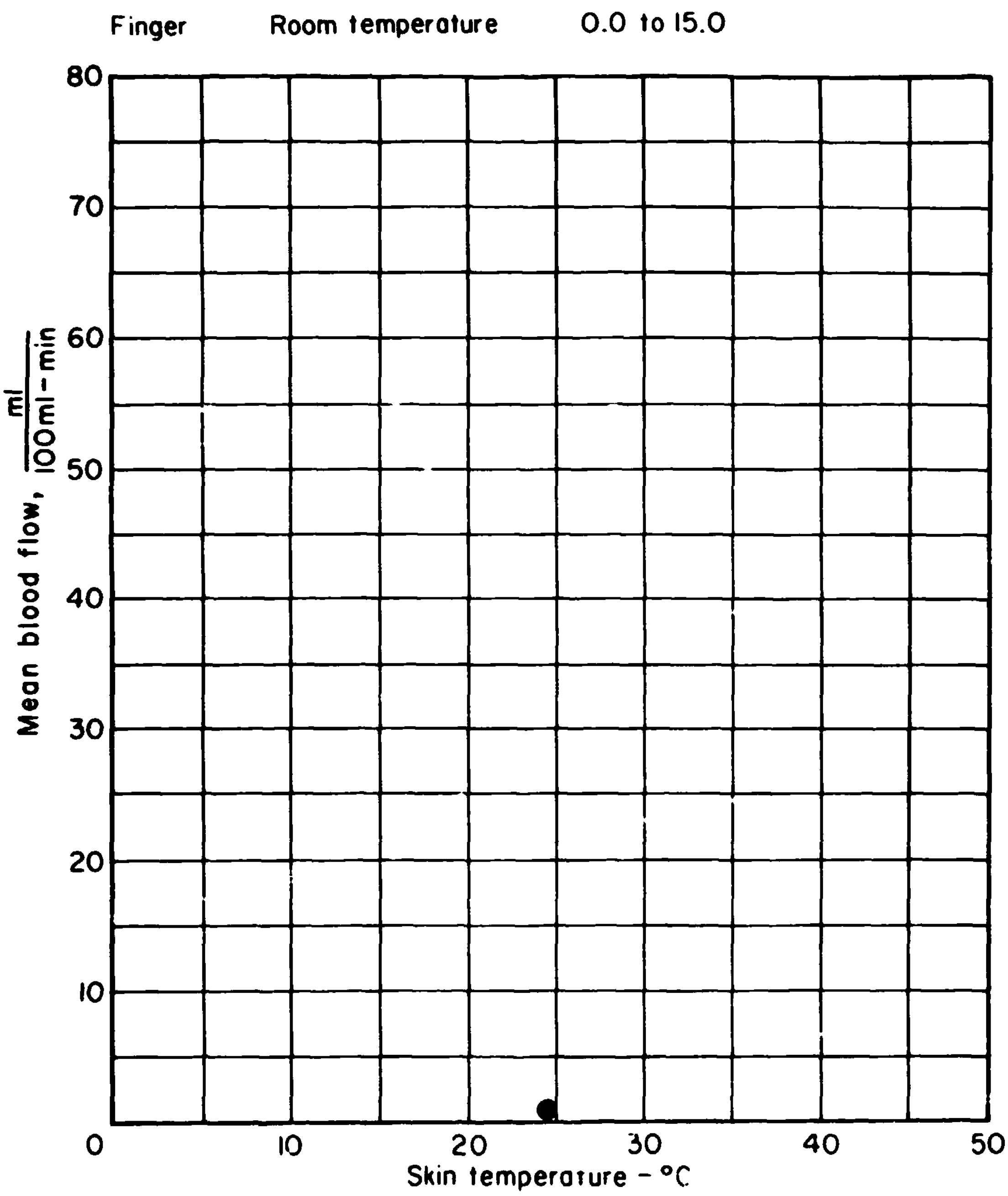

Figure 18. Finger blood flow vs. skin temperature, room temperature = 0.0 to 15.0°C.

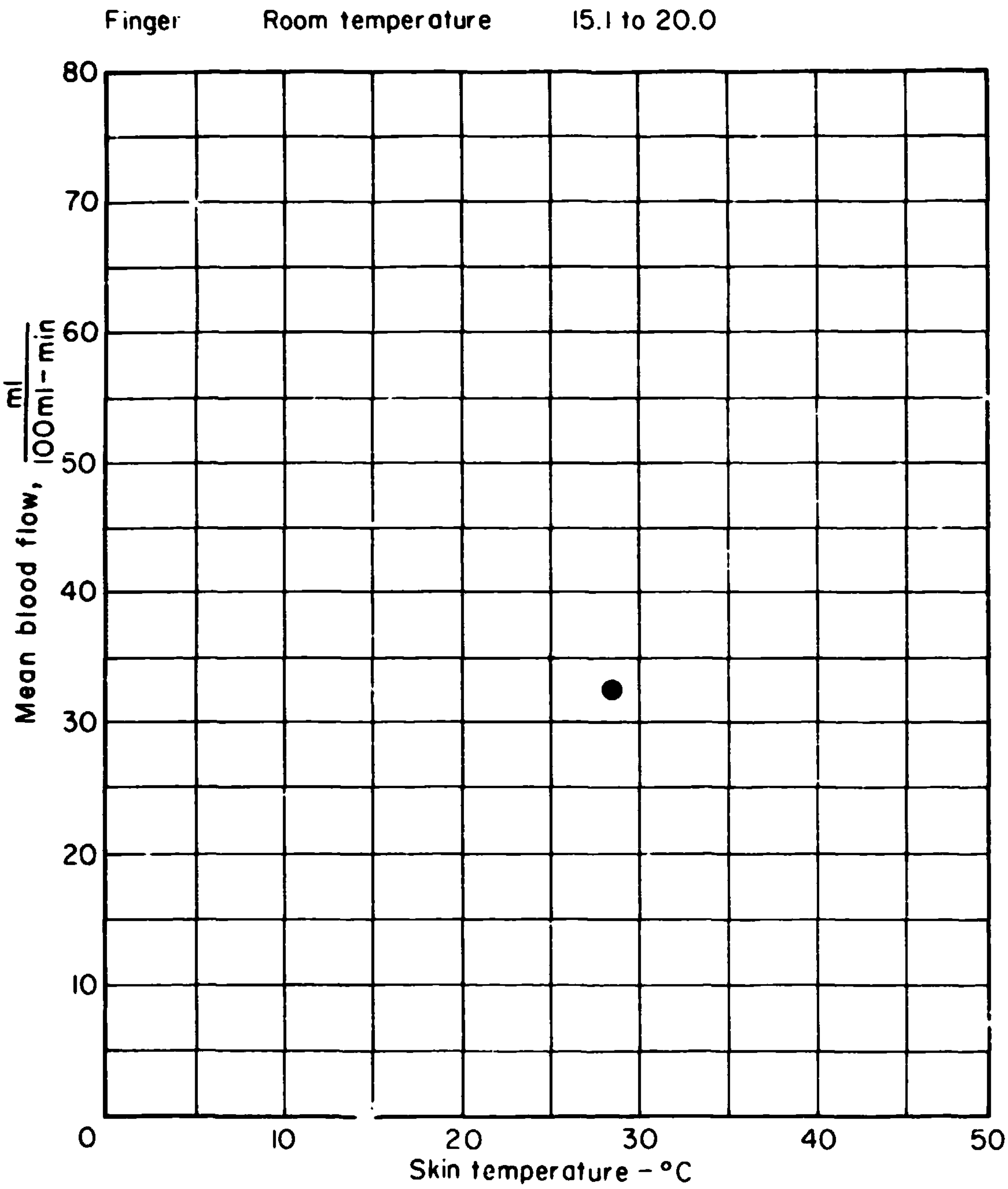

Figure 19. Finger blood flow vs. skin temperature, room temperature = 15.1 to 20.0°C.

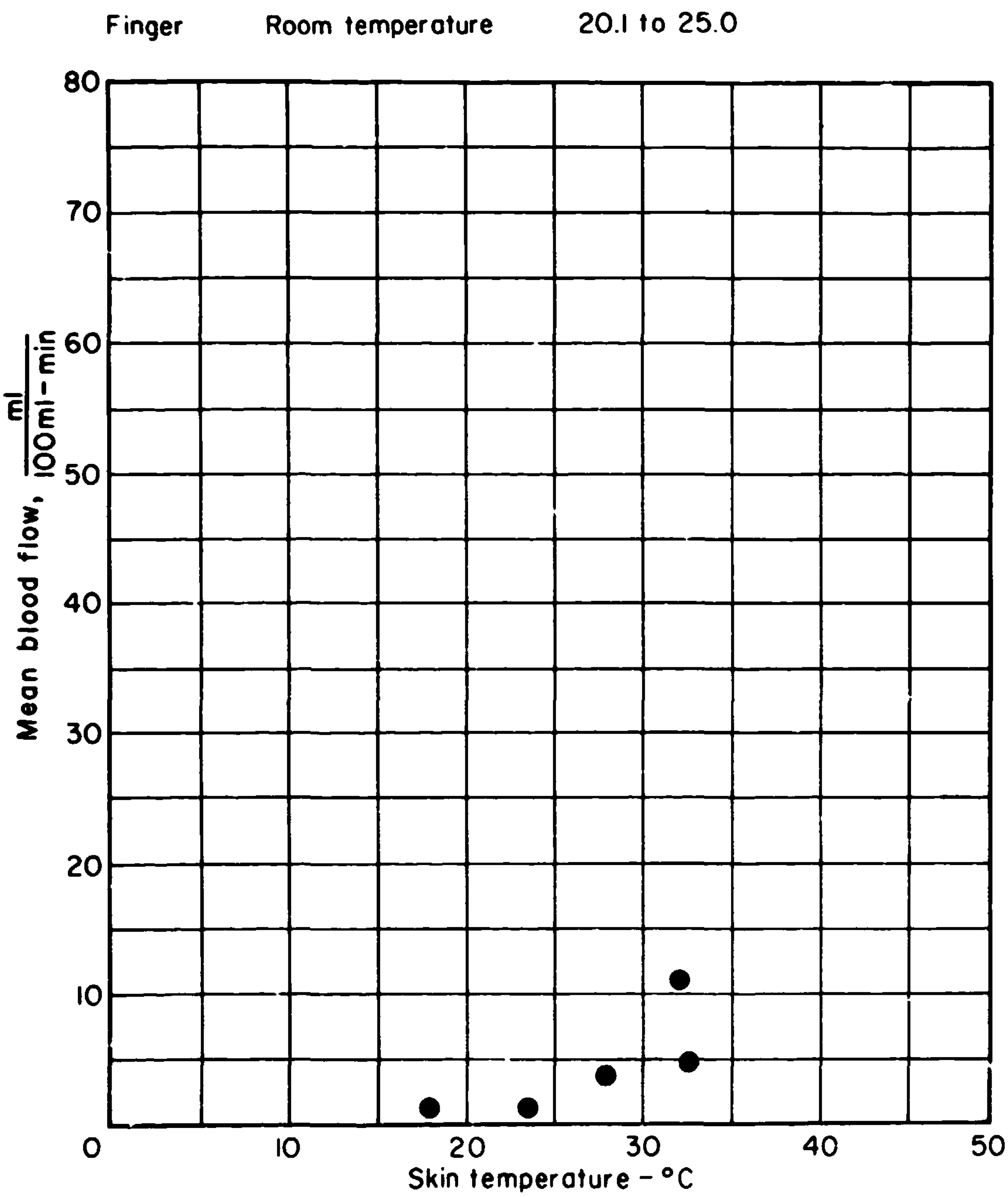

Figure 20. Finger blood flow vs. skin temperature, room temperature = 20.1 to 25.0°C.

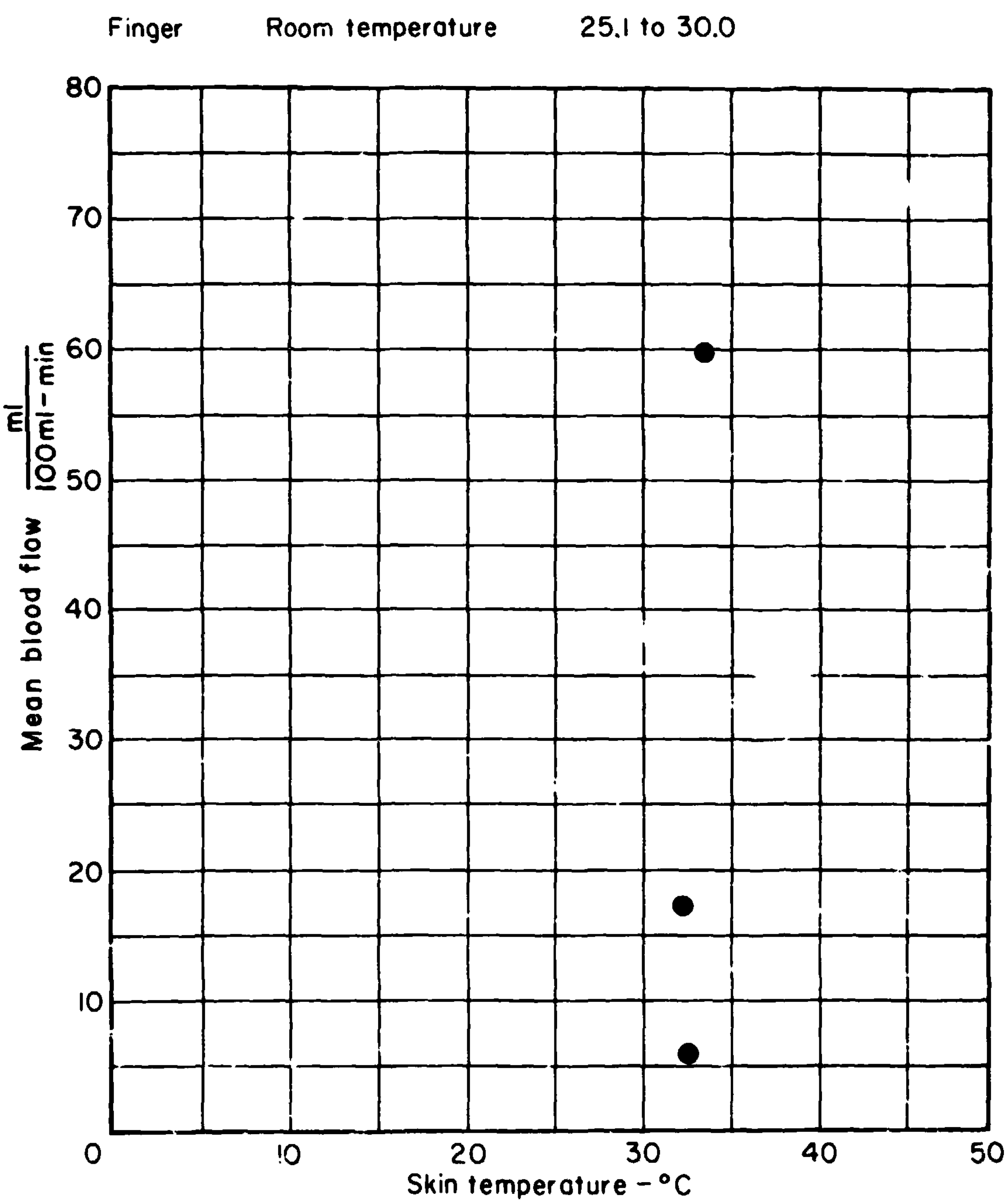

Figure 21. Finger blood flow vs. skin temperature, room temperature = 25.1 to 30.0°C.

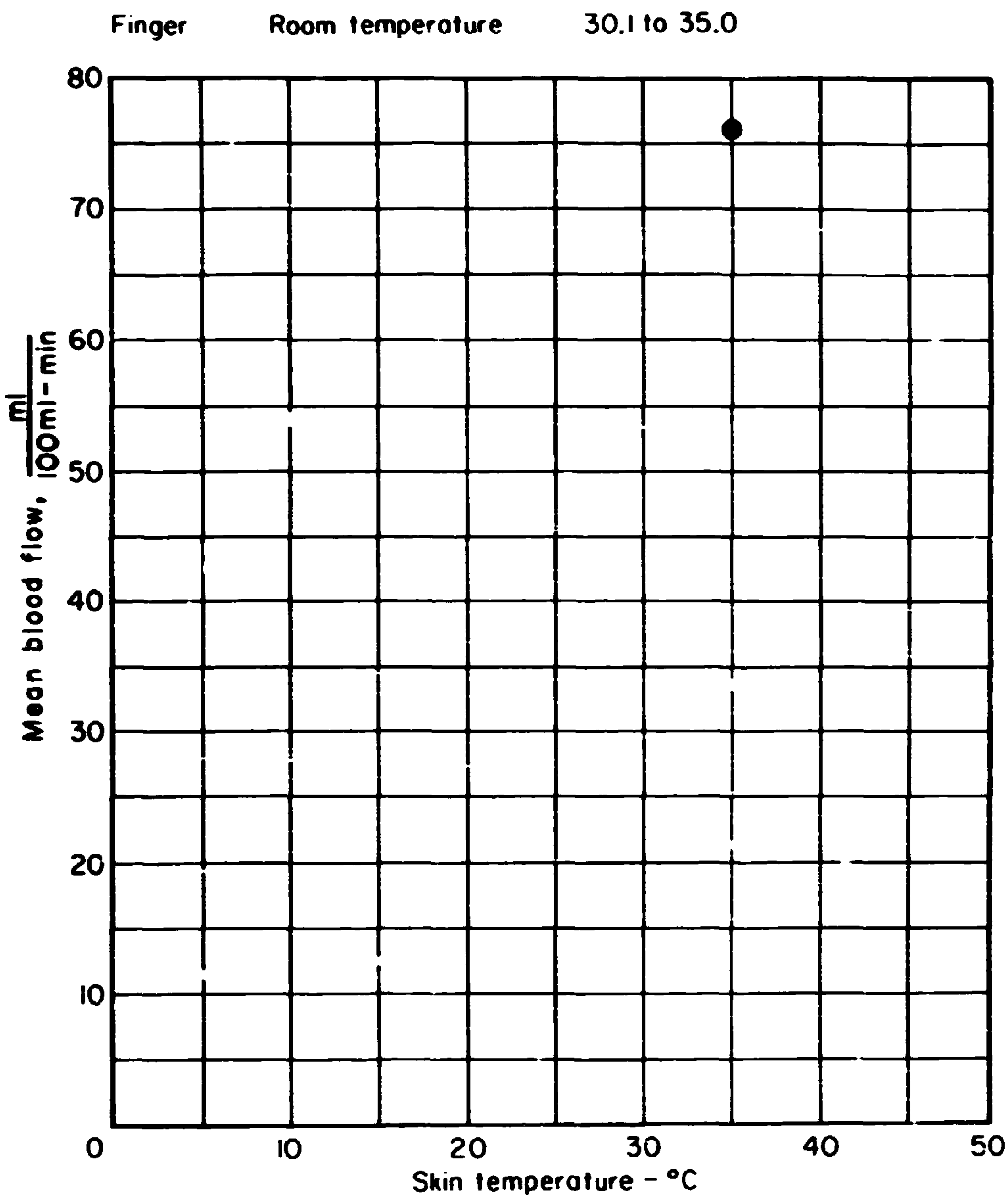

Figure 22. Finger blood flow vs. skin temperature, room temperature = 30.1 to 35.0°C.

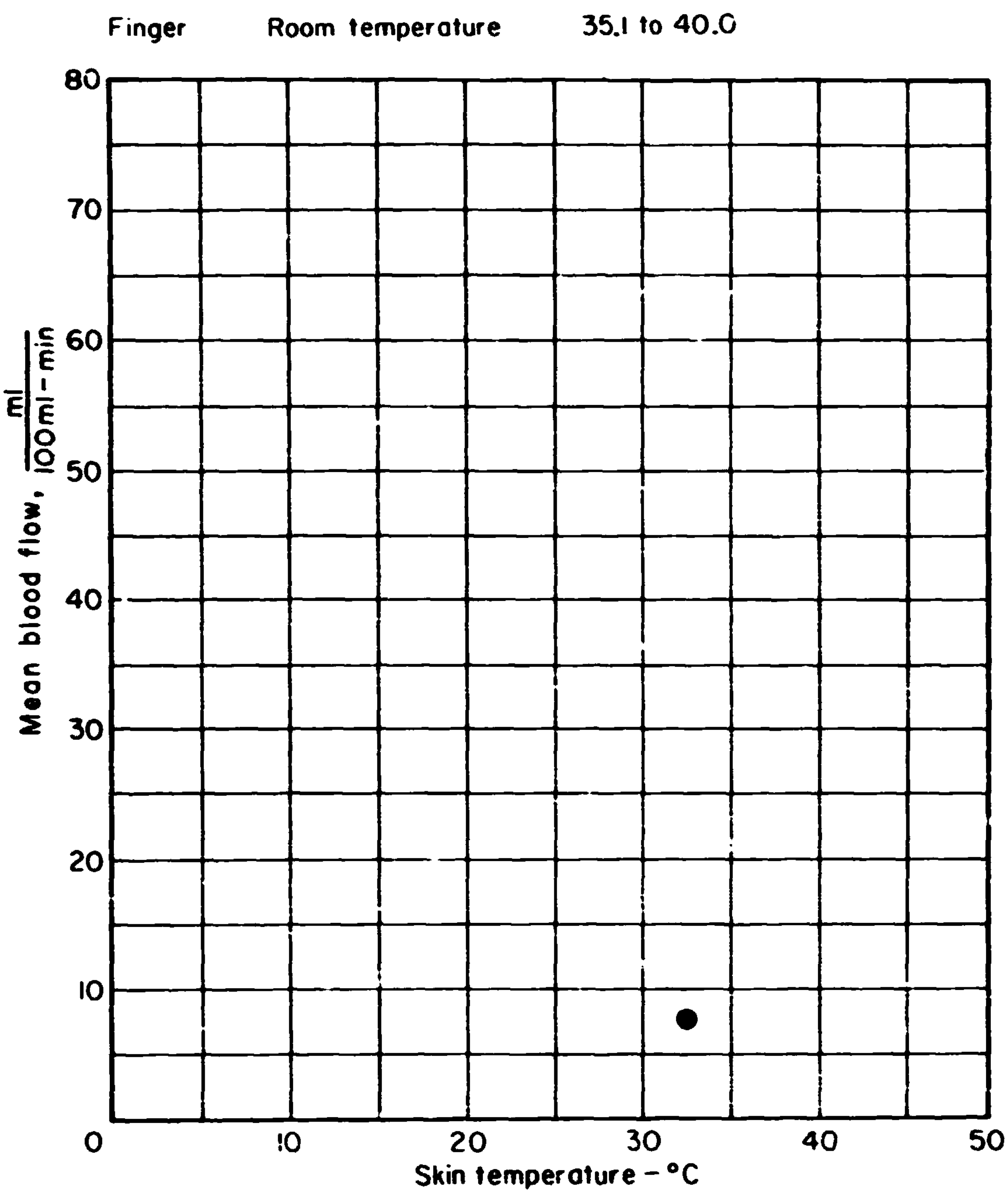

Figure 23. Finger blood flow vs. skin temperature, room temperature = 35.1 to 40.0°C.

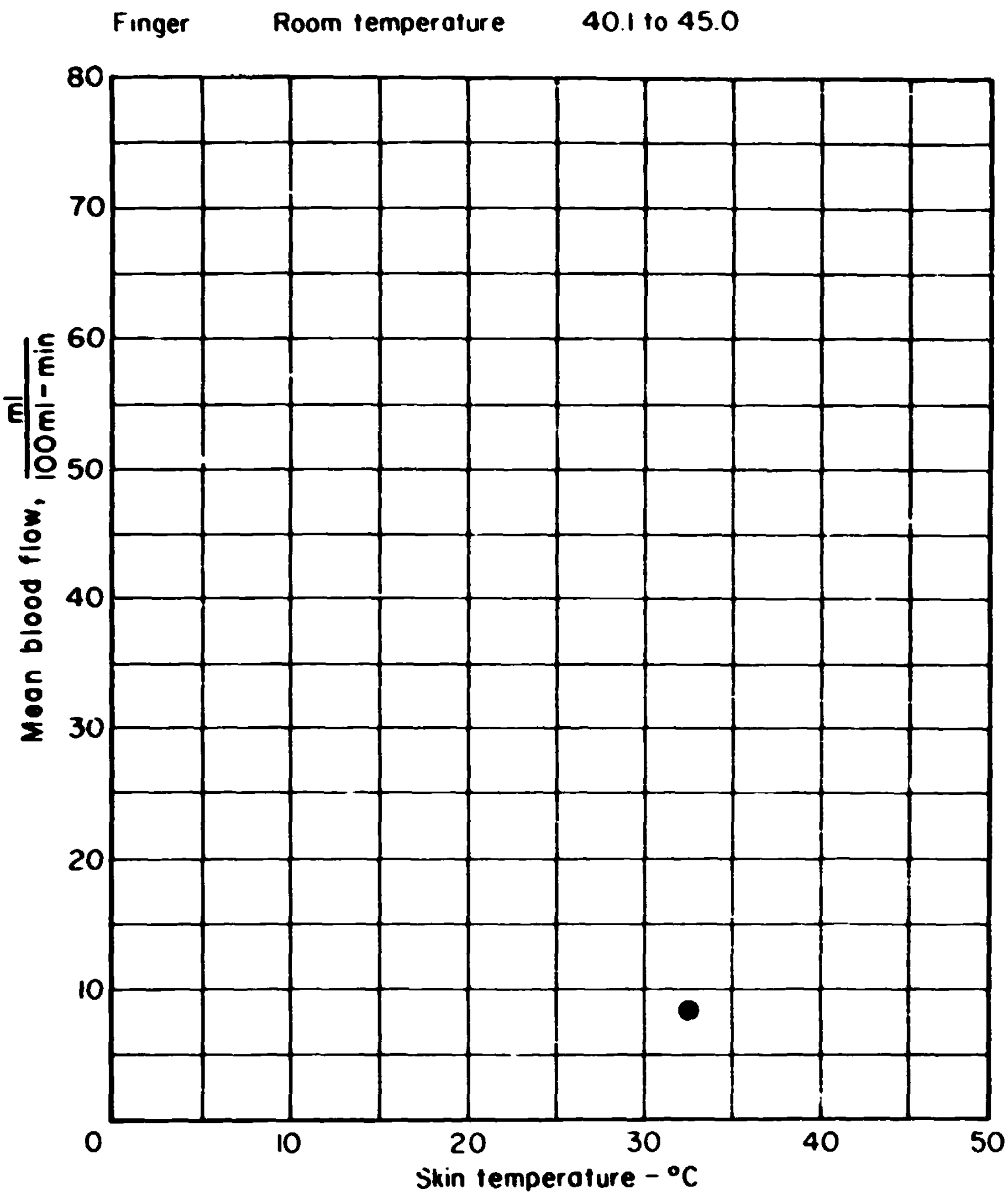

Figure 24. Finger blood flow vs. skin temperature, room temperature = 40.1 to 45.0°C.

All of the data shown in Figures 3 through 24 treat each experimental value equally, independent of the number of subjects used to obtain each blood flow value. The number of subjects used in each experiment was accounted for by fitting a subject weighted curve through the data presented in each room temperature range for each body segment. No attempt was made to develop such a curve for a body segment unless three or more data points were included in a given 5°C room temperature range. The series of subject weighted blood flow vs. skin temperature curves for the forearm, hand and finger are given in Figures 25, 26 and 27, respectively. Three room temperature ranges are represented in Figure 25: 15.1 to 20.0°C, 20.1 to 25.0°C and 25.1 to 30.0°C. Six room temperature traces are given in Figure 26 for the hand blood flow between 0.0 to 40.0°C room temperature. Two room temperature ranges are shown in Figure 27 for finger blood flow, 20.1 to 25.0°C and 25.1 to 30.0°C.

IV. Summary

The various traces shown in Figures 25, 26 and 27 exhibit the same general trends for each of the three body segments. A minimum blood flow is achieved at approximately 20°C skin temperature. At skin temperatures lower than ~20°C cold vasodilation produces an increase in segmental blood flow. The blood flow also begins to increase for skin temperatures above ~20°C. Between skin temperatures of 20°C to about 32°C the rate of increase with temperature is approximately linear with a slope of ~0.2 to 0.7 $\frac{\text{ml}}{\text{100 ml-min}}$ /$^\circ$C. Above 32°C the

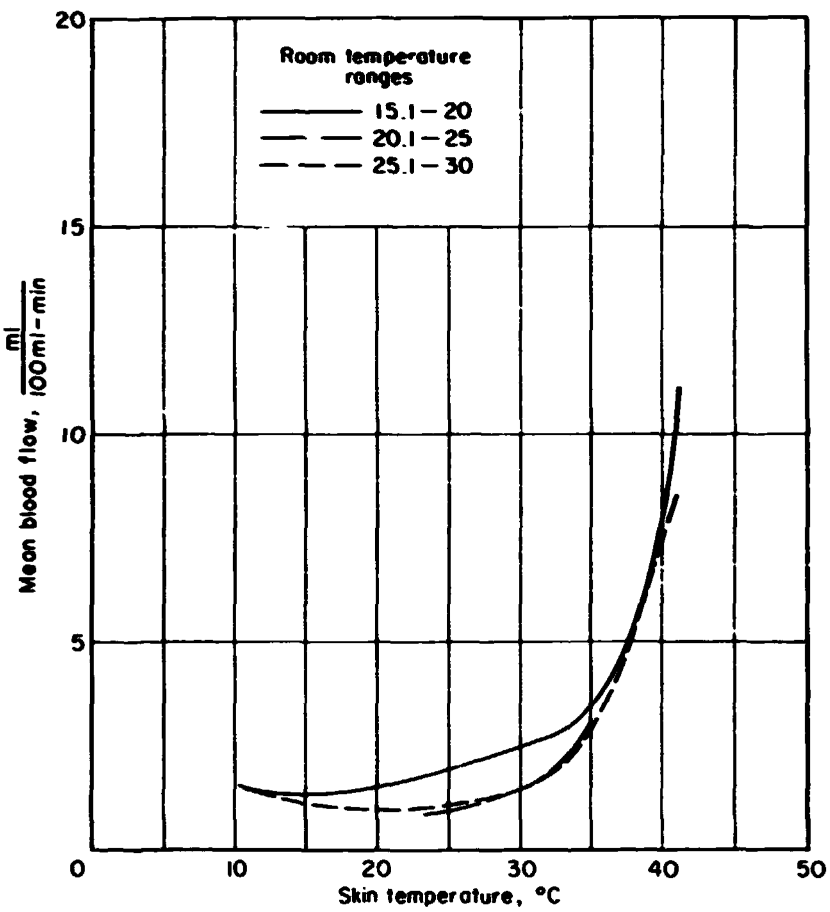

Figure 25. Forearm blood flow vs. skin temperature, for various subject weighted room temperature ranges.

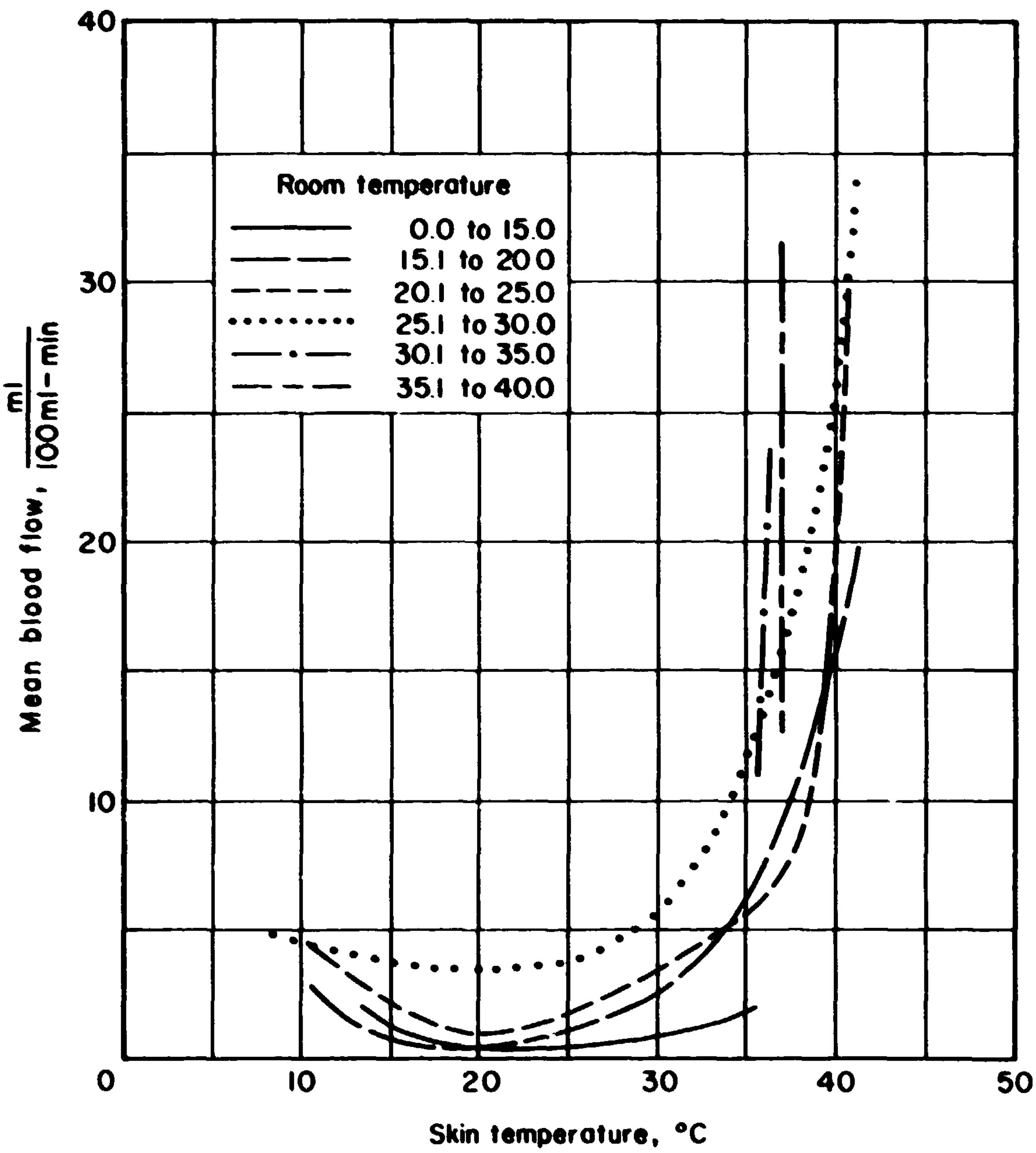

Figure 26. Hand blood flow vs. skin temperature, for various subject weighted room temperature ranges.

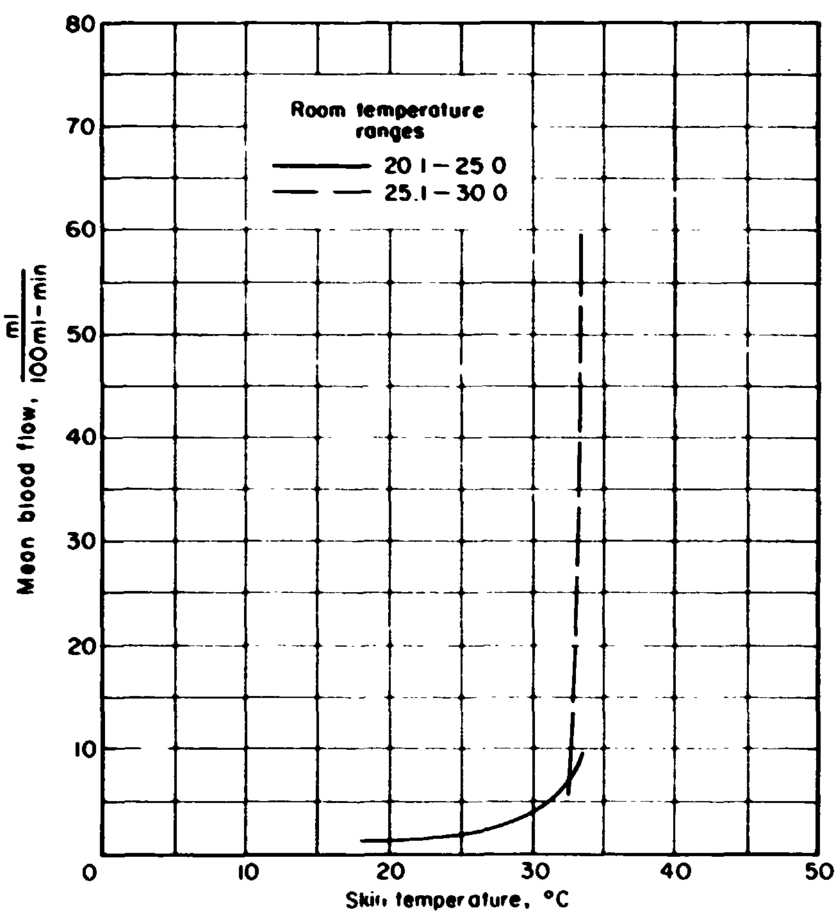

Figure 27. Finger blood flow vs. skin temperature, for various subject weighted room temperature ranges.

rate of increase becomes much larger approaching a vertical slope at about $40^{o}C$ skin temperature.

Based upon the limited data represented in this literature search it is difficult to draw any quantitative conclusions regarding the differences in segmental blood flow or the effect of increasing ambient temperatures at constant skin temperature. However, several qualitative observations have been made as follows:

A. Segmental differences in blood flow with increasing skin temperature;

1. For a given skin temperature between $20^{o}C$ to $32^{o}C$ and equal ambient temperatures more blood per tissue volume per minute passes through the more distal body segments,
2. The skin temperature at which pronounced vasodilation occurs seems to decrease for the more distal portions of the body,
3. At skin temperatures higher than $\sim 32^{o}C$ the rate of increase in blood flow with skin temperature is greater for the more distal body segments,
4. The maximum blood flow at extreme skin temperatures is much larger for the more distal body segments,
5. The extent of cold vasodilation at skin temperatures below $\sim 20^{o}C$ is greater for the hand than the forearm.

B. Influence of ambient temperature on the effect of segmental skin temperature:

1. At a given skin temperature the blood flow through a body segment tends to be higher with increasing ambient temperatures,

2. The absolute effect of ambient temperature upon hand blood flow is less pronounced at lower skin temperatures than at skin temperatures above ~32°C,
3. Above ~35°C the effect of ambient temperature, at a given skin temperature, upon forearm blood flow tends to decrease,
4. The rate of increase in segmental blood flow with skin temperature above ~32°C is higher in a warm environment than in a cold one.

Acknowledgement

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APPENDIX B: ABSTRACTS OF REPORTS YIELDING QUANTITATIVE BLOOD FLOW VALUES.

Abramson, D. I. and Fierst, S. M.

"Resting blood flow and peripheral vascular response in hypertensive subjects."

<u>American Heart Journal</u>, 23:84-96, January-June, 1942

Authors' Summary

The rate of resting blood flow was studied in a series of seventy hypertensive and ninety normal subjects by means of the venous occlusion plethysmographic method. It was found that in the hypertensive patients the resting blood flow in the forearm and leg was significantly greater than that in the normal group.

In the hand, however, the average blood flow was much less in the hypertensive than in the control subjects. The fact that the blood vessels in the hand are under the control of the vasomotor center, whereas those in the forearm and leg are little, if at all, affected by vasoconstrictor impulses, was considered significant in this respect.

A period of local anoxemia was found to elicit a response of equal magnitude in both the hypertensive and the normal subject. Similarly, the blood flow repayment after a specified amount of work was the same in the two groups. Evidence was obtained which suggested that the venous bed in the extremities in hypertension is in a state of normal tonus.

Abramson, D. I., Rickert, B. L., Alexis, J. T. and Hlavova, A.

"Effect of ambient temperature on circulatory response to experimental ischemia in the human forearm and hand."

Arch. Phys. Med. Rehabil., 52:97-109, March, 1971.

Authors' Abstract

The effect of a wide range of local ambient temperatures on the magnitude of circulatory response to 15 minutes of arterial occlusion was studied for a total of 138 times in the forearm and in the hand of 64 normal persons, using venous occlusion plethysmography. In the forearm it was found that the local blood flow repayment in the period of reactive hyperemia progressively increased with the use of a stepwise elevation of the water temperature in the plethysmograph (bath temperature). At the same time there was a corresponding increase in the height of the peak alteration, in the time this occurred, and in the duration of the augmented local circulation in the postocclusion period. In the hand the changes in general were not so clearcut as those in the forearm, although the same trends were observed. The vascular beds in the skin, subcutaneous tissue, and muscle all contributed to the circulatory changes elicited by ischemia. Information obtained by comparing the magnitude of the actual blood flow repayment with the figure representing the theoretical or predicted blood flow debt supported the view that under physiologic conditions, the cutaneous circulation in the hand, besides its role in the satisfaction of the metabolic needs of tissues, also has a very important function in the process of heat dissipation. In the forearm, this aspect of the circulation is of minimal significance.

Abramson, D. I., Zazeela, H. and Marrus, J.

"Plethysmographic studies of peripheral blood flow in man."

American Heart Journal, 17:206-217, January-June, 1939.

Authors' Summary

The various physiologic factors which may modify normal resting blood flow determinations are discussed, and methods for obviating them are presented.

The normal ranges of blood flow values for the hand, forearm, and foot under different states of vasomotor control are presented and their significance discussed.

A local reflex is described which produces vasoconstriction of the blood vessels of the lower extremity on release of the occlusion pressure used in obtaining blood flow figures.

Bader, M. E. and Macht, M. B.

"Indirect peripheral vasodilation produced by the warming of various body areas."

J. of Applied Physiol., 1(3):215-226, September, 1948.

Authors' Summary

Skin temperatures, rectal temperature and blood flow through the left hand were studied in two healthy young males before and after infra-red heating of various skin area to 42^{o} to $44^{o}C$. Heat was applied for 80 to 90 minutes after a steady state had been attained. The regions heated were the face, chest, left foot and lower leg. The surface areas, as determined for one subject, were 378 cm^2, 364 cm^2, and 1040 cm^2 respectively.

At an ambient temperature of $15^{o}C$, face-warming resulted in a significant rise in skin temperature of the left hand. The average rise was $9.8^{o}C$, the maximum increase being $15.3^{o}C$ and the minimum increase being $3.5^{o}C$. Face-warming at this ambient temperature caused a slight rise in the toe temperature of one subject and no change in the toe temperature of the other subject.

At an ambient temperature of $15^{o}C$, face-warming produced a significant increase in blood flow through the hand, as measured by venous occlusion plethysmography. The average increase in blood flow through the left hand was 3.1 cc/100 cc limb tissue/min.

At an ambient temperature of $15^{o}C$, warming of either the chest or of one lower extremity from the toes to just below the knee caused no significant changes in skin temperature or peripheral blood flow.

At an ambient temperature of $23.5^{o}C$, warming either the chest or the face to 42^{o} to $44^{o}C$ for 90 minutes resulted in significant rises in skin temperature of the hands and toes. Face-warming resulted in an average hand skin temperature increase of $9.3^{o}C$, and an average rise of $6.3^{o}C$ in toe temperature. Chest-warming resulted in an average hand skin temperature increase of $7.5^{o}C$ and an average rise of $5.6^{o}C$ in toe temperature.

At an ambient temperature of 23.5°C, both face-warming and chest-warming produced an augmentation of blood flow through the left hand. Face-warming was followed by an average increase in flow of 6.0 cc/100 cc limb tissue/min. Chest-warming elicited an increase of 3.8 cc/100 cc limb tissue/min.

No consistent alterations in rectal temperature or skin temperature of back, forearm or thigh were noted in any of the warming experiments.

Significant differences in the effectiveness of warming various skin areas as a means of inducing indirect vasodilation in the extremities have been demonstrated. The experimental results suggest that maintaining a high skin temperature of the face may be of value in the prevention of pathologic changes in the extremities caused by cold-induced ischemia.

Bader, M. E. and Mead, J.

"The effect of local cooling and heating of the finger and wrist during exposure to high ambient temperature."

Federation Proceedings of the American Physiological Society, 8:6, March, 1949.

Authors' Abstract

Utilizing plethysmograph cups containing salt solution bath, surrounded by a thermoregulated air stream, with thermocouples on the skin beneath the cups as well as in the bath, measurements of blood flow through finger and wrist (a 1" segment approximately 1" above the radial prominence) were made in a warm environment (32^{o}C). Control observations were made on one arm while local cooling and heating of the two regions were carried out on the other arm.

With a bath temperature maintained at 0^{o}C the finger skin temperature fell to and reamined approximately at 7^{o}C, but blood flow through the cooled finger did not differ significantly from base line values prior to cooling, or from the control values in the uncooled finger. Stimuli such as pain, startle and deep respiration produced sudden diminution in blood flow through both fingers; the decrease was transient, blood flow rising rapidly to normal levels within 2 minutes. The cooled finger, however, responded with much greater diminution than did the control. Local warming (bath 44^{o}C, skin 43^{o}C) of the finger produced no significant increase in blood flow. In the wrist, local cooling (bath 0^{o}C, skin 12^{o}C) did produce a decrease in blood flow; warming increased the flow above base line levels.

In an individual exposed to 32^{o}C, local thermal stimuli do not appreciably affect finger blood flow, except that cooling increases the sensitivity to some general vasoconstrictive stimuli. In the wrist, the flow is directly responsive to local temperature changes. The presence of arteriovenous shunts in the fingers may be a factor in this difference.

Barcroft, H. and Edholm, O. G.

"The effect of temperature on blood flow and deep temperature in the human forearm."

J. Physiol., 102:5-20, 1943.

Authors' Summary

The blood flow and deep muscle temperature have been measured in the human forearm for 2 hr after its immersion in water at temperatures ranging from 13 to 45·0°C.

The average forearm blood flows range from 0·5 cc/100 cc forearm/min at 13·0°C to 17·6 cc at 45·0°C.

The flow time relations fall into three groups:

(a) 13-35·0°C. Slight decrease in flow during the 2 hr. Not conspicuous except in first 15 min.

(b) 37-42·5°C. The flow increases to a maximum in about 1 hr, then decreases steadily.

(c) 45·0°C. Increases to a maximum in 30-45 min, then remains constant.

The significance of these time relations is discussed.

The higher the water temperature the more frequent are the spontaneous flucturations in blood flow.

The deep muscle temperature not far from the middle of the thickness of the upper part of the forearm ranged from 18·0°C after 2 hr immersion at 13·0°C to 39·0°C after 30 min immersion at 42·5-45·0°C.

Barcroft, H. and Edholm, O. G.

"Temperature and blood flow in the human forearm."

J. Physiol., 104:366-376, 1946.

Authors' Summary

The temperatures of the skin, subcutaneous tissue and deep muscle measured in the upper part of the resting forearm immediately after baring were 33·0, 33·6 and 36·2°C respectively. The average blood flow in the resting covered forearm is 3·1 cc/100 cc forearm/min. These figures are compared with those for the forearm in water at different temperatures.

Although it is not possible exactly to reproduce the conditions in the adequately clothed forearm by immersion in water, a water-bath temperature of 34·0°C produces less alteration in these conditions than any other bath temperature.

The use of this water-bath temperature during plethysmographic determinations of the forearm blood flow has some advantages; they are discussed.

The various forearm temperatures were measured at short intervals for 2 hr while the forearm was: (i) Uncovered and exposed to air. The final temperature readings were, skin 27·9°C, subcutaneous layer 28·5°C, deep muscle 30·7°C. (ii) Immersed in water. The final subcutaneous temperatures ranged from 14·6°C (water-bath, 12°C) to 38·7°C (water-bath, 41°C). For the deep-muscle layer the corresponding figures were 18·6 and 37·8°C respectively.

Bargeton, D., Durand, J., Mensch-Dechene, J., and Decaud, J.

"Exchange of hand heat. The role of circulatory reactions and variations of the local temperature of arterial blood." (Title Translation)

J. Physiologie, 51:111-150, 1959.

Translation of Authors' Abstract

Studies of heat loss from the human hand when the latter is submerged in water is a function of local transport conditions. Reduction of heat loss leads to significant saving of calories. The temperature of the hand is a function of the surrounding temperature except below 13° in water and 5° in air; increased blood circulation tends to raise the temperature and maintain it at 12°C. However, in the so-called physiological zone heat loss in the bath at 15°C is almost the same as that observed in a bath at 35°C.

Brown, G. M., Hatcher, J. D. and Page, J.

"Temperature and blood flow in the forearm of the Eskimo."

J. Applied Physiol., 5:410-420, 1953.

Authors' Summary

An investigation of forearm temperature and blood flow has been carried out on the Eskimo in the Arctic and on Canadian medical students in a temperate climate. All observations were made at the low ambient temperature which the Eskimo requires for comfort.

The degree of spontaneous fluctuation in forearm blood flow is greater in the Eskimo and increases in both groups as the local temperature of the forearm increases. In water baths above 38°C a more rapid increase in blood flow occurs in the Eskimo. The increased blood flow in the forearm of the Eskimo in extremely cold baths is unaltered by distant noxious stimuli. The volume of forearm blood flow is the same in both groups when maximum vasodilation is produced by the 45°C baths. The blood flow of the Eskimo in the clothed forearm and at any given water bath temperature below 45°C is greater than that of the white man. This is in agreement with the suggestion of increased heat production in the Eskimo.

In water baths below 38°C, the forearm muscle temperature of the Eskimo is less than that of the control group. It is probable that a greater cooling of arterial blood and, consequently, of the muscle occurs as a result of the greater venous return in the Eskimo. The increased circulation in the hand is very important in this respect. A reversal of this arteriovenous heat exchange appears to take place at 45°C.

Brown, G. M. and Page, J.

"The effect of chronic exposure to cold on temperature and blood flow of the hand."

J. Applied Physiol., 5:221-227, 1952.

Authors' Summary

A comparative study on hand blood flow and temperature has been carried out on Eskimos in the Canadian Eastern Arctic and on medical students living in a temperate climate. One of the effects of chronic exposure of the individual to cold is a reduction in the ambient temperature required for comfort. At this low ambient temperature, the hand blood flow of the Eskimo is twice that of the white man and the skin temperature of his hand is greater. At any given water bath temperature, the hand blood flow of the Eskimo is greater. The volume of the hand blood flow of the Eskimo changes more slowly in response to local cold. The degree of spontaneous fluctuation in hand blood flow is greater in the Eskimo and increases in both groups as the local temperature of the hand increases. The alterations which occur in the hand blood flow following chronic exposure to cold would appear to enhance hand function in the cold.

Catchpole, B. N. and Jepson, R. P.

"Hand and finger blood flow."

Clinical Science, 14:109-120, 1955.

Authors' Summary

A plethysmographic method of estimating finger blood flow is described and its advantages and limitations discussed. Finger and whole hand blood and heat flows are recorded under resting conditions at 15, 20, 25 and 30°C hand environmental temperature and again following a reactive hyperaemia test and body heating. The redistribution and quantity of finger and hand heat and blood flow under such conditions is described. The value of the heat flow disc technique for the investigation of peripheral blood flow is discussed.

Coffman, J. D. and Cohen, A. S.

"Total and capillary fingertip blood flow in Raynaud's phenomenon."

New England J. of Med., 285*5):259-263, July, 1971.

Authors' Abstract

Total (plethysmography) and capillary (radioisotope disappearance rate) fingertip flows were measured in 24 patients with Raynaud's phenomenon and compared to 10 normal subjects in a warm room and during reflex sympathetic nerve stimulation by body cooling. Arteriovenous shunt flow was estimated by subtraction of capillary from total flow. Patients with Raynaud's phenomenon had a significantly smaller capillary flow in both warm (6.4 vs. 10 ml per 100 g per minute) and cool (4.0 vs. 7.0 ml) rooms than normal subjects. With body cooling, total and arteriovenous shunt flow, but not capillary flow, decreased significantly in normal controls, whereas all three decreased in Raynaud's phenomenon. During oral reserpine treatment 11 patients with Raynaud's phenomenon showed a significantly larger capillary flow during warming (8.7 vs. 5.7 ml) and cooling (6.2 vs. 2.8 ml). Patients with Raynaud's phenomenon have a smaller finger nutritional (capillary) flow than normal subjects, and this flow decreases significantly during sympathetic stimulation; reserpine produces increased finger nutritional flow in these patients.

Cooper, K. E., Edholm, O. G. and Mottram, R. F.

"The blood flow in skin and muscle of the human forearm."

J. Physiol., 128:258-267, 1955.

Authors' Summary

Forearm blood flows were measured, at a room temperature of 23-25°C before and after iontophoresis of adrenaline into the skin of the arm.

Evidence is presented suggesting that the skin blood flow is effectively stopped by the adrenaline iontophoresis.

Over a range of forearm blood flow from 1·45 to 10·5 ml/100 ml forearm/min, in thirty-one experiments, the muscle blood flow was found to vary between 1·8 and 9·6 ml blood/100 ml muscle/min, and the skin blood flow between 0 and 70·5 ml/100 ml skin/min. The muscle blood flows and the skin blood flows have been plotted against the resting forearm flows, the relationship being shown.

The errors in the technique, the comparison of these results with those of other workers, and the possibility of predicting skin and muscle flows from the total forearm blood f'ows are discussed.

Ferris, Jr., B. G., Forster II, R. E., Pillion, E. L. and Christensen, W. R.

"Control of peripheral blood flow: Responses in the human hand when extremities are warmed."

American J. Physiol., 150:304-314, 1947.

Authors' Summary

The blood flow of the hands of two lightly clad, healthy, white, male subjects was investigated at ambient temperatures ranging from 16.4° to 30.2°C, by means of two plethysmocalorimeters. In this investigation, one hand was heated to various levels of skin temperature and any alterations in the skin temperature and blood flow of the opposite hand were recorded.

Deep tissue temperatures indicated that the heating and cooling of the respective extremities was not confined to the skin.

Further studies were conducted in which either one or two legs were immersed to a depth of 39 cm in hot water baths (38°C, 40°C, and 42°C) at an ambient temperature of 17.5°C; the effects on hand skin temperature and blood flow were observed.

When a "steady state" has been reached at ambient temperatures of 21.5°C and lower, the blood flow in the hand appears to be dependent upon the overall need of the body for the conservation of dissipation of heat. Indirect vasodilation can be induced if sufficient heat is applied.

At ambient temperatures of 21.5° to 25°C, a delicate vasomotor balance exists and slight additions of heat to one part of the body produce vasodilatation in other parts.

At an ambient temperature of 30°C, an increase in the blood flow of the heated hand occurs. This may be regarded as a protective mechanism for the removal of excess heat. At this temperature, no significant changes were observed in the unheated hand.

The results of these studies appear to indicate that under cold ambient conditions (21.5°C or lower), the central mechanism controls peripheral blood flow for the purpose of conservation of dissipation

of heat, whereas in higher temperature ranges, local control may become active and indirect vasodilation may be induced.

Forster II, R. E., Ferris, Jr., B. G. and Day, R.

"The relationship between total heat exchange and blood flow in the hand at various ambient temperatures."

American J. Physiol., 146:600-609, 1946.

Authors' Summary

An air filled combination plethysmograph and calorimeter has been constructed which measures the blood flow in the hand, and the heat loss by radiation, convection and evaporation. Measurements have been made of blood flow and of heat loss with the entire body exposed to ambient temperatures of from 15 to 38°C.

Hand blood flow rates as low as 0.15 cc per hundred cubic centimeters of hand tissue were recorded after exposure of the body to the cold for several hours.

The temperature drop in the blood as it passes through the hand can be calculated from the figures obtained. It is submitted that there must be considerable cooling of arterial blood before it enters the hand.

Grayson, J.

"Reactions of the peripheral circulation to external heat."

J. Physiol., 109:53-63, 1949.

Author's Summary

An improved plethysmograph is described for the measurement of finger blood flows, and a technique is described for the estimation of blood flow changes in the fingers and forearm in response to changing environmental temperatures.

The response of the skin circulation to rising environmental temperatures is described. It consists of:

(a) An increase in skin blood flow as the environment warms to approximately 36°C.

(b) A decrease in skin blood flow as the environment rises in temperature from 36 to 40°C.

(c) An increase in blood flow as the environmental temperature rises above 40°C.

During phase (a) and (b) the body temperature remains steady or falls, and there is no change in muscle blood flow.

During the final phase (c) the body temperature increases, forearm blood flow rises and perspiration begins.

The vasoconstriction that occurs in the skin when the environmental temperature rises above 36·0°C may be a temperature regulating mechanism.

Forearm blood flows do not respond to environmental temperature changes until the body temperature has risen.

The efferent pathway for these vascular effects is in the sympathetic nerves.

Hertzman, A. B. and Randall, W. C.

"Regional differences in the basal and maximal rates of blood flow in the skin."

J. Applied Physiol., 1(3):234-241, September, 1948.

Authors' Summary

The basal blood flows in the various skin regions of the body were estimated from the consecutive recordings by the photoelectric plethysmograph of the cutaneous volume pulses in these skin regions. Rates of blood flow were calculated by applying to these records the flow equivalent of the skin pulse as estimated previously on the finger. The total cutaneous blood flow was obtained from the sum of the flows in the various skin regions. The values thus estimated were somewhat higher than those which have been calculated from thermal data but were still of the same order of magnitude (160-250 cc/M^2/min.). Reasons for the differences between the values for skin blood flows as derived from thermal and skin pulse data are discussed.

Regional differences in the basal rates of cutaneous blood flow are exhibited in the data. Flows are approximately uniform and equal in the skin of the trunk, arm and leg but considerably higher in the palmar and plantar surfaces and in the skin of the face and head.

Regional differences in the maximal rates of cutaneous blood flow (maximal dilatation as elicited by heat or by the iontophoresis of histamine or of mecholyl) follow the same general regional pattern as shown in the basal rates of flow and appear to be set by the vascular morphology (size and number of vessels).

An argument is briefly summarized to show that the estimation of the rates of cutaneous blood flows from the photoelectric recordings of the skin volume pulses is sufficiently correct to have value in the study of vascular reactions in the skin.

Hillestad, L. K.

"Plethysmographic studies of the blood flow through normal hands."

Angiology, 13:161-168, April, 1962.

Authors' Summary

An experimental study of the normal hand flow by means of plethysmography has been done, and a system founded for distinguishing between normal and pathologic hand blood flow.

The great range of normal resting hand flow made this method unsuitable for separating normal from disordered hand blood flow.

Introduction of the reactive hyperemia flow following graded circulatory arrest made such a distinction possible.

Furthermore, it became possible to distinguish between vasospastic and obliterative arterial disease of the hand.

The hyperemia flow curve and its use are discussed. It is demonstrated that the peak flow alone may be an unreliable representative for the hyperemia flow. For a correct assessment the total increase of flow should be incorporated in the calculations. In this report the hyperemia flow was expressed by the peak flow, the area and the repayment. Their different behavior by direct heating is shown.

A collecting pressure of 50 or 60 mm Hg gave the best volume increase and did not interfere with the arterial inflow immediately after release of the circulatory arrest.

In sequences of equal periods of circulatory arrest a small decrease of hyperemia flows occurred, contrary to what has earlier been found.

The methodologic variability of hand plethysmography has been examined during single experiments and in the course of some weeks. The variation found made plethysmography acceptable for clinical research. The variation was less with the subjects seated than supine.

Hillestad, L.

"Research on peripheral hemodynamics in various disease states."

Acta. med. scand., 188:191-195, 1970.

Author's Abstract

By means of plethysmography at the local temperatures of 32 and 40°C a basis has been provided in terms of blood flow for distinction between vascular disorders of different etiology. This procedure of local heating produced a conspicuous fall of the blood flow in arteritis and in structural arterial disease on the border of gangrene. The significance of this observation is briefly discussed. A considerable vascular reserve capacity was demonstrated in threatening gangrene as well as in complete vasoconstriction. The obvious inability to put this reserve to use even under such extreme needs is commented. Examples are given of the benefits derived from a correct clinical assessment and use of hemodynamic measurements.

Killian, J. A. and Oclassen, C. A.

"Comparative effects of water baths upon body temperature."

American Heart J., 15:425-433, 1938.

Authors' Summary

Mustard baths containing 0.6 percent mustard have accelerated the rate of peripheral blood flow into both hands and feet above the levels found for water baths at similar temperatures, between approximately 35°C and 40°C. In three experiments on the hand the average increase found for the mustard baths above the levels of the water baths was 74 percent. In seven experiments on the foot, the average increase found for the mustard baths above the levels for the water baths was 51 percent.

Cooling the surface of the skin of either the hands or the feet, by immersion in water at 30 to 25°C, depresses the rates of peripheral blood flow to levels of 40 to 25 percent of the average levels at the average normal temperature of the skin.

In comparative experiments at 25°C on one subject there was noted no significant difference between the effects of mustard baths and water baths upon the rates of peripheral blood flow in the hands. However, adding mustard to the water at 30°C markedly increased (150 percent) the rate of peripheral blood flow in the hand above the level for the water bath. At 35°C a smaller difference was noted (46 percent), and at 40°C no significant difference was found between the effects.

At temperatures of 25 and 30°C the mustard bath did not affect the rate of peripheral blood flow in the foot more than the water bath. At temperatures between 35 and 40°C, the mustard bath did increase the rate of blood flow from 17 to 69 percent above the average rates for water baths at these temperatures.

Ludbrook, J.

"The effect of the thermal environment on pressure-flow curves for human skin."

Aust. J. exp. Biol. med. Sci., 49:185-196, 1971.

Aut'or's Summary

A pressure-box was used to reduce mean perfusion pressure in the upper limb. Pressure-flow curves for the skin of the hand and forearm were constructed under a variety of conditions. The blood flow to the skin of the forearm was examined by plethysmography before and after adrenaline iontophoresis, after alterations to the local thermal environment and after body-heating. The skin of the hand was examined by the latter two techniques and by heat-flow discs. No evidence was found for autoregulation of blood flow in skin under any of these circumstances.

Roddie, I. C. and Shepherd, J. T.

"The blood flow through the hand during local heating, release of sympathetic vasomotor tone by indirect heating, and a combination of both."

J. Physiol., 131:657-664, 1956.

Authors' Summary

The blood flow through both hands of each of six normal subjects was measured by venous occlusion plethysmography.

When the temperature of the water in one plethysmograph was raised from 32 to 44°C, the blood flow through that hand rose to an average value of 33 ml/100 ml/min, while the flow through the opposite hand kept at 32°C remained substantially unchanged. On now releasing vasomotor tone by immersion of the feet and legs in water at 44°C, the flow through the locally heated hand averaged 50 ml, while that through the other hand averaged 28 ml/100 ml/min.

When vasomotor tone was released by immersion of the body in a bath at 42-43°C a period of equilibrium was not obtained, but the flow through the locally heated hand remained at a higher level throughout. At the end of the experiment the flow through this hand averaged 56 ml, compared with 38 ml/100 ml/min through the hand in water at 32°C. A similar final result was obtained when the order was reversed and vasomotor tone was released before local heating was applied.

It is concluded that the hand blood flow is raised to much higher levels by a combination of local heating and release of sympathetic vasomotor tone than by either procedure separately.

Spealman, C. R.

"Effect of ambient air temperature and of hand temperature on blood flow in hands."

American J. Physiol., 145:218-222, 1945.

Author's Summary

Measurements of blood flow in hands were made on young men (18 to 35 years of age) sitting in uncomfortably warm, comfortable, and uncomfortably cold environments with hands immersed in water at temperatures ranging from 2 to 35°C.

Under comfortable environmental conditions, blood flow was less in moderately cold hands (0.9 cc/100 cc/min for hands in water at 15°C) than in very cold hands (4.3 cc/100 cc/mm for hands in water at 5°C) or in warm hands (5.9 cc/100 cc/min for hands in water at 35°C). A qualitatively similar relationship existed in uncomfortably warm environment, however, blood flow in moderately cold hands (water temperature, 15°C) was about the same as in very cold hands (water temperature, 2°C).

At any given hand temperature, blood flow was greater the warmer the body. This effect was most pronounced in moderately cold hands (ea. 15°C) where blood flow in the case of the uncomfortably warm environment was about twenty times that in the uncomfortably cold environment, and least pronounced in very cold hands (ea. 10°C) where the difference was only about three fold.