Oxygen Tension of Tissues by the Polarographic Method

III. The Effect of Local Heat on the Oxygen Tension of the Skin of Extremities

By ORVILLE HORWITZ, M.D., GEORGE PEIRCE, M.S., AND HUGH MONTGOMERY, M.D.

Simultaneous measurements of skin oxygen tension by polarography and skin temperature by thermocouple were made in patients with peripheral arterial disease and in individuals with normal extremities over a range of skin temperature of 10 to 50 C. The oxygen tension of the skin was found to increase as the skin temperature was raised to about normal body temperature in the ischemic extremity and to a significantly higher temperature in the normal extremity. Possible reasons for these changes are discussed.

Over a period of years various authors have considered the therapeutic effects of environmental temperatures varying from 6 to 38 C. on ischemic extremities. Those who favored the lower temperatures reasoned that lowering the metabolism was the primary consideration, while those favoring the higher temperatures were more impressed with the need of increasing the circulation by means of vasodilatation. Clinically the subjective symptom of pain and the objective sign of skin color are still the criteria by which the environmental therapeutic temperature is regulated.

In polarography we have at our disposal a method of measuring the amount of oxygen available at a given point in the tissue adjacent to the tip of a small platinum electrode. The range of skin temperature within which the greatest amount of oxygen is available can be found by raising skin temperature systematically while measuring skin oxygen tension polarographically. This range may not prove to be optimum therapeutically, but is worthy of consideration. Insofar as the clinically ideal skin temperature range differs from the one giving maximum oxygen availability, an adverse clinical effect of temperature upon other tissue substances than oxygen is implied. The object of this study is to discover the skin temperature range within which oxygen is most available.

Method

Ten subjects with normal extremities and 10 patients with peripheral arterial disease were studied individually. All of the patients had ischemia of the limb as judged by clinical symptoms and as measured by vasodilatation tests. (In each patient at least one pulse was absent to palpation). The leg under observation was placed in a sealed box (fig. 1) in which the air temperature could be regulated from 0 to 60 C. Four platinum electrodes (P) as described by Montgomery and Horwitz were inserted intradermally as shown in P, figure 1. Eight thermocouples for temperature measurement were distributed as follows: four (B and D) on the skin, each within 2 cm. of an inserted electrode; three (C) in the air in the box (A) within 10 cm. of one of the electrodes, and one (E) in the air of the room. All temperature measurements were recorded every two minutes by a Brown potentiometer connected to each thermocouple. The temperature in the box was first lowered until the skin temperature was 10 to 16 C. (fig. 2); then raised 3 degrees at a time until the skin temperature was approximately 50 C. in the case of the normal extremity, or in the case of the ischemic extremity, until intense pain required the withdrawal of the limb from the box, and an end of the study. Temperature was held constant at each new level until a constant oxygen tension was obtained.

The determination of skin temperature by this method must be subject to some error because of the influence of the air temperature as well as the skin temperature upon the thermocouple, and because surface temperature differs slightly from

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OXYGEN TENSION OF TISSUES BY POLAROGRAPHIC METHOD

Fig. 1. Loci of insertion of electrodes and placement of thermocouples for study of right leg. A. Sealed box in which air temperature may be controlled. B. Points on right leg where thermocouples were placed for measurement of skin temperature. C. Points in the air inside the box where air temperature was measured. D. Point on left leg where skin temperature was measured by thermocouple. E. Thermocouple for measuring room temperature. F. Points of intradermal insertion of electrodes for measuring oxygen tension.

Intracutaneous temperature. Such an error must necessarily decrease as the difference between skin temperature and air temperature decreases.

RESULTS

Results Common to Normal and Ischemic Extremities. As the temperature of the skin was lowered from about 35 to about 10 °C, oxygen tension decreased by at least 60 per cent of the original (35 °C.) value. As the skin temperature increased from about 10 °C. to about 50 °C., there was invariably an increase of oxygen tension of the skin by at least 1000 per cent of the value at the lower (10 °C.) temperature. An increase of skin temperature above 38 °C. produced the familiar reddening so ably described by Lewis. In all cases in which the skin temperature was allowed to reach 46 °C. the oxygen tension had started either to diminish or to level off (figs. 3 and 4). As a limb was heated or cooled, changes in oxygen tension appeared to lag behind changes in temperature. The temperature of the skin of the limb in the sealed box tended to remain closer to its original temperature than did the temperature of the air in the box (fig. 2).

Results in Normal Extremities. No normal subjects experienced pain although in most cases skin temperatures were raised to 50 °C. Reversal of oxygen tension invariably occurred at 45 °C.

Fig. 2. Illustrating relationship between skin temperature in sealed box, skin temperature in room air and air temperature inside and outside the sealed box, in the case of subject S. A.
Fig. 3. Illustrating relationship between oxygen tension and temperature of the skin of normal extremities in 8 of the 10 subjects. Oxygen tension readings are expressed on a relative rather than on an absolute basis with 100 representing the maximum value obtained by any one electrode. Standard deviations of similar electrodes (in dead skin) were shown to be slightly less than 10. Each determination was corrected for the physical effect of temperature upon the electrode reading. Skin temperatures below 20°C are not graphed here.

Fig. 4. Illustrating relationship between oxygen tension and temperature of the skin of ischemic extremities in 8 of the 10 patients. Oxygen tension readings are expressed on a relative rather than on an absolute basis with 100 representing the maximum value obtained by any one electrode. Standard deviations of similar electrodes (in dead skin) were shown to be slightly less than 10. Each determination was corrected for the physical effect of temperature upon the electrode reading. Broken arrow, pain first noted; solid arrow, pain unbearable. Skin temperatures below 25°C are not graphed here.

or lower. For statistics of these results see table 1.

Results in Ischemic Extremities. All patients experienced local pain if the temperature of the ischemic area was raised to 39.5°C. The pain invariably became unbearable if the temperature was raised to 45°C. (fig. 4). In half of the patients oxygen tension began to decrease even though some pain was experienced first (fig. 4). However, such reversals were not noted in cases where unbearable pain necessitated cessation of the study. Neither the pain nor the
reversal of oxygen tension were necessarily present in the nonischemic areas to which heat was applied.

**Table 1.—Results Obtained in Normal Subjects and in Patients with Ischemic Extremities**

<table>
<thead>
<tr>
<th>Effects</th>
<th>Number of Subjects</th>
<th>Average skin T. producing effects*</th>
<th>Stand. Dev. of T. producing effects</th>
<th>Average simultaneous T. of air in sealed box</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Oxygen tension reversal in normal subjects (no pain)</td>
<td>10</td>
<td>43.1 (°C.)</td>
<td>0.6 (°C.)</td>
<td>47.9 (°C.)</td>
</tr>
<tr>
<td>2. Oxygen tension reversal in patients with ischemic extremities</td>
<td>5</td>
<td>40.6 (°C.)</td>
<td>0.6 (°C.)</td>
<td>45.3 (°C.)</td>
</tr>
<tr>
<td>3. Occurrence of pain in patients with ischemic extremities</td>
<td>9†</td>
<td>38.9 (°C.)</td>
<td>0.6 (°C.)</td>
<td>44.2 (°C.)</td>
</tr>
<tr>
<td>4. Unbearable pain in patients with ischemic extremities</td>
<td>9†</td>
<td>42.0 (°C.)</td>
<td>0.8 (°C.)</td>
<td>48.1 (°C.)</td>
</tr>
</tbody>
</table>

* Statistically significant difference between Nos. 1 and 2. No statistically significant difference between Nos. 2 and 3.
† In the case of SC (see fig. 4) it became necessary to terminate the study for reasons other than pain.

**Discussion**

These studies indicate that up to a certain temperature, (within one or two degrees of normal body temperature) oxygen tension increases as skin temperature increases. Tissue oxygen tension must depend upon (a) delivery of oxygen to the tissue and (b) utilization of oxygen by the tissue. From our experimental data we can infer that as temperature increases, the delivery of oxygen to the tissue increases at least with skin temperatures up to near normal body temperature. Considering the determinants of skin oxygen tension in more detail we know that:

(A) Oxygen delivery to tissue depends on the following factors:

1. Blood flow to the tissue. Local vasodilatation, and therefore increased blood flow, occurs as a result of heat. The circulation, however, can obviously be increased to a greater extent in normal limbs, than in patients with peripheral arterial insufficiency.

2. Dissociation of oxygen from hemoglobin, which in turn depends on: (a) The saturation of hemoglobin in arterial blood. In all the patients studied the hemoglobin of the arterial blood may be assumed to be 95 per cent saturated with oxygen since none of them had any demonstrable cardiorespiratory disease. (b) Temperature of the peripheral blood. Increase of temperature up to at least 43°C. augments the dissociation of oxygen from hemoglobin. (c) The pH of the peripheral blood. A slight decrease of pH of capillary blood resulting from an increased metabolism [see (B) below] will also augment the dissociation of oxygen from hemoglobin. Hence it is possible that an increase in metabolic utilization of oxygen by the tissue may be in itself a factor favoring the delivery of oxygen.

(B) Utilization of oxygen by the tissue. Tissue metabolism is the main factor in decreasing the available oxygen. Gessler has shown that in vitro metabolism of skin increases as temperature rises from 34°C. to 48°C. He also showed that at 48°C. the metabolism of skin begins to decrease and that at 52°C. metabolism stops. It is entirely possible, however, that increases in metabolism may also be an indirect factor in increasing oxygen tension through the medium of pH changes (above) and other mechanisms as yet unknown.

There is no reason to believe that skin oxygen is lost to environmental air since the tension of oxygen in air is greater than that in skin. One cannot altogether exclude small exchanges of oxygen between skin and subcutaneous tissues. The diffusion of oxygen of air to skin is known to be small in relation to the large increments in skin resulting from increments in skin temperature.

Doubtless all these variables play a part in producing the results shown in figures 3 and 4. However, no quantitation of the separate factors in intact skin is as yet available.

Because of the possible temperature error and the considerable standard deviation of the electrode itself (see Method), we do not intend to establish a specific temperature at which
oxygen tension of the skin ceases to rise in response to local heat, either in the normal or the ischemic extremity. Our data, however, do show that as the temperature of the skin increases as a result of heat applied locally more oxygen is available to skin tissue, until the temperature of the skin is raised to about body temperature in an ischemic extremity or to a significantly higher temperature in the normal extremity.

SUMMARY

1. The oxygen tension of the skin of human extremities was measured over a range of skin temperature from 10 to 50°C.

2. Skin oxygen tension invariably became extremely low when skin temperature was lowered to 15°C.

3. In normal extremities oxygen tension of the skin increased as the skin temperature rose to several degrees above body temperature. Further increases in skin temperature reduced oxygen tension. No pain resulted.

4. In extremities with occluded arteries oxygen tension in the skin increased with rising skin temperatures up to approximately body temperature. Further increases in skin temperature caused pain that prevented continuation of the heat but did not necessarily result in decreased oxygen tension.

5. Maximal oxygen tension of the skin of an extremity made ischemic by arterial occlusive disease results from raising local temperature as high as possible without producing pain.

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