EFFECT OF BATHS AT DIFFERENT TEMPERATURES ON OXYGEN EXCHANGE AND ON THE CIRCULATION

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The experiments here reported were undertaken to test further the general applicability of the empirical equations for the calculation of cardiac output from blood pressure and pulse wave velocity measurements (1935). Baths were employed, since in this way great variations in vaso-motor tone and pulse rate, as well as of body temperature, were attainable. To render the equations useful in clinical conditions, it is essential to show that they are valid in conditions where these functions are abnormal.

METHODS. Emphasis has been placed throughout on the comparison of estimates of the cardiac output obtained by calculation with those derived from the rate of acetylene absorption. As in previously reported experiments (1936) the two methods were used alternately.

For the acetylene estimations of cardiac output oxygen consumption was measured by the Sanborn clinical apparatus. Where the changing condition of the subject created difficulties, the value used was obtained by interpolation from estimates before and after the acetylene procedure. In the rebreathing procedure the reclining position of the subject coupled with the hampering of movements by the water made mixing in the lungs difficult, and in many cases, where the initial samples were taken relatively early, mixing was certainly incomplete, so that the estimates had to be discarded. Consequently, if samples were taken relatively early, the subject had to be propped up into a sitting posture, where thermal conditions were temporarily altered through evaporation. Most commonly two samples were taken after some 13 and 19 seconds respectively with the subject so propped up; in a few experiments adequate mixing seemed to be attained with samples taken at 11 and 16 seconds.

Estimation of cardiac output from the blood pressures followed the technic previously described; in the earlier experiments apex beat records were used to determine the start of ventricular ejection, in the later experiments sternal records (as described in 1936) were employed. It proved to be difficult to read diastolic pressure accurately in the hot
bath experiments. Under conditions of peripheral vasodilatation the
diastolic criterion was much less clearly marked, particularly in young
subjects. The development of a negative wave in the brachial pulse and
the sharp upstroke of the oscillometric pulsation were found at compres-

TABLE 1
Comparison of mean values for cold baths, basal in air, baths at 35° and various
stages of warm baths
(Means of individual subject averages)

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>O$_2$</th>
<th>AV Diff.</th>
<th>CI (Acet.)</th>
<th>F</th>
<th>CI (Calc.)</th>
<th>S</th>
<th>D</th>
<th>R</th>
<th>PULSE WAVE VELOCITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cold baths</td>
<td>213</td>
<td>62.7</td>
<td>2.14</td>
<td>57.4</td>
<td>2.07</td>
<td>114</td>
<td>69</td>
<td>130</td>
<td>3.02 6.39 7.22 8.9</td>
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<tr>
<td>Bath 32.1°</td>
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<td>Rectal 36.9°</td>
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<tr>
<td>2. Basal in air (in other</td>
<td>198</td>
<td>59.2</td>
<td>2.04</td>
<td>59.8</td>
<td>2.18</td>
<td>103</td>
<td>65</td>
<td>118</td>
<td>3.15 5.49 6.65 0.3</td>
</tr>
<tr>
<td>experiments)</td>
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<tr>
<td>3. Neutral baths</td>
<td>195</td>
<td>62.2</td>
<td>2.28</td>
<td>60.7</td>
<td>2.24</td>
<td>99</td>
<td>61</td>
<td>108</td>
<td>3.14 5.39 6.32 8.7</td>
</tr>
<tr>
<td>Bath 35.1°</td>
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<td>Rectal 36.9°</td>
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<tr>
<td>4. Warm baths early</td>
<td>220</td>
<td>48.7</td>
<td>2.76</td>
<td>82.3</td>
<td>2.69</td>
<td>103</td>
<td>63</td>
<td>93</td>
<td>3.63 5.98 6.18 9.0</td>
</tr>
<tr>
<td>Bath 37.9°</td>
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<tr>
<td>Rectal 37.6°</td>
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<tr>
<td>5. Warm baths middle</td>
<td>246</td>
<td>53.5</td>
<td>2.81</td>
<td>91.8</td>
<td>3.47</td>
<td>108</td>
<td>59</td>
<td>78</td>
<td>3.99 5.78 6.56 8.9</td>
</tr>
<tr>
<td>Bath 38.8°</td>
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<tr>
<td>Rectal 38.2°</td>
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<tr>
<td>6. Warm baths late</td>
<td>253</td>
<td>58.6</td>
<td>2.73</td>
<td>91.2</td>
<td>3.18</td>
<td>110</td>
<td>59</td>
<td>86</td>
<td>4.15 6.09 6.71 9.7</td>
</tr>
<tr>
<td>Bath 38.6°</td>
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<tr>
<td>Rectal 38.8°</td>
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</tbody>
</table>

F represents pulse rate, S and D estimates of lateral systolic and diastolic pressure.
C I indicates the cardiac output per square meter per minute (expressed as an index,
though this is normally only used for basal states). R is the calculated effective
peripheral resistance, and pulse wave velocities 1 to 4 represent heart to subclavian,
subclavian to femoral, subclavian to brachial, and femoral to dorsalis pedis velocities
respectively.

sions which differed from one another to an unusual extent. The latter,
however, gave consistent values if the records were read with great care
with the assistance of a cylindrical lens.

The experiments were made on the same subjects that were used in
experiments on meals (1936), and the subjects are therefore given the same
numbers. They were basal and were deprived of fluid; they were immersed in baths to their necks. The heating and regulating of the bath were arranged as described by Bazett and Burton (1936), except that the paraffin cover was omitted.

At the beginning of every experiment the bath temperature was regulated at 35°; later it was either cooled or warmed. The bath temperature was read from time to time, and the rectal temperature was recorded continuously by the use of a resistance thermometer (Leeds and Northrup type).

Experimental data. Baths at 35°. Observations were made in 25 experiments, and in all 4 subjects the conditions in baths at this temperature were very similar to those of the basal state in air. This is demonstrated in the average values shown in table 1. In the baths the arterial-venous oxygen (A-V) differences and the blood pressures were somewhat lower, as was also the calculated value for the effective peripheral resistance (R). These changes are those to be expected in a slightly warmer environment. The peripheral pulse wave velocities were also slightly slower, and this may also have depended on the raising of the temperatures of the peripheral areas to a uniform surface temperature, which would occur in such baths. Though all the differences were slight, the changes in the average values are probably significant, since the degrees of change appeared to be correlated with the subject's sensation of temperature (rather than with the difference in temperature between the rectum and the bath). The individual values are shown in table 2; the contrast in the effects of the baths in subjects 4 and 10 on pulse rate, blood pressures and A-V oxygen differences, and the intermediate position of the other subjects, is so consistent, that it must be significant. The baths appeared cool to subject 4, where the rectal-bath temperature difference was high, as well as to subject 8 where this difference was low. Subject 8 was the thinnest subject; this was probably a factor.

### Table 2

<table>
<thead>
<tr>
<th>Subject</th>
<th>F</th>
<th>PERCENT CHANGE</th>
<th>S</th>
<th>PERCENT CHANGE</th>
<th>D</th>
<th>PERCENT CHANGE</th>
<th>R</th>
<th>PERCENT CHANGE</th>
<th>A-V</th>
<th>PERCENT CHANGE</th>
<th>Rectal</th>
<th>Sensation</th>
</tr>
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<tbody>
<tr>
<td>4</td>
<td>77.5</td>
<td>-3.4</td>
<td>95.6</td>
<td>-1.6</td>
<td>62.1</td>
<td>-0.3</td>
<td>94</td>
<td>-2.6</td>
<td>53.0</td>
<td>-1.2</td>
<td>37.09</td>
<td>Cool</td>
</tr>
<tr>
<td>8</td>
<td>49.0</td>
<td>-0.6</td>
<td>104.0</td>
<td>-2.2</td>
<td>62.9</td>
<td>-2.4</td>
<td>123</td>
<td>-7.4</td>
<td>51.0</td>
<td>-11.8</td>
<td>36.70</td>
<td>Cool to neutral</td>
</tr>
<tr>
<td>14</td>
<td>63.3</td>
<td>+4.2</td>
<td>95.2</td>
<td>-3.6</td>
<td>55.5</td>
<td>-9.8</td>
<td>102</td>
<td>-10.8</td>
<td>52.4</td>
<td>(-19.9)*</td>
<td>37.04</td>
<td>Neutral</td>
</tr>
<tr>
<td>10</td>
<td>53.1</td>
<td>+8.1</td>
<td>102.5</td>
<td>-8.0</td>
<td>63.2</td>
<td>-10.6</td>
<td>114</td>
<td>-10.8</td>
<td>51.1</td>
<td>-12.6</td>
<td>36.92</td>
<td>Warm to neutral</td>
</tr>
</tbody>
</table>

* The number of observations on this subject basal in air were few.
The mean discrepancy of the cardiac outputs in baths estimated from
the blood pressures from those determined by acetylene was ±14.7 per
cent of the acetylene values.

Cool baths. Six experiments were made on the 4 subjects. Baths
were cooled suddenly to 32°, occasionally to 31°. Baths below 32° were
apt to produce shivering; this interfered with the records and such tem-
peratures were consequently avoided. The mean values obtained are
given in table 1. The oxygen consumption was usually increased con-
siderably during the initial sudden cooling; after this it returned towards
a normal value and occasionally became completely normal or even sub-
normal. The value in the table represents the average level during this
later period. The cardiac output was usually reduced but was occa-
sionally increased by both methods of estimation; the A-V difference was
usually increased. The blood pressures and the value of R were always
raised. The changes in pulse wave velocity were slight, though prob-
ably significant; an increase in the rate in the peripheral vessels accom-
panied cold, while the velocity from the heart to subclavian was reduced
in spite of the rise in blood pressure. The pulse rate was slowed or
showed no change; there was no significant change in the average values
for stroke volumes. The following abbreviated protocols represent the
data on which the mean values are based.

Protocol 1. X/12/34. Subject 4. Weight 43.1 kilos with no measurable weight
loss during the experiment; at 9:30 a.m. entered bath at 35.1°C. The experimental
period was divided into 4 stages: (a) 10:18 a.m. to 10:30 a.m. with bath at initial
temperature of 35.1°C, rectal temperature 37.15°C.; (b) 10:30 a.m. to 10:50 a.m.
when bath temperature accidentally fell slowly to 34.5°, rectal to 37.05°; (c)10:30
a.m. to 12:21 p.m. with bath at 35.1°, rectal temperature at 36.9°; and (d) 12:21 p.m.
to 1:44 p.m., with the bath at 32°, the rectal temperature at first rising to 37.0° (by
12:45 p.m.) and then dropping to 36.7° (by 1:44 p.m.).

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>OXYGEN CONSUMPTION</th>
<th>A-V Diff.</th>
<th>CI (C4H6)</th>
<th>F</th>
<th>CI (Calc.)</th>
<th>S</th>
<th>D</th>
<th>R</th>
<th>PULSE WAVE VELOCITIES</th>
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<td>(a)</td>
<td>—</td>
<td>—</td>
<td>76</td>
<td>2.35</td>
<td>96</td>
<td>58</td>
<td>97</td>
<td></td>
<td>3.1</td>
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<tr>
<td>(b)</td>
<td>—</td>
<td>—</td>
<td>75</td>
<td>2.0</td>
<td>103</td>
<td>65</td>
<td>125</td>
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<td>3.1</td>
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<tr>
<td>(c)</td>
<td>162</td>
<td>51.2</td>
<td>2.4</td>
<td>74</td>
<td>2.4</td>
<td>110</td>
<td>72</td>
<td>106</td>
<td>2.4</td>
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<td>(d)</td>
<td>284</td>
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<td>12:23</td>
<td>153</td>
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<td>12:30</td>
<td>180</td>
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<td>12:37</td>
<td>187</td>
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<tr>
<td>12:44</td>
<td>187</td>
<td></td>
<td>57.9</td>
<td>2.35</td>
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<tr>
<td>12:48</td>
<td>187</td>
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<tr>
<td>1-1:20</td>
<td>1:33</td>
<td>222</td>
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</table>

* Pulse wave velocities assumed to be the same as in period (c).

In this and following protocols the oxygen values represent consumption per
minute estimated from a 6 to 15 minute period. The various symbols used are the
same as those of table 1. Values for blood pressure and pulse wave velocity represent
the mean values of some 4 to 20 estimates.
The experiment demonstrates that a mere fall of bath temperature to 34.5\(^\circ\) (b) greatly increased the blood pressure, though the cardiac output was probably not increased and may have been decreased; the pulse rate was slightly affected. The later fall of temperature (d) increased the A-V difference; oxygen consumption was high during the initial cooling, returned to a normal level, rose again ultimately when the rectal temperature had ceased to rise.

An example may be given where the oxygen consumption was reduced in the cold bath.

**Protocol 2. IX/21/34. Subject 8.** Weight 56.0 kilos, with no measurable weight loss during the experiment; at 10:00 a.m. entered bath at 35.2\(^\circ\)C. The experimental period was divided into 2 stages: (a) from 10:33 a.m. to 12:26 p.m. with bath at initial temperature of 35.2\(^\circ\)C, rectal temperature at 36.55\(^\circ\)C.; and (b) from 12:26 p.m. to 1:32 p.m. bath temperature at 31.9\(^\circ\), rectal temperature at first rising to 36.61\(^\circ\) (by 12.28) but after 12:50 p.m. falling to 36.28\(^\circ\) by the end of the period.

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>(O_2) CONSUMPTION</th>
<th>A-V Diff.</th>
<th>CI (C(_{4})H(_2))</th>
<th>F</th>
<th>CI (Calc.)</th>
<th>S</th>
<th>D</th>
<th>R</th>
<th>PULSE WAVE VELOCITIES</th>
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<tbody>
<tr>
<td>(a)</td>
<td>214</td>
<td>52.1</td>
<td>2.5</td>
<td>52</td>
<td>2.0</td>
<td>106</td>
<td>66</td>
<td>130</td>
<td>3.0 6.4 6.1 10.2</td>
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<tr>
<td>Initial cooling</td>
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<td>185</td>
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<tr>
<td>12:56-1:29</td>
<td>207</td>
<td>66.8</td>
<td>1.76</td>
<td>45</td>
<td>2.05</td>
<td>128</td>
<td>79</td>
<td>144</td>
<td>2.95 6.2 5.5 9.2</td>
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<tr>
<td>1:13</td>
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</table>

The two examples quoted demonstrate that conditions are not stable for oxygen consumption, nor probably for cardiac output, during such a period of cooling. In other experiments the oxygen consumption sometimes showed much greater increases, in one case amounting to 45 per cent.

The mean discrepancy between the cardiac output calculated from that estimated by acetylene was ±11.3 per cent of the acetylene value.

**Warm baths.** There were 18 experiments on the 4 subjects. The maximal increase in rectal temperature was 2.9\(^\circ\), the maximal level 39.8\(^\circ\), the minimal 1.3\(^\circ\) and 38.65\(^\circ\). The rates of change varied between 0.6\(^\circ\) and 3.6\(^\circ\) per hour. The highest bath temperature was 39.5\(^\circ\). The weight loss varied between 1.3 and 5.2 per cent of the body weight; losses of the lower order occurred in the female subjects 4 and 14 and of the higher in the male subjects 8 and 10.

The bath temperature was sometimes allowed to rise gradually but more commonly was initially raised rapidly and was then kept constant. In both cases it was ultimately, with very few exceptions, regulated at a somewhat lower level, such as would maintain a constant rectal temperature (see fig. 4). In some experiments the two modes of heating were
combined. Except in a few cases, where the rate of rise was fast enough to induce hyperpnea, the early symptoms were mild and were only slightly exaggerated by the more rapid changes in temperature. In the later stages the subjects suffered from restlessness, prostration, and air hunger. After the bath subjects 4 and 10 recovered rapidly, except for prolonged thirst in the more dehydrated subject 10; subject 8 had in addition to the thirst a hoarse voice which lasted till the next day; subject 14 showed weakness and a tendency to faint after leaving the bath.

The average effects are shown in table 1. Some abbreviated protocols are also submitted to illustrate the types of reaction. These are chosen from experiments in which the rates of rise of bath and rectal temperature were slow, since these experiments were relatively uniform as far as the temperature changes were concerned, yet the type of response differed.

Protocol 3. VII/15/35. Subject 4. Weight 45.2 kilos with loss of 0.6 kilo (1.3 per cent); at 9:45 a.m. entered bath at 35.1°C. The experimental period was divided into 4 stages: (a) 10:10 to 11:30 a.m. with bath at its initial temperature and rectal temperature 37.1°C; (b) 11:30 a.m. to 1:00 p.m. with bath temperature rising gradually to 37.75°C, and with the subject's rectal temperature rising at 0.68°C per hour and exceeding that of the bath; (c) 1:00 to 1:47 with the bath temperature rising to 38.5°C, with the rectal rising at 0.78°C per hour to 38.35°C and always below that of the bath; (d) 1:47 to 2:10 with bath temperature rising to 38.8°C and the rectal to 38.65°C at a rate 0.84°C per hour.

Protocol 4. XI/7/34. Subject 8. Weight 55.0 kilos with loss of 1.7 kilo (3.1 per cent); at 9:58 a.m. entered bath at 35.2°C. The experimental period was divided into 3 stages; (a) 10:37 to 12:19 p.m. with bath at the initial temperature and rectal temperature 36.95°C; (b) 12:19 to 2:03 p.m. bath temperature rising gradually to 38.85°C, and the subject's rectal temperature rising at 1.05°C per hour to 38.45°C; (c) 2:03 to 2:47 p.m. with bath dropped to 38.3°C and then maintained steady, and rectal temperature rising at first and then remaining steady at 38.65°C.

The stroke volumes were in period (a) 43 cc., in (b) 45 cc., in (c) 36 cc. (mean estimates) and in (d) 32 cc. (calculated estimate).

During period (c) the pulse rate was progressively rising and at the end of the period was 102; the cardiac output was reduced by both methods of estimation; the stroke volume was lowered from 71.5 cc. (mean estimate) in period (a) to 38.5 cc. in period (c).
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Protocol 5. VII/2/35. Subject 8. Weight 56.7 kilos with loss of 1.8 kilo (3.2 per cent); at 9:30 a.m. entered bath at 35.2°C. The experimental period was divided into 4 stages: (a) 10:12 to 11:58 a.m. with the bath at its initial temperature and rectal 36.7°; (b) 11:58 a.m. to 1:22 p.m. with the bath temperature rising gradually to 38.2° and with the subject's rectal rising at 1.35° per hour to 37.7°; (c) 1:22 to 2:06 p.m. with bath temperature rising very slowly to 38.6° and the rectal rising at 1.35° per hour to 38.6; (d) with the bath temperature dropped to and maintained at 38.5° and rectal rising at 0.48° per hour to 38.9°.

The stroke volume in period (a) was 75.5 cc. (mean estimate); in period (d) it was by acetylene 52.0 and by calculation 95.5 cc.

These examples show good agreement between the two methods of estimation of cardiac output in protocols 3 and 4, marked disagreement in protocol 5. Such marked disagreements were not dependent on chance experimental error, for they were never observed in subjects 4 and 10, though obtained consistently in subjects 8 and 14 in experiments made during the summer months. During the winter these discrepancies disappeared, but reappeared the following summer. They were not seen except when the calculated cardiac indices exceeded 3.4 nor marked unless they exceeded 4 liters. In determining the mean discrepancies between the two estimates the data obtained during the summer months are excluded except for data obtained very early during heating, and the discrepancy is then ±12.9 per cent of the acetylene value (13 comparisons). In the summer experiments on subjects 8 and 14 the mean discrepancy was 52.1 per cent in 10 comparisons, with the calculated values always the greater; such experiments account for the discrepancies seen in the last two conditions of table 1. In summer experiments on subjects 4 and 10 on the other hand the mean discrepancy was only ±10.4 per cent, though it is significant that in 6 of the 7 comparisons the calculated values were the higher.

The individual comparisons of the two estimates are shown graphically in figure 1. While there is considerable scatter, no consistent discrepancies are disclosed except in the summer data with warmth (indicated by triangles); these are detectable in both pairs of subjects, though barely so in subjects 4 and 10.

The absence of consistent discrepancies in the earlier stages of heating, whether in summer or winter, is indicated by the composite data of figure...
2, which were obtained by averaging the means of the values for individual subjects. This graph also illustrates the physiological changes observed, and the mean time intervals of their occurrence. Such mean values, however, mask some of the physiological changes, since summer and winter values differed in several respects. Consequently some of the data are regrouped into summer and winter means in table 3, and

Fig. 1. Calculated cardiac outputs per square meter per minute as ordinates plotted against acetylene estimates as abscissae. Values obtained in cold baths are indicated by crosses, in neutral baths by closed circles, in warm baths in winter experiments and very early observations in similar experiments in the summer by open circles. Late observations in warm baths in the summer are indicated for subjects 4 and 10 by closed, for subjects 8 and 14 by open triangles. The lines drawn represent the theoretical correspondence and the limits within which the data should fall if the error of each estimate did not exceed ±0.2 liter per sq. m. per minute; 70 per cent fall within these limits if the summer data on subjects 8 and 14 are excluded.

such differences, as are considered significant, are indicated in the table in italics. The final periods of heating differ in the winter from those in the summer by showing a higher A-V difference, a greater reduction in stroke volume by both methods of estimation, a greater increase in pulse rate, a smaller increase in pulse pressure, and a rise instead of a fall in diastolic pressure. All these changes are such as might accom-
pany commencing circulatory failure as the result of dehydration, yet in the winter experiments the temperature changes were slightly less, and the weight losses also lower.

Though there was agreement between the two methods in these differences, the magnitude of the effect was estimated quite differently. Acetylene indicated a reduction of stroke volume on warming both in the

Fig. 2. From a central zero representing neutral baths at 35° the data obtained, in cold baths to the left and in warm baths to the right, are plotted in relation to time in minutes as abscissae. The values are all composite mean values. Similar means for the subjects basal in air are indicated on the extreme left. For symbols see table 1.

summer and winter except for two experiments in the summer where a temporary increase appeared to be present; one of these two experiments is quoted in protocol 3. On the other hand the stroke volumes calculated from blood pressures usually appeared to be increased slightly in the period of rising temperature during the summer, and to be reduced later on the average only to normal values, while in the winter the stroke volumes were definitely subnormal in both stages. To account for such
discrepancies one of the methods must show a systematic error in the summer experiments; the probable real changes in cardiac output consequently will be discussed later in relation to the validity of the two methods.

The oxygen consumption increased as the body temperature rose, and approximate calculation of the value of the temperature coefficient $Q_{10}$ was possible, since the changes were considerable. Comparison has been made with the data obtained in baths at $35^\circ$, since those obtained at lower temperatures were complicated by a variable metabolic response to cold (see Burton and Bazett, 1936), while the thermal gradients with

<table>
<thead>
<tr>
<th>TABLE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comparison of summer and winter mean values</strong></td>
</tr>
<tr>
<td>Summer experiments (duration 138 minutes); winter experiments (duration 126 minutes)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUMMER</th>
<th>WINTER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bath at $35^\circ$</strong></td>
<td><strong>Period of rising temperature</strong></td>
</tr>
<tr>
<td>Oxygen usage per square meter</td>
<td>120.5</td>
</tr>
<tr>
<td>A-V difference (cc. per liter)</td>
<td>54.2</td>
</tr>
<tr>
<td>Stroke volume (Acet.) (cc. per sq. meter)</td>
<td>37.6</td>
</tr>
<tr>
<td>Stroke volume (Calc.) (cc. per sq. meter)</td>
<td>37.6</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>61.0</td>
</tr>
<tr>
<td>Systolic pressure (S)</td>
<td>100.9</td>
</tr>
<tr>
<td>Diastolic pressure</td>
<td>61.7</td>
</tr>
<tr>
<td>Pulse pressure (lateral)</td>
<td>39.2</td>
</tr>
</tbody>
</table>

In this table all the data are grouped into two periods, one of rising temperature, and the other, when the rectal temperature was nearly constant and the subject was dehydrated, in the ultimate stage of the experiment.

the subjects in air were less uniform. Values so calculated for $Q_{10}$ vary so much that the rectal temperature must provide a very inadequate indication of the changes in mean body temperature, but more consistent and more probable values are obtained if comparisons are made on the basis of average body temperature as estimated from surface and rectal temperatures according to the formula developed by Burton (Burton and Bazett, 1936). If the average data of periods 3 and 6 of table 1 are compared, the values calculated for $Q_{10}$ are 3.95 on a rectal temperature and 2.95 on an average temperature basis. In these periods the subject was approximately in a steady state; if periods 4 and 5 are considered, where this was not the case, $Q_{10}$ values of 5.6 and 6.9 are obtained on a rectal, of 2.3 and 3.2 on an average temperature basis. Even
the individual data agree with a value for \( Q_{10} \) of about 2.9, when hyperpneic reactions did not complicate the issue. The complete data on subject 8, in whom such reactions were minimal, are shown in figure 3; they fall close to a curve for a \( Q_{10} \) of 2.9, if calculations are made on an average temperature basis, though on rectal temperatures values falling between 2.1 and 10.3 with a mean of 5.0 may be calculated. In other subjects, with more irregular oxygen consumption accompanying hyperpnea, occasional individual \( Q_{10} \) values may exceed 6.5 even on an average temperature basis, while calculated from rectal temperatures they may exceed 69.0. During the hyperpneic response to rapidly rising temperatures there appears to be some factor which increases oxy-

![Graph showing oxygen consumption against temperature](http://ajplegacy.physiology.org/)

**Fig. 3.** Oxygen consumptions in cubic centimeter per minute are plotted as ordinates against estimated average body temperatures as abscissae. The points represent all the data in both cold and warm baths for subject 8. The line represents the theoretical values on an average subject if \( Q_{10} = 2.9 \), and its dotted prolongation the probable divergence from this line in an average subject in response to sensations of cold. The extreme values for \( Q_{10} \) for the individual estimates for subject 8 were 1.8 and 4.5 with an average of 2.88.

The changes in *arterial-venous oxygen differences* are indicated in tables 1 and 3 and in figure 2. A reduction in the A-V difference was commonly seen especially in the early stages of the summer experiments. On the other hand there were undoubtedly very high A-V differences present in the terminal stages of winter experiments (reaching in one case on subject 10 to 82.5, a value established by the use of multiple samples). In the middle stages of an experiment when the A-V differences were low (or occasionally high as in protocol 5) the values, whether low or high, are of doubtful accuracy. This will be discussed later.
The blood pressure changes are indicated in tables 1 and 3 and in figure 2. As with A-V differences the changes in diastolic pressure differed in the summer and winter. In both seasons there was a tendency to an initial fall in diastolic pressure, but this was often reversed in the later stages, particularly in the winter experiments (table 3 and protocol 4). Systolic pressures might change in either direction but more commonly rose, especially in the later stages (table 3 but contrast protocol 3). Pulse pressures were increased by warmth, even when, as in winter experiments, there could be little doubt that the stroke volume had been decreased; the increase in pulse pressure was, however, not so great in the winter experiments where the decrease in stroke volume was marked. The increase in pulse pressure accompanying a decrease in stroke volume appeared to be correlated with a decrease in the distensibility of the large vessels, as was indicated by an increase in the pulse wave velocity in these vessels (fig. 2). This increase in pulse wave velocity was particularly marked in the winter experiments (compare protocols 4 and 5), and could not be correlated with changes in blood pressure level for it might occur with either a fall or rise in blood pressure (protocols 3 and 4).

The pulse rate was raised in warm baths. The changes on warming, like those on cooling, preceded changes in rectal temperature and cannot be explained as entirely due to changes in the temperature of the heart, though such changes may be an important factor in the later stages. But the increase in pulse rate on warming did not depend solely on surface temperature, as may be seen in figure 4, which shows the relation of pulse rate changes in two experiments to both bath and rectal temperatures. Even in the later stages it did not depend solely on rectal temperature, for the pulse rate was faster during heating than at the final higher plateau of rectal temperature (table 1 and fig. 4). In the final stages of an experiment with the onset of symptoms of marked dehydration the pulse rate was accelerated (fig. 4 and protocol 4).

DISCUSSION. The validity of the cardiac output estimates. The data presented indicate that the circulatory changes induced by hot baths are not identical in the summer and winter months, though the differences are least marked in estimates of cardiac output by acetylene. Even by this method, however, higher cardiac outputs are indicated in the summer experiments, for cardiac indices of 2.7 or more were obtained in 13 out of 17 summer estimates, while indices of 2.7 were only exceeded on 4 occasions on exposure to heat in the winter. Since the possibility of error from recirculation in the acetylene method is admittedly a function of the circulation time and therefore of cardiac output, it is justifiable to exclude first from consideration the data obtained in the summer, when the cardiac outputs were high. If these be excluded, good agreement is seen between the two methods of estimation, as is indicated by figures 1
and 2, but there is a considerable scatter of the data and chance errors appear to be considerable. This is not surprising since the two estimates could not be made simultaneously and the subject was never in a steady state, while the chance error of either method may readily amount to ±10 per cent. Even in the preliminary baths at 35° the subject had to be propped up and exposed to new temperature conditions during the acetylene procedure. The discrepancies may well depend partly on physiological variables, and the absence of any systematic error may be accepted.

The validity of the acetylene estimates for varying cardiac outputs when the period of sampling extended to 19 seconds has been put to the test by the use of multiple samples, as suggested by Grollman. Some of these data have been already presented (Scott et al., 1935), and indicate that no serious error is introduced within 24 seconds when the cardiac index is 2.2 or less, but that the critical time lies between 19 and 24 seconds with indices slightly exceeding 2.5. In the data there reported for indices below 2.2 the mean values were respectively 1.96 and 1.88 for sampling durations of 19 and 24 seconds, for indices above 2.5 they were 2.65 and 2.24. A duration of 19 seconds appears to be within the critical period for indices below 2.8, for in recent winter experiments samples have been taken after 11 and 16 seconds and compared with others ob-

Fig. 4. The pulse rate changes in two summer experiments are plotted in relation to bath and rectal temperatures. Abscissae indicate the time in minutes from the commencement of warming. The solid lines represent an experiment on subject 4, the dotted lines one on subject 14. Bath temperatures are indicated by the lower curves with closed and open circles, rectal temperatures by crosses. The cardiac indices of subject 4 are indicated above and of subject 14 below; underlined values were obtained by acetylene, the others by calculation.
tained after 14 and 19 seconds of rebreathing. Four such comparisons have been made; the two pairs of samples have been obtained within 15 minutes and the sequence of the tests varied. The mean indices obtained were for the shorter intervals 2.79, for the longer 2.76 and the values calculated from the blood pressures were 2.74. For still higher outputs such times must be too long, and if a high output is associated with a considerable cutaneous circulation and low A-V differences the error introduced by recirculation must make the A-V differences approach the normal, so that there may be no indication that a gross error is present. This has been the case in the longer time intervals, where errors have been evident, both in our data (Scott et al., 1935) and in those of Gladstone (1936). The latter worker finds evidence of appreciable errors even within 12.5 seconds in the high cardiac outputs of hyperthyroidism.

The evidence of Christensen et al. (1933) that high outputs following exercise may apparently be correctly estimated by acetylene is not valid in this connection; after exercise oxygen consumption is high, and decreased acetylene absorption may be balanced by decreased oxygen intake as oxygen tension falls; analyses of alveolar air are not given, so that this balancing of errors cannot be excluded. In the high outputs of pyrexia, with a fast skin circulation, such balancing is less likely to occur.

The levels of the A-V differences and cardiac outputs in the earlier stages of heating, particularly in the summer, are therefore open to question. If the outputs were as high in the summer as those indicated by calculation (attaining an absolute value of about 8 liters per minute in protocol 5) the acetylene procedure used cannot be considered reliable, and gross over-estimates of the A-V differences and under-estimates of the cardiac output may have been made. In favor of such an hypothesis is the fact that the lowest A-V differences and highest cardiac outputs were observed in the few summer experiments in which the sampling periods were kept within 16 seconds. The differences in the blood pressure and pulse rate pictures also throw doubt on the apparent constancy of the stroke volume in the period of rising temperature that is indicated by acetylene in the comparison of summer and winter experiments (table 3). The high outputs with an actual increase in stroke volume indicated in the earlier periods of heating by calculation from the blood pressures are therefore considered tentatively the more probable.

The changes observed in the winter are more certain; here not only are the results of the two methods in agreement, but also the acetylene values may be confirmed by triple sampling. In the summer such triple sampling is more apt to indicate the uncertainty of the values obtained than to establish their accuracy. The difference presumably depends on a real low cardiac output in the winter, one well within the range of the acetylene method. The high A-V differences of protocol 4 (c) were so estab-
lished and are included in the report (Scott et al.) under the heading of subject 3—pyrexia. Similarly the high A-V differences of 82.5 to which reference has already been made was reported under the heading of subject 4—pyrexia; it was obtained in the terminal stages of an experiment accompanied by great restlessness and prostration. Even in subjects 4 and 14, in whom there was little dehydration, higher A-V differences were observed in the winter, though a value of 60 cc. per liter was only once exceeded; in contrast in the summer months the values in these subjects often remained below the initial level. There can be no doubt that in the final periods a fall in cardiac output and rise in the A-V difference develops; this is probably dependent on dehydration which is less readily endured in the winter than in the summer.

The circulatory changes produced by the baths, as estimated on the above assumptions of validity, may be briefly discussed. On immersion in water at a neutral temperature no change in cardiac output is produced through any hydrostatic effect altering venous return, as was suggested by Tigerstedt (1917). Exposure to cold causes peripheral arteriolar constriction, increases the effective resistance, and raises blood pressure. A metabolic reaction follows if the stimulus is adequate, and, where the metabolism is increased, blood flow tends also to rise, though oxygen utilisation is increased. The pulse is slowed reflexly, either directly from sensations of temperature or secondarily as the result of the blood pressure changes; later changes in blood temperature may also affect it. Peripheral arteriolar constriction appears to be associated with dilatation of the large arterial trunks as judged by pulse wave velocities.

Exposure to warmth dilates the peripheral arterioles and lowers the effective resistance and tends to lower mean blood pressure. The latter change is, however, antagonised by an increased cardiac output, which is achieved mainly by an increased pulse rate, though in the summer there may also be an increase in stroke volume. Systolic pressure may be raised, and diastolic lowered; if the pulse rate increase is very great, the latter change is antagonised. In the later stages of heating dehydration occurs and is accompanied by restlessness, a sign of incipient circulatory failure. In attempting to compensate for this condition, in which the low cardiac output is quite out of proportion to the high oxygen consumption, the effective peripheral resistance is increased and there appears also to be constriction of the large arterial trunks as indicated by increased pulse wave velocities (compare the adjustment to splanchnic dilatation, 1936), so that the blood pressure levels are maintained or even raised. Oxygen utilisation is increased and high A-V oxygen differences may be recorded; if one assumes that the circulation through the skin is still maintained at a high level, these values must imply the mixing of this blood with highly unsaturated blood from deeper areas.
There can be little doubt that it is possible for the stroke volume to be decreased some 30 to 50 per cent with no decrease in pulse pressure, or even with an increase of over 20 per cent in this pressure. Pulse pressure is apt to be misleading in regard to stroke volume unless the distensibilities of the vessels are taken into consideration. Division of the pulse pressure by diastolic pressure (Stone, 1915), by mean pressure (Liljestrand and Zander, 1928) or by the square of the systolic pressure (Bazett, 1919) all fail to provide any adequate correction for this factor.

The changes observed are similar in many respects to those described by others, but the marked fall of diastolic pressure is not found; the changes in this pressure were however similar to those observed in anesthetised dogs by Cheer (1928). The cardiac failure following hyperpnea described by Davies and Holmes (1930) was not found, but the conditions for its occurrence were rarely present. The rapid pulse wave velocities at high temperatures did not appear to depend on the more rapid conduction of waves, which had a rapid upstroke (Ranke, 1934), for the changes were often opposite in direction in central and peripheral vessels (protocols 1 and 4 and table 1). The suggestion of Böger and Wezler (1936) that contraction of a vessel makes it more distensible, appears impossible; if this were true, cold must cause relaxation of the brachial and other peripheral large arteries and constriction in the more central aorta (table 1), a most improbable contingency.

The pulse rate changes appear to be mainly reflex in origin, as was suggested by Benson (1934), but they are certainly not determined by the surface temperature alone, nor is it necessary for the surface temperature to exceed that of the rectum (protocol 3), for an effect to be produced. The final result must certainly be modified not only by blood temperature but by reflex effects from the arterial and venous pressure levels. This view as to the relative importance of deep temperature changes and reflex effects reverses the view expressed earlier by Bazett (1931).

**SUMMARY**

1. Comparisons have been made between estimates of cardiac output by the acetylene procedure and by calculation from blood pressures and pulse wave velocities, when the subjects were immersed in cool, neutral or warm baths. In spite of marked changes in the vascular conditions the two methods gave results which indicated the same picture and did not differ from one another on the average by more than ±14.7 per cent, provided that experiments made in the summer months on two subjects be excluded. Normal agreement was obtained in these subjects in the winter.

2. Such systematic discrepancies were only seen when the cardiac outputs estimated from the blood pressures exceeded 3.4 liters per square
TEMPERATURE ON CIRCULATION

meter per minute; it is argued that the cardiac outputs were probably high, and beyond the capacity of the acetylene method with the sampling times used.

3. On such interpretations the cardiac output might be slightly increased or decreased with a slowing pulse in cool baths. It was considerably increased with a larger stroke volume and increased pulse rate in the early stages of warm baths and was reduced to a basal level in spite of a high oxygen consumption in the later stages of warm baths as the result of dehydration. In this latter stage the stroke volume was very small. The subjects were much more susceptible to such dehydration in the winter, so that the initial increase in cardiac output was less marked, and any increase in stroke volume rarely demonstrable.

4. In the terminal stages of winter experiments with warm baths quite high A-V differences (up to 82.5) might be found. In view of the high skin circulation, these must have implied very low saturations in active tissues.

5. In warm baths both systolic and diastolic pressures may be lowered initially, but the fall in diastolic pressure is far less than those commonly described. During incipient circulatory failure following dehydration both pressures tend to be raised.

6. The large arterial trunks show properties which imply their utilization as a blood reservoir; the pulse wave velocity in the ascending aorta is slowed in cool baths when the peripheral arterioles are constricted, quickened in warm baths when these are dilated, and becomes still more rapid as the individual attempts to compensate for dehydration.

7. The pulse pressure may be considerably increased, even when the stroke volume is decreased; such changes depend on decreased distensibility of the large arterial trunks.

8. Pulse rate changes to temperature are not explicable as the simple effect of either surface or rectal temperature changes; the factors involved are complex.

9. The increased oxygen consumption with rise in body temperature cannot readily be related to changes in rectal temperature; if, however, it be compared to changes in average body temperature the data give a value for $Q_{10}$ of about 2.9.

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REFERENCES


Burton, A. C. AND H. C. BAZETT. This Journal 117: 36, 1936.

Cheer, S. N. This Journal 84: 591, 1928.


