Temperature Changes in Blood Flowing in Arteries and Veins in Man


The interchange of heat between arteries and adjacent veins was described first by Claude Bernard (1), who made many measurements of arterial temperatures in animals and described moderate cooling of arterial blood in large vessels such as the femoral artery in the dog. The existence of this factor in the economy of heat exchange has long been known (2-4). However, only recently has it been realized that cooling of blood in the arteries can be great enough to be of considerable practical importance.

In order to meet war problems methods of measurements of the heat exchange of the hand and foot were devised (5). These were later modified and extended by Forster et al. (6), who combined estimates of heat exchange with measurements of blood flow. The latter data showed that considerable precooling of arterial blood in passage to the hand or foot had to be assumed in order to explain the observed heat exchanges. The same hypothesis was essential also to explain bizarre temperature changes, which were sometimes observed in the data of Mendelson et al. Some of these data will be discussed in a subsequent paper. In order to confirm or deny this hypothesis direct measurements of intravascular temperatures were made at the O.Q. M.G. laboratory in 1945 by a combined group of workers from this laboratory and from the University of Pennsylvania. The experiments were later continued at the University.

The initial experiments consisted in sampling the temperatures existing in peripheral arteries and veins of the arm under different conditions. Needle thermocouples were used, which proved difficult to maintain within an artery with certainty for any length of time. For the later experiments thermocouples protected by a fine plastic tube were employed. These can be threaded through a fine needle for considerable distances up a vessel, so that their presence within the vessel is assured. The plastic tube has non-wetting properties and does not cause clotting, so that the couples may be

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1 We would like to acknowledge gratefully assistance from the Life Insurance Medical Research Fund in meeting part of the expenses of this work, as well as from a grant from the Office of Naval Research which aided the development of the plastic tube.
left in place for hours. Consequently the later experiments have concerned mainly the change in vascular temperatures that result during adjustments to new conditions.

METHODS

The needle thermocouples consisted of hypodermic needles of 0.46 to 0.65 mm. external diameter threaded with an enameled silk-covered constantan wire of 0.08 to 0.1 mm. diameter, and also with a copper wire of 0.06 mm. diameter insulated only with enamel. Both wires were soldered to the needle orifice. The fine wires extended up into the glass barrel of a 2 ml. syringe, where they were separated by spaghetti tubing and

![Fig. 1. X-ray photographs of the thermocouples in the left arm in experiment 11. At the left, the couple in the wrist vein may be seen coursing up from the entrance through the skin distal to the wrist joint to the point marked 'tip'. The radial couple can be distinguished in the original photograph ending more proximally, as is also indicated in the figure. The photograph to the right indicates more clearly the couples in the brachial artery and median basilic vein. The needles may be seen withdrawn from the skin and lying free on proximal parts of couples.](image-url)
soldered to heavier wire. The heavy wire was gripped by a cork inserted into the open proximal end of the syringe barrel. The reference junction was kept in a thermos flask at any convenient temperature.

The plastic-covered thermocouples were made in various sizes from an outside diameter of 0.4 to 0.6 mm. The wires used were the same as those described above, though in most cases the silk insulation of the constantan wire was discarded in order to simplify their manufacture. If the wires be carefully treated, the insulation of the two wires with enamel seems adequate. This is not the case within needles, where the metal cover greatly facilitates short circuits. The plastic-covered couples are made in the following manner. Tubing of a polyvinyl plastic is drawn out for the narrowest couples until its external diameter is 0.4 mm., when its internal diameter is about 0.2 mm. It is baked at this length for one or two days at a temperature of about 105°C., and becomes increasingly rigid the longer it is baked. Lengths up to 28 cm. have been threaded by making a thermocouple of Y shape and using the tail of the Y to draw the remainder through the tube. After the couple and the limbs of the Y have been threaded, the tail can be removed. A ligature at the proximal end of the tube fixes the wires and the couple is arranged to lie just within the distal lumen. The distal orifice is plugged with beeswax. The proximal ends of the fine wires are soldered to heavier wire and are bound with adhesive tape.

The finer plastic tubes may be introduced into the vessels through hypodermic needles of special tubing with a light wall. The smallest tubing has been 0.71 mm. O.D. and 0.59 mm. I.D. For easier threading the needle tubing has been soldered into hubs with the proximal end protruding slightly beyond the end of the hub. The plastic tubing and needles are those developed by Peterson and Risman (7) for use in blood pressure recording. They have been merely adapted to the present use. The needles are withdrawn along the plastic tube after this is in the artery.

Technic of Measurement. Except for a few early experiments the couples have been connected to Kipp and Zonen microgalvanometers of 0.2 second period for photographic recording, or else to a mirror galvanometer with reflectors and enclosed scale. Selective switches have allowed more than one thermocouple to be attached to a single galvanometer. Surface temperature measurements have been made by copper-constantan couples of wire of 0.13 mm. diameter. To measure tissue temperatures the needle couples have been inserted into the tissues and approximate corrections for errors due to conduction have been made (4). Rectal temperatures have been taken either by clinical thermometers or thermocouples. For the latter a larger plastic tube has been employed with constantan wire of 0.1 mm. and copper wire of 0.2 mm. diameter to form the couple, which has been inserted to a depth of 15 cm. or more.

All the couples have been standardized under the conditions of use over the range for which they have been employed (commonly within 24 hours of their experimental use). Sensitivity has been reduced when necessary by the introduction of additional resistances.

The introduction of needle couples into an artery can often be recognized by both operator and subject by a sudden reduction in the resistance of the needle; the subject may also recognize a characteristic ache, particularly when large needles are used. This ache is generally absent when small needles are used for large arteries. The temperature of the thermocouple under cool conditions shows a sudden jump of 1.0 to 1.5°C. as the needle pierces the arterial wall.

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2 Irvington Varnish and Insulator Co., Irvington, N. J.
A similar procedure may be used for introduction of the plastic tubes into veins, if they are introduced centripetally. Even in arteries the tubes can be introduced more easily centripetally, since when passed peripherally the tip may catch in a small branch. The couples may readily be demonstrated by x-rays after introduction.

Conditions of the Subjects. The subjects usually sat quietly for some while in a cooled or warmed room. In the experiments with plastic tube couples the times used were extended to more than 6 hours. In these experiments also local cooling or heating of the limb peripheral to the couples was employed.

RESULTS

Observations in the initial experiments with needle thermocouples

In the initial experiments sample measurements of radial, brachial or venous blood temperatures were made with a single needle thermocouple introduced successively into different vessels. Other couples were used to record surface temperatures in the hand and over the points at which the vessel temperatures were sampled. Usually only one, or at most two, galvanometers were employed, so that few observations were exactly contemporaneous. The subjects were seated usually about 20 minutes to 1½ hours before the readings were taken so that temperatures changed slowly, and comparisons of different vessels with one another were not impaired seriously. The subjects were lightly clad (light shirt and trousers) and when in a cold room sat until shivering threatened to be troublesome. The data obtained in these early experiments are shown in table 1, where the duration recorded is the time from the beginning of exposure to the measurement of the radial temperature. Measurements of brachial and venous temperatures usually followed immediately. In experiment 4 measurements were also made of tissue temperature by transfixion of the thenar eminence with the same needle thermocouple that was used for the vascular measurements. The gradients are indicated in figure 2, which shows also the vascular temperature.

In this experiment the radial temperature was so low as to cause doubt as to the position of the needle in the artery, even though a large arterial hematoma had formed. A second puncture somewhat proximal to the first was therefore made by Dr. John Talbott. His great experience in such punctures was valuable and we are much indebted to him for his assistance. In spite of further cooling of the hand a somewhat higher (though comparable) value was obtained and a second hematoma gave evidence of puncture of the vessel. The rise in temperature appeared anomalous until later experiments demonstrated that any compression of the vessels distal to the point of measurement could produce such a result through interference with the return of cooled blood in venae comites. The initial hematoma lying distal to the second puncture should have had precisely this effect.

The data in table 1 are self-explanatory. It is obvious that while individual differences doubtless exist, the temperatures recorded in vessels,
whether arterial or venous, are lower the colder the environment and the longer the time of exposure to such cold conditions. The fall of temperature between the brachial and radial varied from 0.8°C at a comfortable room temperature to 8.5°C in the cold, i.e., from about 0.03°C to 0.35°C per cm.

**Table 1. Temperatures in arteries and veins of arms estimated with needle-thermocouples**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Time (min)</th>
<th>Room Temp.</th>
<th>Brach. Art.</th>
<th>Radial Art.</th>
<th>Elbow Vein</th>
<th>Surface Temperatures</th>
<th>Rectal1</th>
<th>Est. Grad.2</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>°C.</td>
<td>°C.</td>
<td>°C.</td>
<td></td>
<td>Elbow</td>
<td>Wrist</td>
<td>Aver. hand</td>
</tr>
<tr>
<td>D</td>
<td>35</td>
<td>4</td>
<td>28.9</td>
<td>27.8</td>
<td>28.8</td>
<td>14.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>51</td>
<td>6</td>
<td>25.1</td>
<td>32.9</td>
<td>34.3</td>
<td>26.0</td>
<td>13.9</td>
<td></td>
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<tr>
<td>B</td>
<td>90</td>
<td>11.9</td>
<td>33.9</td>
<td>25.4</td>
<td>35.8</td>
<td>29.0</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>95</td>
<td>9</td>
<td>21.5</td>
<td>34.3</td>
<td>37.3</td>
<td>26.8</td>
<td>19.4</td>
<td></td>
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<tr>
<td>F</td>
<td>103</td>
<td>0</td>
<td>22.2</td>
<td>34.8</td>
<td>35.9</td>
<td>22.8</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>56</td>
<td>10</td>
<td>28.1</td>
<td>35.5</td>
<td>37.9</td>
<td>23.5</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>55</td>
<td>13.0</td>
<td>35.5</td>
<td>20.1</td>
<td>30.1</td>
<td>26.8</td>
<td>19.4</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>45</td>
<td>13.6</td>
<td>35.8</td>
<td>30.5</td>
<td>35.0</td>
<td>26.8</td>
<td>19.4</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>105</td>
<td>22.0</td>
<td>36.3</td>
<td>30.2</td>
<td>33.2</td>
<td>28.4</td>
<td>27.9</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>22.0</td>
<td>37.1</td>
<td>30.2</td>
<td>32.0</td>
<td>33.1</td>
<td>32.2</td>
<td></td>
</tr>
</tbody>
</table>

1 A, before; B, after.  
2 Estimated gradient across arterial wall.  
3 In this experiment measurements of tissue temperature in the thenar eminence were also made. See fig. 2.

When the Kipp microgalvanometers were used, pulsatile variations in arterial temperature of 0.1°C to 0.15°C were often visible in both the brachial and radial arteries, if the environment was cold. Even the dicrotic waves could sometimes be recognized in spite of the relatively slow characteristics of the galvanometer. Such pulsations could not be ascribed to loss of heat from the vessel to the air along the needle, for they were later confirmed with the other type of couple, in which thermal conductivity was negligible.

**Observations with plastic-covered couples**

The first experiment of this series (exp. 11) to be considered was carried out in a very warm room. It is selected because in this experiment the thermocouples were inserted considerable distances for the purposes of x-ray demonstration; there can therefore be no doubt of their presence in blood vessels. A tendency to bleeding along the tract, as well as the high initial
temperatures, guaranteed that the ‘arterial’ thermocouples were within the arteries rather than in venae comites. Figure 1 reproduces x-ray photographs showing the couples within the vessels of the upper arm and forearm.

**Abbreviated Protocol. Experiment II.** Room temperature 33.9°C dry bulb and 28.3° wet bulb. Thermocouples were introduced in the following order: 1 in rectum to depth of about 15 to 20 cm.; 2 in left femoral artery with insertion to depth of over 15

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**Fig. 2. DATA FROM EXPERIMENT 4** approximately corrected to represent conditions at the time of the second puncture of the radial artery. The abscissae represent the depth in mm. from the puncture on the palmar surface of the thenar eminence to the center of the tissues, and to the exit of the needle (zero depth to the right) on the dorsal surface of the space between the 1st and 2nd metacarpals. The ordinates represent temperatures in °C.

**Fig. 3 (Exp. II).** TIMES IN HOURS OF THE DAY are plotted as abscissae and the observed temperatures as ordinates. The upper continuous line indicates the rectal temperature, recorded from the most central locality on an anatomical basis. The lower continuous line indicates the temperatures of the forearm vein, which was the most peripheral couple. The temperatures observed in the brachial artery (middle of upper arm) and in the radial (middle of forearm) are shown by the upper and lower dotted lines. The solid circles indicate temperatures recorded in the common iliac artery and the crosses those in the median basilic vein. At point a the left arm was inserted somewhat obliquely to the middle of the forearm in water at 19.3°C., but the thermocouples in the forearm remained slightly above the level of the water. The temperature of the water rose steadily to 27°C within the next 72 minutes to the time marked c. At point b both feet were immersed to some 6 inches above the ankle in water at 18.8°C.; the temperature of this water gradually rose to 22.4°C at point c, when it was lowered to 13.5°C by the addition of ice. At point d the temperature of both baths was lowered further by ice to levels of 7°C to 8°C. The cooling was rapid enough to cause considerable pain both in the arm and feet, so that the arm had to be removed temporarily from the water shortly after d; the arm was returned to the water at f while the feet were removed; at g the arm was also taken out, and both arm and feet thereafter remained in the air in the warm room. There was some tendency to faint, accompanied by a cold sweat in the period between e and g. Normal sweating from heat had ceased about 13:40 and returned at 14:50. The temperature in the wrist vein fell at 14:30 to 20.3°C at 14:33 to 20.1°C and at 14:36 to 21.5°C, as is approximately indicated in the insert below the abscissa line.
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cm. so that the couple must have been in the common iliac; 3 in left brachial artery inserted about 15 cm. to a level 12 cm. above the elbow joint in the middle of the upper arm; 4 in left radial artery inserted to a distance of about 15 cm. above wrist joint to the middle of the forearm; 5 in left median basilic vein inserted to a level equivalent to that of the brachial couple; and 6 in the superficial vein draining the left index finger, punctured in the neighborhood of the anatomical snuff box just distal to the wrist joint with the couple inserted for about 12 cm. to the middle of the forearm. For positions of 3, 4, 5 and 6 see figure 1.

The position of all the couples with the exception of 6 was definite. Thus the venous couple 5 passed up the superficial vein and could be palpated just beneath the skin in the middle of the inner aspect of the upper arm. However, the thermocouple 6 introduced into the tributary of the same vein at the wrist could not be so palpated, even though according to the x-rays (which were taken in two planes) it passed up the forearm along the path of this superficial vein. Possibly the somewhat thick wall of the vein merely prevented its recognition. The distance between the two couples in the arm arteries was estimated as 21 cm. and that between those in the veins as 25.5 cm. The rectal thermocouple was introduced at 9:45 a.m. and couple 6 was introduced at 11:35.

The temperatures recorded during this experiment are shown in figure 3 from 11:00 till 15:45, and the procedures followed are indicated in the subscription of this figure.

In the warm room the subject was sweating until loss of heat to the cooled limbs caused its cessation slightly before the point c indicated in figure 3. During the initial period the temperatures recorded in the rectum and in the vessels did not differ greatly. Either the rectum, common iliac or brachial artery might temporarily show the highest temperature, and the temperature of the radial could also exceed for a while that of the rectum. The differences were small. The venous temperatures were not much lower. In the warm environment the temperature of the more central median basilic vein was below that of the wrist vein (cooling of blood in its return passage), though this reversed venous gradient disappeared when the hand was cooled. These differences in the venous thermal gradients are typical of warm and cold conditions. When the hands and feet were cooled in water (at a, b, c, and d in fig. 3) considerable discrepancies were observed between the rectal temperature and those recorded in the arterics. The arterial temperatures also differed among themselves. Large gradients were set up between the brachial and radial. The initial effect of cold applied to the peripheral part of a limb was usually to produce rises in temperature in the rectum and central arteries, which, however, were temporary. During rewarming, the temperatures in peripheral vessels started to rise while those of central vessels were still falling. When limbs were put in or out of cold water, at the late stages of this experiment, conditions were complex.

The marked cooling of a central large artery, that may result ultimately from exposure of a more peripheral area to extreme cold in the presence of vasoconstriction (as the result of a cool environment), is well illustrated by
experiment 12. The temperatures recorded in this early experiment were obtained with a single plastic-covered couple introduced first into the radial artery and then later into the brachial where it was retained for 135 minutes. Surface temperatures were also recorded from the area over the brachial couple.

Abbreviated Protocol Experiment 12. Room temperature 13.3°C dry bulb, relative humidity moderate. The subject entered the room at 14.30 with a rectal temperature of 37.5°C. After exposure of the subject in shirt and light trousers for 25 minutes the radial temperature was 33.0°C. At 15:06 the brachial was punctured and the thermocouple was introduced centripetally along it. When introduced a distance of about 2 cm. along the artery a temperature of 35.1°C was recorded; there was some bleeding along the track of the needle and light compression below the position of the couple was being used. On cessation of this bleeding the compression was removed and the temperature fell to 34.4°C and only rose another 0.1°C on introduction of the couple to a distance of 4.5 cm. The needle was then removed causing a return of bleeding, to control which compression of the artery was employed at the point of puncture distal to the couple. During this compression the arterial temperature rose to 36.1°C, and later fell again to 35.25°C after removal of the compression. Manual compression of the brachial artery above the level of the couple on the other hand caused only slight falls in temperature (of about 0.2°C in 15 seconds) with a return to a value slightly above that originally recorded soon after the compression was released. After this the subject sat quietly in the cold room for 20 minutes during which time the brachial arterial temperature fell slowly from 34.7°C to 34.0°C while the skin temperature superficial to it varied between 22.1°C, 21.8°C and 22.5°C. At this time the subject had been sitting for 100 minutes in the cold room. At 16.10 ice water was sponged over the hand and forearm but all applications were at least 15 cm. distal to the position of the couple. The temperature in the brachial artery began to rise within 10 seconds, increased 0.6°C in 1 minute and 0.86°C in 3½ minutes after which it began to fall again slowly. The surface temperature over it also rose 0.4°C. After the peripheral sponging had been continued for 10 minutes the surface temperature over the artery had fallen by 0.6°C to 21.9°C but the brachial arterial temperature though falling was still 0.5°C above its original value. The hand and forearm were then sponged with water at 20°C. This cold water felt by contrast very warm and some flushing of the skin could be seen. The warming of the skin peripherally initiated a cooling of the brachial artery starting within 4 or 5 seconds and caused a fall from 34.5°C to 31.6°C in 5 minutes, while the surface temperature over the vessel showed no significant alteration. At this time (16:28) the subject moved to a warm room for x-ray examination and returned to the cool room 35 minutes later. In spite of the long exposure to warmer conditions the skin temperature had only risen by 0.7°C to 22.7°C and the brachial artery by 0.4°C to 32.0°C. Six minutes after entering the cold room it had risen to 32.75°C. Ice water was reapplied to the hand and forearm for 10 minutes with a fall of brachial temperature to 31.1°C without any initial rise. Lastly, 171 minutes after entering the room, the couple was gradually removed by withdrawing it back along the artery (distally). Dislodging the tube started bleeding, which again necessitated manual compression below the couple. The temperature within the artery steadily rose from 31.1°C to 33.3°C during this compression even though the couple was being withdrawn through a distance of 4 cm. during this period. Rectal temperature at the conclusion of the experiment was 36.6°C.
This experiment has been described in some detail since it demonstrates how great may be the cooling imposed on a large artery like the brachial by cooling followed by rewarming applied peripherally. Such a central artery showed an initial rise in response to peripheral cooling and a later precipitous fall, when the peripheral area began to rewarm. These changes are entirely similar to those normally seen in the rectum when the whole body is cooled and then warmed, but they are much more in evidence in vessels than in the rectum. Lastly, the experiment shows that during such exposure to cold only slight changes in the arterial temperature are produced by manual compression central to the couple. On the other hand a rapid rise is induced if such manual compression is applied distal to the thermocouple in such a way as to impede the return of blood along the veins adjacent to the artery. The experiment therefore gives additional evidence of exchange of heat between the warm blood in the artery and the cold blood in the veins.

One more experiment may be quoted. It differed from the others in that the subject was exposed at first for a long time to a cold room, and then the room was warmed rapidly and was maintained at the higher temperature, while local warming and cooling were employed on the experimental limb. This experiment employed photographic recording and gave therefore indications of the rapidity of changes. On the other hand the temperature levels were open to doubt probably to the extent of 1° to 1.5°C. during the period when the room was being warmed, since the recording equipment was also exposed to the rising temperature and parasitic currents could have been present.

Abbreviated Protocol. Experiment 13. Room temperature 21° dry bulb and 15.5° wet bulb. The subject had been exposed to moderate summer weather and the room felt comfortable. The course of the initial stages of the experiment is indicated in figure 4. The rectal temperature there shown was taken 25 minutes after the room was entered. An initial puncture of the left radial artery caused a partial faint, during which the temperature of 34.8° was recorded. After 8 minutes, recovery was not complete, so the couple was withdrawn and introduced on the right side 25 minutes later without trouble. Couples were then inserted into other vessels of the right arm as indicated in the figure. The estimated distance each couple passed centrally after entering the vessel was for the arteries 2 cm., for the wrist vein 5½ and for the median basilic vein 4 cm.

Conditions in the wrist vein were exceptional. The point of introduction was similar to that used on the left arm in experiment II. However, the superficial veins were constricted and the couple passed directly deep to the point of entry along a chance communicating vein to travel up the forearm in deep tissues. It was probably in close apposition to the radial artery. Unfortunately circumstances prevented x-ray examination, but the couple on removal retained a Z shape strongly confirming this interpretation of its position.

The procedure consisted of sitting still till 12:55 in the cool room and then in a rapidly warming room till 14:15 after which the room temperature remained about 34.5°
dry bulb and 28.0° wet bulb. During this time the only experimental modifications of conditions were manual arterial compressions for two minutes each, in the middle of the forearm in the cool room at 10:56, in the rapidly warming room at 13:43 and in the stabilized warm room at 15:45. The first caused a fall of radial temperature of 1.7°, the second a fall of 0.6° and the last produced no definite change. The temperatures of the wrist vein were recorded simultaneously in the second and third compressions. The second compression gave a fall of 0.2° (much less than that of the artery) and the third no significant change. The temperatures recorded at the end of the warm period appeared high, but as has been stated the apparent levels may have been somewhat distorted by parasitic currents. Records were obtained photographically and changes were known accurately. Even at the end of this experimental warm period the close approximation of brachial and radial temperatures recorded in experiment II was not seen.

After 15:50 the effects of hot and cold baths applied to the hand distal to all the thermocouples was tested; these observations are shown in figure 5, where the time scale is expanded to make the changes clearer.

The photographic records demonstrated that considerable ‘pulsatile’ changes in temperature may occur in an artery, particularly during the readjustments to new conditions. Samples of the records are shown in figure 6. It will be noticed that marked pulsations are visible in the records from the arteries in the early stages of cooling in the cold room and again during the recovery after the hand had been violently cooled. In the latter the increased ‘pulsation’ accompanying a missed beat may be seen, amounting in this case to about 0.7°C. The actual changes must have been greater, since the damping of the thermocouple change by the plastic cover and of the record by the inertia of the galvanometer would both tend to minimize the responses.

The rectal temperatures were taken with an ordinary clinical thermometer at the beginning and end of the experiment. If they had been taken at a deeper level with a thermocouple they might have been somewhat higher but any error is unlikely to have exceeded 0.3° to 0.5°.

Both in cold and warm rooms the deep vein in the wrist showed higher temperatures than did the more central but more superficial vein, except when the hand was cooled in water. The deep peripheral vein was much more affected by the condition of the hand and its temperature could approximate that of either cold or hot water, to which the hand was exposed. The changes recorded in the temperature of both the radial artery and of this vein seemed to be mutually interdependent. The marked fall of radial temperature on exposure of the hand to very cold water was explicable as a secondary effect of the much greater change observable in the vein.

DISCUSSION

The experiments were diverse in character but had one common objective, namely the demonstration of the absence of uniformity or constancy in ‘blood temperature’. None of the positions explored can be assumed to indicate with certainty the temperature level or the direction of change of temperature of the thermo-regulating center, for all may be affected by
local conditions. One might expect that the temperature of the abdominal aorta or that of the jugular bulb might be reliable indicators of the temperature of the center. The data here reported, however, indicate that the common iliac artery is not entirely free from the effects of local cooling. Measurements made in the jugular bulb will be reported later, but even in this vessel local influences probably are not negligible. A common central temperature, more or less identical in the main central vessels, is found only when an individual has been maintained at rest for a considerable interval in a warm room, and when a rapid circulation has aided the attainment of a steady state, as was the case in the early part of experiment II.

The absence of a definite uniform central temperature is perhaps less disturbing than are the very great gradients in temperature that exist in periods of readjustment, not only in the tissues but also in the blood stream along the course of the main arteries. Under such conditions temperature
is a very variable factor, and the process of rewarming may be associated with paradoxical steep falls in temperature in some localities.

There are many indications of a rapid transfer of heat from an artery in its course along a limb under all conditions except those of a warm environment. The existence of a steep thermal gradient across the thin wall of an artery, which as indicated in table I may amount to 1° or 2°C., must necessarily be associated with considerable heat transfer. High thermal gradients between brachial and radial arteries, as indicated in the same table, sometimes reached 0.35°/cm. These temperature differences were substantiated by marked pulsatile changes in arterial temperature, which often were obtained. Some of these are reproduced in figure 6. Such variations in temperature with the pulse were particularly marked in periods of readjustment when thermal conditions were rapidly changing.

Rapid cooling of blood within an artery, as indicated by all these observations, cannot occur unless the heat is accepted by some other tissue, yet warmer skin surfaces lying over arteries were not observed. An exchange of heat between the arteries and adjacent venae comites, by which the returning blood is warmed as the arterial blood is cooled, provides the only reasonable explanation. Under such conditions pulsatile rewarming of venous blood should also occur. Some indication of such a phenomenon has been obtained, but any evidence was inconclusive. Only lack of imagination has prevented scientists from realizing how great must be the exchange of heat between such vessels at different temperatures separated by thin walls with little capacity for insulation. The anatomical conditions in a peripheral artery such as the radial are evident in a diagram utilized by Leonard Hill et al. in 1897 (8) for another purpose. It would be difficult to imagine any anatomical arrangement more suited to heat exchange.

The effects of vasomotor changes on such a system cannot be simple. The known factors may be considered by taking as an example the vasodilatation to warmth following exposure to cold. Increased rapidity of flow shortens the duration of exposure of arterial blood to cooling effects, and tends to decrease the degree of cooling. On the other hand the increased rapidity of flow in the veins decreases the rewarming of venous blood and so extends centrally the distribution of cooled venous blood. Thus the thermal gradient between the vessels temporarily is increased counteracting any tendency to reduced heat exchange per ml., and accounting for greater pulsatile changes in temperature.

The interaction of these various factors gives complicated effects during rewarming. Commonly the vasodilatation causes an initial rapid return of cooled venous blood, which through its low temperature and large volume
accepts much heat from the artery and induces a rapid fall in temperature in peripheral arteries. The rapidity of blood flow later reduces the thermal difference between the artery and the periphery (i.e., raises surface temperature). The temperature at which the venous blood starts its return passage is increased, as is that of the blood in the main venous channels. Consequently, the ultimate effect is a general increase in temperature in all these vessels including the artery.

Fig. 6 (Exp. 13). REPRODUCTIONS OF ACTUAL RECORDS: top left, from the radial artery at 10:55 after subject had been exposed to the cool room for 88 minutes. The needle, through which the couple had been introduced, was still in the artery but distal to the couple. Top right, records from arteries and veins at 12:50 just before the room was warmed. The subject was in approximate equilibrium after 205 minutes in the room. Bottom left, similar records obtained at 14:30 when the warm temperature of the room had been steady for 15 minutes. Bottom right, records obtained at 14:36 just after removal of the hand from very cold water and 431 minutes after the subject entered the room.
When the dilatation follows a period of exposure to cold, the sudden increased thermal conductivity also affects the situation through the more rapid convective transfer of heat. The tissue insulation values are reduced and the peripheral areas of the body are heated at the expense of those more centrally located. The rapid fall in the temperature of the brachial artery, such as that observed in experiment 12 must be regarded as such a reaction and one entirely comparable to the fall in rectal temperature that accompanies the initial stages of rewarming after the whole body has been cooled.

The rise in arterial temperature in the response of vasoconstriction such as occurred in experiment 12 is an example of the opposite reaction. The temperature of the returning venous blood is lowered but its rate of flow is also slowed. The artery is at first exposed to a smaller quantity of blood cooled to the normal extent and its temperature rises. Later the colder venous blood reaches central positions and the arterial temperature falls. When the venous blood has not been originally greatly cooled, the rise resulting from slowed flow may not be seen, as was the case in experiment II at point a. Where the cold stimulus is extreme, and where preceding alternations of vasoconstriction and dilatation complicate the picture, the initial increase in temperature in the central arteries also may be absent, as was the case at the end of experiment II.

Conditions in the rectum are those of an area, which is centrally located but which is supplied with blood affected by local cooling or warming. Both the arteries and veins of the rectum anastomose freely with those supplying neighboring skin, such as that of the buttocks. The common iliac artery is demonstrated not to be immune from cooling effects arising in the iliac veins, so that the inflow of blood from the internal iliac artery must also be affected by venous return in these vessels. Thus cooling of such vessels from local exposure of the legs could exert cooling effects on the rectum greater than those to the body as a whole. In addition venous blood from the buttocks has a possible path for return through the connections with the rectal vessels. The use of this path may perhaps be affected not only by vasomotor reactions but also by postural changes. Any return along such paths would be apt to affect the temperature of the arterial inflow, and reduction of such venous flow by vasoconstriction would be the most likely explanation for the sudden rise of rectal temperature that accompanied the immersion of a single arm in cool water in experiment 13.

None of the vessels investigated is representative of central body temperature for they all appear to be affected by local temperature changes. Thus in experiment II, after immersion of the hands in cold water, discrepancies between rectal and arterial temperatures reached values of 0.5°, 1° and 2° C., respectively, for the common iliac, brachial and radial, while later
immersion of the feet in cold water gave different relations. The greatest cooling in the central areas in this experiment occurred in the period of re-warming when all the limbs had been removed from the bath, but they developed with very different degrees of lag. The minimum developed in the median basilic vein after some 5 minutes, in the brachial and femoral after 15 minutes and in the rectum after 45 minutes. The cooling of the central vessels and rectum in this experiment had to have a peripheral origin since the room was very warm. The temperature of the radial artery fell below room temperature, though the point of measurement was well above the water level, while even the brachial temperature fell to a value only 1.7° above that of the room with an abruptness incompatible with mere air-cooling.

Precooling of arterial blood by venous blood would appear teleologically to be a disadvantage in the adjustment of an individual to a warm environment. However, under such conditions the superficial veins are dilated and venous return is mainly through low resistance superficial paths, along which cooling can continue. Possibly some reciprocal constriction of deep veins occurs, but no method of investigation has been found. The superficial venous return, however, can account for reversed surface thermal gradients in the forearm in the warmth described by Pennes (9), for the high temperatures of finger and toes (5, 10) as well as for reversed thermal gradients in the superficial veins here reported and also earlier described (4).

Bizarre effects may be seen. Thus in experiment 11 during recovery the radial artery temporarily appeared to have a temperature lower than that in a superficial vein. Whether true or not, such a condition is not impossible. An effect, in which cooled arterial blood rapidly lowered the surface temperature of a hand during rewarming, is described as another instance in a later paper (11).

The statement has been made (12) that exposure of the skin surface to cold causes an initial but temporary rise in temperature within the neighboring muscle and that this indicates a vasodilatation in the blood vessels to the muscle in the response to cold. The observations are undoubtedly correct, but the deductions are not warranted in view of the data here reported. The change in muscle temperature merely parallels that which long has been known to arise in the rectum, and which is described here in the large arteries. The change could occur merely as the result of a reduced return of cooled venous blood due to constriction of skin vessels and a consequent rise in temperature of the blood supplying the muscle. There is, however, no definite evidence that dilatation might not occur also; this point remains an open question.
The values here given for arterial temperature are not in disagreement with those in the literature; they merely were obtained under a much wider range of conditions and so have demonstrated the existence of larger variations. Previous values given by Bazett and McGlone (4) agree with them, though these earlier values were cited with some diffidence. Pennes (9) has reported in warm rooms temperatures in brachial arteries which agree with those obtained here under similar conditions.

The variety of temperatures recorded in the large vessels and the differences that may exist between the temperature of the rectum and temperatures in the large central vessels render past evidence on temperature control open to doubt. Reexamination of this subject has already started and the data obtained will be reported later.

In conclusion it is pertinent to remark on the misconceptions that arise from the fictitious assumption of a uniform 'body' temperature. Not only is tissue temperature variable even in homoiotherms, but important variations in arterial blood temperature are common. Thus the blood in arteries such as the radial artery and dorsalis pedis may have a temperature between 20° and 25°C. Such temperatures imply an increase in resistance to flow, from the change in blood viscosity alone, of some 30 per cent, even supposing that the increase in viscosity of the blood in the vessels is no greater than that which would occur in water. It is certainly unlikely to be less than this. On the contrary in still smaller vessels, such as the digital arteries, both the temperature change and that in viscosity are likely to be much greater. The physiological and medical significance of such changes may be great.

Other effects of temperature changes must also be present. Cooling alters the dissociation of water and the pH at neutrality; isoelectric points of proteins are altered and the blood becomes much more alkaline (13-15), while the dissociation curves of blood for gases are shifted, altering the actual gas tensions in the tissues (16). Temperature changes alter the balance of electrolytes in the blood between corpuscles and plasma (17). It is possible that chemical or osmotic differences set up by thermal gradients are concerned in the stimulation of thermo-receptors (18). All these changes indicate an urgent need for the study of temperature as a variable in the biochemistry and physiology of blood and tissues.

SUMMARY

1. Measurements of temperature in the brachial and radial arteries and common iliac artery as well as in superficial veins are reported. Thermocouples were left in place for hours and the effects of cooling and heating on vascular temperatures were determined.

2. The temperature of the blood in transit in the limbs, even in the arteries, is by no means either uniform or constant. It varies in different
vessels at any one time, and in any single vessel is much affected by the conditions of cooling distal to it. A gradient of 0.3°C per cm. or more may exist along the brachial and radial arteries, and pulsatile changes in temperature of 0.2°C. or more may accompany each pulse wave.

3. Cooling of arterial blood in transit in the arteries of the limbs is dependent on the rewarming of cold blood returning in adjacent veins from more distal areas. If the blood in these veins is cold, compression hindering flow causes a rise in temperature in the artery proximal to the point of compression.

4. Temperatures as low as 21.5°C for the radial and 31.1°C for the brachial artery have been recorded without the subject’s being unduly cold, or the rectal temperature particularly low.

5. The temperatures of the rectum, brachial artery and common iliac artery may all differ considerably from one another and undergo changes of different magnitude and with greatly different degrees of lag.

6. The temperatures in superficial veins of the wrist and forearm are much lower in a cold environment, the more peripheral the point of measurement. In a hot environment this gradient is apt to be reversed.

7. Attention is drawn to the chaos introduced into physiology by the fictitious assumption of a constant blood temperature.

REFERENCES