Oxygen Tension of Tissues by the Polarographic Method

II. Detection of Right to Left Shunts by Changes in Skin Oxygen Tension Resulting from Inhalation of Oxygen

By Hugh Montgomery, M.D., Harry F. Zinsser, Jr., M.D., and Orville Horwitz, M.D.

Normal individuals breathing pure oxygen obtain full saturation of their hemoglobin, whereas those with right to left shunts do not. Oxygen hemoglobin dissociation curves indicate that increases to full oxygen saturation of hemoglobin are accompanied by marked increases of the oxygen tension. When breathing oxygen fails to produce full saturation, relatively little change in oxygen tension occurs. When the cutaneous circulation is rapid, changes in skin oxygen tension have been shown to vary directly with changes in blood oxygen tension. Taking advantage of these facts the authors have described a method of detecting significant right to left shunts by polarographic measurements of skin oxygen tension.

IT HAS long been known that right to left shunts lower the arterial oxygen saturation. The essential factors involved in this phenomenon were presented in the Lundsgaard and Van Slyke monograph of 1923. More recently, certain technics such as the exercise test and the test utilizing inhalation of 100 per cent oxygen have been employed in the detection of right to left shunts. In the presence of such shunts, these tests demonstrate changes in the arterial oxygen saturation that are considered diagnostic. The changes in arterial oxygen saturation have been measured either by chemical analysis of arterial blood samples or by use of the oximeter. When the oximeter is used, the necessity for repeated arterial sampling is eliminated, although an initial arterial sample must be analysed to permit standardization of the instrument.

The oxygen inhalation test for the recognition of right to left shunts is based on the failure of patients with such shunts to achieve full arterial oxygen saturation in contrast to nonshunt patients who develop 100 per cent saturation. The nature of the oxygen dissociation curve is such that the increase to 100 per cent oxygen saturation occurring in nonshunt patients, when they inhale oxygen, often involves only a small change in oxygen saturation. For the same degree of change on the curve, oxygen tension measurements would show greater differences. The polarographic method permits estimation of changes in arterial oxygen tension by measurements of oxygen tension in skin having a fast circulation. Therefore, studies were conducted using the polarographic technic to measure the effect of oxygen inhalation on the skin oxygen tension of patients with and without right to left shunts.

Methods

The polarographic method for measuring oxygen tension of skin has been described in detail. In the present study, however, no attempt is made to convert readings to absolute values of oxygen tension in millimeters of mercury. Rather, the results during inhalation of oxygen are expressed simply in terms of percentage increase over the control galvanometric readings obtained during breathing of room air. Measurements were made in duplicate using two electrodes in order to minimize the chance for error resulting occasionally from inactivation of an electrode by extravasated blood at its tip. In each instance, the results recorded from the less actively responding electrode were discarded.

From the Peripheral Vascular and Cardiac Sections of the Robinette Foundation, Medical Clinic, Hospital of the University of Pennsylvania.

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Estimations of cutaneous circulation were made by pyrometric measurements of environmental and skin temperature. In all experiments, the patient was kept warm to assure the fast skin circulation which is necessary to make skin oxygen tension approximate that of arterial blood. In all but one patient the skin temperature of the forearm exceeded the environmental temperature by at least 4 degrees Centigrade.

Oxygen for inhalation was administered as 100 per cent oxygen utilizing a demand valve mask when a good facial fit of the mask was obtainable.

### Table 1.—Patients with Right to Left Shunts

<table>
<thead>
<tr>
<th>Patient, Age and Sex</th>
<th>Diagnosis</th>
<th>Presence of right to left shunt proved by:</th>
<th>Hemoglobin in Grams</th>
<th>% Arterial O₂ Saturation Breathing Air</th>
<th>Temp. Skin °C</th>
<th>Temp. Room °C</th>
<th>Per Cent Rise Skin Oxygen Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. M., 33, Male</td>
<td>Eisenmenger Complex</td>
<td>Angiocardiography Card. Catheterization Circulation times Exercise Test</td>
<td>23.9</td>
<td>78.4</td>
<td>87.5</td>
<td>31.5</td>
<td>26</td>
</tr>
<tr>
<td>J. G., 17, Male</td>
<td>Tetralogy of Fallot</td>
<td>Angiocardiography Circulation times</td>
<td>26</td>
<td>82</td>
<td>86.5</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td>M. S., 9, Male</td>
<td>Multiple defects.</td>
<td>Angiocardiography Card. Catheterization Circulation times</td>
<td>15.5</td>
<td>87</td>
<td>—</td>
<td>31</td>
<td>23.3</td>
</tr>
<tr>
<td>L. A., 17, Female</td>
<td>Tetralogy of Fallot</td>
<td>Angiocardiography Circulation times</td>
<td>22.3</td>
<td>89</td>
<td>—</td>
<td>28.5</td>
<td>23.5</td>
</tr>
<tr>
<td>R. T., 5, Male</td>
<td>Tetralogy of Fallot</td>
<td>Angiocardiography Circulation times</td>
<td>17.7</td>
<td>69</td>
<td>—</td>
<td>31</td>
<td>26</td>
</tr>
<tr>
<td>D. B., 16, Male</td>
<td>Eisenmenger Complex</td>
<td>Angiocardiography Card. Catheterization Circulation times</td>
<td>18.6</td>
<td>77.8</td>
<td>84</td>
<td>31</td>
<td>23</td>
</tr>
<tr>
<td>A. B., 7, Female</td>
<td>Tetralogy of Fallot</td>
<td>Angiocardiography Circulation times</td>
<td>16.8</td>
<td>88</td>
<td>—</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

Otherwise, oxygen was administered through an oronasal B-L-B mask at 15 liters per minute with considerable wastage.

In most of the patients, analyses of arterial oxygen saturation were made before and during inhalation of 100 per cent oxygen, to provide further control of the study. These values were derived from measurements of oxygen content and capacity of blood specimens obtained anaerobically from the brachial or femoral artery. Specimens were analyzed promptly or were kept in ice water for short periods of time before analysis. In most instances a modification of the manometric method of Van Slyke and Neill was used. In a few experiments the spectrophotometric method was employed.

### Investigative Procedure

The patient was permitted to sit, recline, or lie supine according to his comfort. The loose skin of the forearm was then punctured to approximately two-thirds its thickness by a 25 gage needle to facilitate insertion of an electrode through the resulting hole. The fingertips were submerged in the saline bath that completes the circuit. Galvanometric readings were taken until a satisfactory control level was established. The patient then inhaled oxygen for 15 minutes, after which he resumed the breathing of room air. Readings were taken at approximately two minute intervals before, during, and after oxygen inhalation, and continued until such time as they returned to constant values near the control level.

### Subjects

Seven patients who had congenital cardiac disease with right to left shunts were studied. Proof of such a shunt was established beyond...
question in every patient by angiocardiographic demonstration of an overriding aorta,\textsuperscript{12} and into the overriding aorta, and in 2 by the finding of identical right ventricular and systemic

\textbf{Table 2.—Patients without Right to Left Shunts}

<table>
<thead>
<tr>
<th>Patient, Age &amp; Sex</th>
<th>Diagnosis</th>
<th>Hemoglobin in Gm.</th>
<th>% Arterial O₂ Sat. Breathing</th>
<th>Temp. Skin °C</th>
<th>Temp. Room °C</th>
<th>Per Cent Rise Skin O₂ Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. H., 8, Male</td>
<td>Isolated Pulmonary Stenosis</td>
<td>11.7</td>
<td>97.8 (1.46)</td>
<td>30</td>
<td>25</td>
<td>337</td>
</tr>
<tr>
<td>E. S., 22, Female</td>
<td>Atrioseptal Defect</td>
<td>12.8</td>
<td>90.0</td>
<td>30.5</td>
<td>25.5</td>
<td>210</td>
</tr>
<tr>
<td>J. B., 28, Male</td>
<td>Mitral Stenosis with congestive failure</td>
<td>15.2</td>
<td>95.2 (1.50)</td>
<td>31.5</td>
<td>24</td>
<td>180</td>
</tr>
<tr>
<td>D. H., 46, Female</td>
<td>Mitral Stenosis</td>
<td>12.8</td>
<td>96.6 (2.08)</td>
<td>33</td>
<td>24</td>
<td>460</td>
</tr>
<tr>
<td>N. W., 32, Male</td>
<td>Mitral Stenosis with congestive failure</td>
<td>14.9</td>
<td>99.5 (1.91)</td>
<td>29.5</td>
<td>26</td>
<td>100</td>
</tr>
<tr>
<td>C. G., 31, Female</td>
<td>Mitral Stenosis with congestive failure</td>
<td>16.8</td>
<td>—</td>
<td>30</td>
<td>26</td>
<td>712</td>
</tr>
<tr>
<td>M. H., 34, Female</td>
<td>Mitral Stenosis and Polycythemia</td>
<td>18.7</td>
<td>95.4 (1.98)</td>
<td>32.5</td>
<td>27.5</td>
<td>206</td>
</tr>
<tr>
<td>R. R., 16, Female</td>
<td>Mitral Stenosis with congestive failure</td>
<td>12.6</td>
<td>96.6 (1.98)</td>
<td>30.5</td>
<td>25.5</td>
<td>136</td>
</tr>
<tr>
<td>R. Q., 39, Male</td>
<td>Mitral Stenosis with congestive failure</td>
<td>16.1</td>
<td>—</td>
<td>32</td>
<td>24</td>
<td>230</td>
</tr>
<tr>
<td>F. P., 55, Male</td>
<td>Coronary occlusion with cyanosis</td>
<td>12.0</td>
<td>—</td>
<td>31.5</td>
<td>26</td>
<td>500</td>
</tr>
<tr>
<td>V. C., 45, Female</td>
<td>Sarcoidosis with pulmonary fibrosis</td>
<td>16.0</td>
<td>—</td>
<td>30.5</td>
<td>25</td>
<td>250</td>
</tr>
<tr>
<td>J. M., 26, Male</td>
<td>Tuberculosis with pulmonary fibrosis and polycythemia</td>
<td>19.3</td>
<td>91.8 (2.3)</td>
<td>33.5</td>
<td>26</td>
<td>460</td>
</tr>
<tr>
<td>A. T., 66, Male</td>
<td>Silicosis and Pulmonary Emphysema</td>
<td>14.4</td>
<td>94.6 (1.6)</td>
<td>34</td>
<td>26</td>
<td>130</td>
</tr>
<tr>
<td>L. D., 57, Male</td>
<td>Pulmonary Emphysema</td>
<td>14.2</td>
<td>95.4 (2.05)</td>
<td>34</td>
<td>22</td>
<td>150</td>
</tr>
<tr>
<td>G. R., 52, Male</td>
<td>Post-pneumonectomy</td>
<td>10.7</td>
<td>90.0 (1.72)</td>
<td>34.5</td>
<td>26</td>
<td>450</td>
</tr>
<tr>
<td>M. S., 64, Female</td>
<td>Diabetes Arteriosclerosis Cellulitis of toe</td>
<td>13.1</td>
<td>97.9 (1.8)</td>
<td>32</td>
<td>25</td>
<td>480</td>
</tr>
<tr>
<td>M. C., 52, Female</td>
<td>Post-menopausal bleeding</td>
<td>12.1</td>
<td>95.2 (1.8)</td>
<td>29.5</td>
<td>24.5</td>
<td>152</td>
</tr>
<tr>
<td>S. K., 68, Female</td>
<td>Cystocele</td>
<td>12.6</td>
<td>94.9 (1.9)</td>
<td>32</td>
<td>27</td>
<td>366</td>
</tr>
<tr>
<td>C. W., 61, Male</td>
<td>Ganglion right foot</td>
<td>13.6</td>
<td>98.0 (1.8)</td>
<td>31</td>
<td>25</td>
<td>823</td>
</tr>
<tr>
<td>C. S., 51, Male</td>
<td>Thromboangiitis obliterans with gangrene of foot</td>
<td>13.7</td>
<td>—</td>
<td>29</td>
<td>21.5</td>
<td>250</td>
</tr>
</tbody>
</table>

\* The figures in parentheses represent the excess oxygen in volumes per cent after saturation of hemoglobin had been accomplished.

by the finding of circulation times characteristic of such shunts.\textsuperscript{16} In 3 of the patients, additional confirmation was provided during cardiac catheterization: in one when the catheter was passed arterial systolic pressures, indicating dextroposition of the aorta.\textsuperscript{17} (See table 1).

Twenty control subjects not having right to left shunts were chosen from patients in one of
three categories: (a) 5 in whom no cardiac or pulmonary disease was found, (b) 10 with cardiac disease, and (c) 5 with disease primarily involving the lungs.

No systematic study of entirely normal subjects is included here because it was previously shown that oxygen inhalation produced striking elevations of oxygen tension as measured polarographically in the warm skin of normal individuals.11

RESULTS

Measurements of skin oxygen tension during oxygen inhalation showed a sharp difference in response between the controls and the group of patients with right to left shunts. No patient with such a shunt was able to double the preinhalation level of skin oxygen tension at any time during inhalation of oxygen. The greatest rise in this group was a 42 per cent increase with an average rise of 29 per cent. Every patient in the control group, on the other hand, developed levels of skin oxygen tension at least double those of the preinhalation period. The smallest rise in this group was 100 per cent, and the average rise was 314 per cent. The difference between the two groups is so obvious that statistical analysis would be superfluous.

When arterial oxygen saturation was measured before and after oxygen inhalation, all those with right to left shunts failed to become fully saturated, while all those of the control group increased to 100 per cent saturation.

These results are shown in detail in tables 1 and 2.

DISCUSSION

The skin oxygen tension of patients with right to left shunts does not increase in a normal fashion during the inhalation of 100 per cent oxygen. The abnormality in response is so marked as to provide another test for use in the recognition of patients with right to left shunts. This test furnishes certain distinct advantages over other methods employed to detect such shunts: in addition to being objective, it is safer, quicker, requires less cooperation by the patient, eliminates arterial or venous punctures, and causes considerably less discomfort. These advantages are particularly desirable since so many of the patients are children requiring study at an age when other procedures are difficult, at best. The children who have been subjected to this test did not seem to be appreciably disturbed and were content to remain still throughout the procedure.

While all right to left shunts in the present study were intracardiac, extracardiac shunts of right to left type would be expected to give similar results. Thus, the method would in no way differentiate between the right to left shunts of congenital cardiac disease and other conditions permitting significant amounts of unaccredited blood to reach the peripheral circulation.

Certain technical errors can result in measurements simulating the type of response seen in the presence of right to left shunts. Chief among these is inactivation of an electrode by improper insertion or by a drop of blood at its tip. Throughout the study two electrodes were used simultaneously to reduce the chance for such an error. In later work, more electrodes are being used, and this is to be recommended, particularly when the procedure is carried out by a technician. In place of increasing the number of electrodes, the measurements may be repeated using a different site in either arm. The other potential source of error lies in the improper administration of oxygen by a poorly fitting demand valve mask.

In the present study, all the right to left shunts were known to be of significant degree. Smaller shunts might not be detectable.

SUMMARY

1. Polarographic measurements of skin oxygen tension were made during the inhalation of 100 per cent oxygen on patients with proved right to left shunts.

2. The increase in skin oxygen tension of such patients averaged 29 per cent above the preinhalation measurements.

3. This response differed sharply from the significantly greater rise seen in 20 patients without right to left shunts.

4. The method therefore permits detection of right to left shunts of significant degree and
presents certain distinct advantages over other methods.

Acknowledgment
We wish to thank Dr. Julius Comroe in whose laboratory most of the arterial oxygen samples were analyzed. We wish also to thank Dr. Kenneth Marsh and Dr. Morris L. Stroud III who made some of the polarographic studies.

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