Forearm blood flow and metabolism during stylized and unstylized states of decreased activation

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JEVNING, R., A. F. WILSON, J. P. O’HALLORAN, AND R. N. WALSH. Forearm blood flow and metabolism during stylized and unstylized states of decreased activation. Am. J. Physiol. 245 (Regulatory Integrative Comp. Physiol. 14): R110-R116, 1983.—We have measured forearm oxygen consumption and blood flow changes during two wakeful rest behaviors. We have observed acute reduction of forearm respiration (28%) during an acute stylized rest state (TM) and a nonsignificant small decline (11%) during unstylized ordinary eyes-closed rest. These changes were not associated with significant change of forearm blood flow or glycolytic metabolism. Hence, forearm oxygen consumption decline was due almost solely to decreased rate of oxygen extraction. Small variation of forearm blood flow implies that little of the previous findings of increased cerebral blood flow, which therefore is consistent with increased cerebral blood flow. However, reduced muscle metabolism was a likely contributor to the forearm metabolic decline. The lack of coupling between metabolic and blood flow changes during TM indicates limitation of obligatory coupling between cardiovascular and metabolic function in the rest state of TM.

Behavior: relaxation; transcendental meditation technique; muscle and skin blood flow; lactate generation; oxygen consumption

CURRENT UNDERSTANDING of metabolic and cardiovascular changes associated with behavioral states is based primarily on study of states of increased activation such as defense or stress (5, 7, 11, 13), exercise (13, 24, 32), or differing attentional demands (33). In particular, several investigations have focused on limb blood flow (1, 5, 7, 33), metabolism (5), heart rate, and blood pressure (32, 33). Models have been proposed for interrelationship of cardiac and metabolic changes; e.g., Obrist and colleagues (24) have hypothesized that cardiovascular changes represent adjustments of cardiac output and its distribution to meet metabolic demands in most, if not all, behavioral states.

Few cardiovascular and attendant metabolic data exist, however, on states of acutely decreased activation, although regular elicitation of rest-relaxed states is now common (15, 20, 31). For study of cardiovascular and metabolic changes and their interrelationship at this end of the activation spectrum, the mental technique known as “transcendental meditation” (TM) is convenient, since rapid metabolic and cardiovascular changes consistent with decreased activation have been extensively described during this behavior (4, 12, 19, 20, 31), and there exists a relatively large and homogeneous body of individuals who have been regularly eliciting this state twice daily for periods of 30-40 min over the course of several years (31). Practiced while seated comfortably, the technique allegedly requires no physical or mental control and is enjoyable and easily learned (31). Some of the physiological changes previously described include (31), acute decrease of red cell metabolism (17), increased frontal and central alpha activity in the electroencephalograph (4), and acute decline of adrenocortical activity (16); blood pressure and body temperature do not change acutely (31).

A recent study in this laboratory (19) also indicated significant increase (44%) of that fraction of the circulation that is nonrenal and nonhepatic. Hence, although it has been hypothesized that there is a contribution of muscle relaxation and concomitant decline of metabolic rate (12) to the decline of total metabolic rate during rest-relaxation states, the large increase of nonrenal nonhepatic flow (19) suggests the possibility of substantially increased muscle blood flow (19). Because of these conflicting ideas and because direct measurement of metabolic and circulatory activity of muscle during relaxed behavioral states has not been reported, we have studied relative forearm blood flow and oxygen consumption changes during TM. Also, because a comparable decline of total metabolic rate (12) and a small increase (12%) of nonrenal nonhepatic flow have been reported during ordinary unstylized eyes-closed rest-relaxation (19), subsequently denoted as “R,” relative forearm blood flow and oxygen consumption were also measured during this behavior.

Inasmuch as muscle and skin blood flow comprise approximately 25% of nonrenal nonhepatic blood flow at rest, and cerebral blood flow the bulk of the remainder (13), the previously observed increments of nonrenal nonhepatic blood flow were due to significant increases of skin and muscle blood flow (and, possibly, metabolism) and/or increased brain blood flow. The goal of the present research was to determine more precisely the possible specific tissue contributions to the blood flow changes and to the overall decline of metabolic rate noted during these rest states and the relationship between the metabolic and blood flow alterations. The data may also help...
elucidate more precisely the relationship between, and significance of, different means of rest state induction.

METHODS

Arteriovenous difference of oxygen and lactate content and relative change of pulsatile blood flow were monitored in two separate groups of subjects: 32 normal, lean, young adults (10 women, 22 men, ages 25–35) who were long-term practitioners of TM (that is 4–5 yr of regular elicitation for 30- to 40-min periods twice daily) and 25 individuals of similar background (7 women, 18 men, ages 21–32) who had no experience of a stylized relaxation procedure and were studied prior to learning TM. These two groups will be referred to as the TM and R groups, respectively.

As far as possible, subjects were studied at the same time between 10:30 and 12:00 A.M., while comfortably seated in a dimly lit room. To minimize the effect of testing and interaction of testing with practice, an experimental design similar to that recommended by Campbell and Stanley (9) was used in which no pretest is employed. Subjects of each of the two groups were studied on two occasions, approximately 1 wk apart, each subject serving as his or her own control. On one occasion (treatment, T), subjects of the TM group were asked to close their eyes and practice TM for 45 min followed by an eyes-open recovery period of 30 min; analogously, subjects of the R group were asked to close their eyes and simply rest on the treatment occasion for 45 min followed by an eyes-open 30-min recovery period. These treatment observations will be referred to subsequently as either TMT for the TM group or RT for the R group. On the other (control, C) occasion, subjects of each of the two groups were asked to read a “relaxing” work of their own choice for 45 min followed by a recovery period of 30 min without reading. These control observations will be referred to subsequently as either TMC for the TM group or RC for the R group. The sequence of treatment and reading periods was randomized; in this design, significant departure from constancy of physiological values during treatment and posttreatment recovery periods was measured and contrasted with the trends during the parallel reading and postreading occasion. All subjects were told that it was acceptable to sleep during the practice period if that was their tendency.

After catheters were inserted into a brachial artery and a large antecubital vein of one arm from which blood could easily be drawn without use of a tourniquet, measurements were begun after 2 h to allow physiological changes associated with venipuncture (27) to abate. During this time, subjects were comfortably seated in an enclosed space (6 × 6 × 4 ft) and extension lines for blood drawing and leads for monitoring electrophysiological parameters were attached. Unipolar electroencephalogram, electrooculogram, and electromyogram records were monitored and scored according to standard methods (23) in 14 of the TM subjects and 11 of the R group subjects to determine possible contribution of sleep to metabolic or blood flow changes. A 7-ml sample of arterial and a 7-ml sample of venous blood were taken every 15 min throughout practice and postpractice periods (at times 0, 15, 30, 45, 60, and 75 min) for determination of blood gases and lactate. Arterial and venous blood gases were measured with a Radiometer ABL 1 Blood Gas Laboratory (Radiometer, Copenhagen, Denmark); oxygen saturation was calculated from measured Po2, PCO2, and pH by the device. Lactate was determined by a Technicon AutoAnalyzer procedure (14) (Technicon Instrument, Tarrytown, NY). Oxygen content was assumed to be equal to a physically dissolved component (0.003 PaO2 ml/dl blood) plus the product of measured hemoglobin concentration and calculated oxygen saturation (1.34 × hemoglobin × fractional saturation). As a check on the possibility of a shift in the oxygen-hemoglobin saturation curve, which would render calculated saturations erroneous, oxygen saturation was also measured directly in five subjects (American Optical Oximeter II, NY) of each group and compared with calculated values. Finally, in seven subjects, oxygen content was measured directly by gas chromatography (29) and compared with calculated values.

We chose quadrupolar electrical impedance plethysmography (Minnesota Impedance Cardiograph: model 304A, Zoecon, Minneapolis, MN) as the most optimal method for continuous minimally disturbing measurements of relative change of limb blood flow in normal individuals under resting conditions (6, 8, 11, 21, 23, 34). In this technique, electrodes, consisting of 1 mil aluminum bonded to nonallergenic clear plastic tape were placed on the forearm 1, 3, 6, and 8 in. above the wrist. The forearm was comfortably situated at heart level and subjects were asked to move this arm minimally during the course of the experiment. A 1-mA peak-to-peak 100-kHz current was passed through the two outer electrodes and voltage change (due to tissue impedance change) monitored between the two inner electrodes. Quadrupolar, rather than bipolar, electrode measurement system was utilized to minimize electrode artifacts (8, 21, 34). To maximize recording accuracy, the electrical impedance signal as well as the electrocardiogram were recorded either online or on a four-channel Tandberg analog tape recorder (Tandberg of America, Armonk, NY) for subsequent analysis on a PDP 11/34 computer system (Digital Equipment, Maynard, MA). Using the R wave of the electrocardiogram as a trigger for beginning the digitization and storage of each impedance pulse, an average electrical impedance waveform was calculated and displayed for each 5-min interval of the experimental period; the average signals obtained were well defined (see Fig. 1). In this way 15 average electrical impedance waveforms, each corresponding to a complete cardiac cycle, were obtained for the experimental period; for each average waveform, pulse amplitude (ΔZ) and late diastolic slope (from 0.4 to 0.9 s) were then ascertained.

Based upon a model of the limb as a homogeneous electrical conductor, a change in volume (ΔV) of the forearm due to each arterial blood pulse is directly proportional to the accompanying change in electrical impedance (ΔZ). Pulsatile blood flow (PBF) is then proportional to heart rate (HR) and ΔV; i.e., $PBF = k \times HR \times ΔZ$ (11, 23, 34), where k is a function of electrode separation, total electrical impedance, and conductivity of blood. Therefore, the relative pulsatile blood flow
between two times can be calculated from
\[
PBF_2 = \frac{HR_2 \Delta Z_2}{HR_1 \Delta Z_1}
\]
Percent change of relative forearm pulsatile blood is equal to
\[
\left( \frac{HR_2 \Delta Z_2}{HR_1 \Delta Z_1} - 1 \right) \times 100
\]

Equation 2 was utilized to calculate change of pulsatile blood flow from initial value (Figs. 4 and 5), where \( \Delta Z_2 \) was the amplitude of the average impedance pulse measured at each 5-min interval beginning at time 0 min and \( \Delta Z_1 \) was the amplitude of the average pulse for the first 5-min interval. \( HR_2 \) and \( HR_1 \) were the corresponding average heart rates for these same intervals.

An alternative method of calculating limb blood flow change (8) based on the impedance curve was also utilized. This method employs the descending slope in late diastole (from 0.4 to 0.9 s; see Fig. 1); the slope values replace the \( \Delta Z \) terms in Eqs. 1 and 2. On the assumption of zero arterial flow in late diastole, volume changes of the limb during this period are solely due to the difference between inflow and outflow (8). For normal individuals under resting conditions, this assumption is valid, and high correlation of this method of impedance determination of flow with integrated ultrasonic Doppler flow velocity waveform has been demonstrated (8).

Using the Fick principle (14), relative forearm oxygen consumption can be calculated from
\[
(\dot{V}O_2) = (C_{AO_2} - C_{VO_2}) \times PBF
\]
Therefore, percent change of forearm oxygen consumption between any two times is
\[
\left( \frac{(C_{AO_2} - C_{VO_2}) \times PBF_2}{(C_{AO_2} - C_{VO_2}) \times PBF_1} - 1 \right) \times 100
\]

Equation 4 was utilized to calculate percent change of oxygen consumption from initial value (Figs. 2 and 3), where \( (C_{AO_2} - C_{VO_2})_0 \) is the arteriovenous difference of oxygen content measured at 0, 15, 30, 45, 60, and 75 min and \( (C_{AO_2} - C_{VO_2})_1 \) is that measured at 0 min, while \( PBF_2/PBF_1 \) was evaluated from Eq. 1 at these same times. Equation 4 was also employed to calculate percent change of forearm lactate generation rate (Tables 1-4) by substitution of arteriovenous differences of lactate for the oxygen difference terms.
TABLE 1. Mean values, \(P_{aO_2}, P_{vO_2}, S_{aO_2}, S_{vO_2}\), lactate content, and \% change of lactate generation during and after TM in TM group (TMT)

<table>
<thead>
<tr>
<th>Time, min</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
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<tr>
<td>(P_{aO_2}), mmHg</td>
<td>102.2</td>
<td>101.7</td>
<td>102.4</td>
<td>102.5</td>
<td>104.6</td>
<td>104.5</td>
</tr>
<tr>
<td>(\pm 1.2)</td>
<td>(\pm 1.3)</td>
<td>(\pm 2.4)</td>
<td>(\pm 1.4)</td>
<td>(\pm 1.6)</td>
<td>(\pm 1.5)</td>
<td></td>
</tr>
<tr>
<td>(S_{aO_2}), %</td>
<td>96.5</td>
<td>96.4</td>
<td>96.7</td>
<td>96.9</td>
<td>96.9</td>
<td>96.9</td>
</tr>
<tr>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.3)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td></td>
</tr>
<tr>
<td>Lactate (arterial)*, mg/100 ml</td>
<td>(\pm 5.6)</td>
<td>4.3</td>
<td>4.2</td>
<td>4.0</td>
<td>6.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Lactate (venous)*, mg/100 ml</td>
<td>(\pm 0.4)</td>
<td>(\pm 0.7)</td>
<td>(\pm 0.6)</td>
<td>(\pm 0.7)</td>
<td>(\pm 1.0)</td>
<td></td>
</tr>
<tr>
<td>(S_{vO_2}), %</td>
<td>70.3</td>
<td>77.8</td>
<td>77.4</td>
<td>75.3</td>
<td>71.4</td>
<td>66.0</td>
</tr>
<tr>
<td>(\pm 1.5)</td>
<td>(\pm 2.0)</td>
<td>(\pm 1.7)</td>
<td>(\pm 1.8)</td>
<td>(\pm 2.9)</td>
<td>(\pm 3.5)</td>
<td></td>
</tr>
</tbody>
</table>

Values are means \(\pm SE\). \(P_{aO_2}, P_{vO_2}, S_{aO_2}, S_{vO_2}\), arterial and venous \(O_2\) tension and saturation; TM, transcendent meditation. *Significant trends.

TABLE 2. Mean values, \(P_{aO_2}, P_{vO_2}, S_{aO_2}, S_{vO_2}\), lactate content, and \% change of lactate generation during and after reading control in TM group (TMC)

<table>
<thead>
<tr>
<th>Time, min</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{aO_2}), mmHg</td>
<td>100.6</td>
<td>100.4</td>
<td>101.7</td>
<td>99.9</td>
<td>102.4</td>
<td>100.1</td>
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<tr>
<td>(\pm 1.16)</td>
<td>(\pm 1.20)</td>
<td>(\pm 1.67)</td>
<td>(\pm 1.00)</td>
<td>(\pm 1.11)</td>
<td>(\pm 1.00)</td>
<td></td>
</tr>
<tr>
<td>(S_{aO_2}), %</td>
<td>95.8</td>
<td>96.9</td>
<td>96.4</td>
<td>95.2</td>
<td>96.7</td>
<td>95.4</td>
</tr>
<tr>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
<td></td>
</tr>
<tr>
<td>Lactate (arterial), mg/100 ml</td>
<td>6.1</td>
<td>5.4</td>
<td>6.1</td>
<td>5.7</td>
<td>8.1</td>
<td>4.7</td>
</tr>
<tr>
<td>Lactate (venous), mg/100 ml</td>
<td>(\pm 0.7)</td>
<td>(\pm 0.9)</td>
<td>(\pm 0.8)</td>
<td>(\pm 0.7)</td>
<td>(\pm 0.2)</td>
<td>(\pm 0.2)</td>
</tr>
<tr>
<td>(P_{vO_2}), mmHg</td>
<td>46.2</td>
<td>46.1</td>
<td>41.5</td>
<td>43.6</td>
<td>41.5</td>
<td>41.2</td>
</tr>
<tr>
<td>(\pm 2.0)</td>
<td>(\pm 1.6)</td>
<td>(\pm 1.9)</td>
<td>(\pm 1.7)</td>
<td>(\pm 2.0)</td>
<td>(\pm 2.0)</td>
<td></td>
</tr>
<tr>
<td>(S_{vO_2}), %</td>
<td>70.4</td>
<td>72.8</td>
<td>71.4</td>
<td>71.4</td>
<td>73.1</td>
<td>71.2</td>
</tr>
<tr>
<td>(\pm 2.6)</td>
<td>(\pm 1.9)</td>
<td>(\pm 2.5)</td>
<td>(\pm 2.7)</td>
<td>(\pm 2.0)</td>
<td>(\pm 2.0)</td>
<td></td>
</tr>
<tr>
<td>Lactate (venous), mg/100 ml</td>
<td>7.5</td>
<td>7.6</td>
<td>8.5</td>
<td>6.9</td>
<td>6.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Lactate generation, change, %</td>
<td>(\pm 0.7)</td>
<td>(\pm 0.5)</td>
<td>(\pm 0.5)</td>
<td>(\pm 0.3)</td>
<td>(\pm 0.7)</td>
<td>(\pm 0.9)</td>
</tr>
<tr>
<td>(\pm 1.4)</td>
<td>(\pm 3.6)</td>
<td>(\pm 4.2)</td>
<td>(\pm 3.5)</td>
<td>(\pm 0.1)</td>
<td>(\pm 1.6)</td>
<td>(\pm 1.9)</td>
</tr>
</tbody>
</table>

Values are means \(\pm SE\). \(P_{aO_2}, P_{vO_2}, S_{aO_2}, S_{vO_2}\), arterial and venous \(O_2\) tension and saturation; TM, transcendent meditation.

RESULTS

Tables 1–4 show mean values of whole blood arterial and venous oxygen tension, oxygen saturation, lactate, and percent change of lactate generation during the experiment during TMT, RT, TMC, and RC. The major changes noted are significant increases of venous oxygen tension and saturation and significant declines of arterial and venous lactate during TMT (Table 1); the lactate decrease has also been reported previously (19, 31). Figures 2 and 3 show percent change of forearm oxygen consumption and of arteriovenous \(O_2\) content difference from first determination (time 0 min) during TMT, RT, TMC, and RC. Initial mean values (\(\pm SE\)) of arteriovenous difference of oxygen content were 8.86 \(\pm 0.81\) for TMT and 5.23 \(\pm 1.20\) ml/dl blood for RT, at time 0 min. Forearm oxygen consumption declined significantly dur-
the average, 90% of the TM period was spent in wakefulness with the remainder consisting of stage I sleep, while ordinary rest in the R group consisted of 86% wakefulness with the remaining period spent in stage I sleep. No correlation existed between percent total sleep time and forearm oxygen consumption or forearm blood flow changes in either group.

DISCUSSION

In this study, we have found that the hypometabolic state associated with the stylized practice of TM is accompanied by acute decrease of forearm oxygen consumption and no significant change of glycolytic metabolism as manifested by lactate uptake and release. Because blood flow changed minimally, the observed decline of oxygen consumption was due almost entirely to decreased rates of tissue oxygen extraction. The initial mean values of arteriovenous oxygen difference for TM and R groups, 6.86 and 5.23 ml/dl, respectively, are within the range of previously reported values (4.95-7.30 ml/dl) attributed to oxygen extraction by resting forelimb muscle (2, 7). One limitation of the accuracy of pulsatile blood flow change as a measure of change of total limb blood flow is the possible existence of a significant steady-state component of flow into the limb. However, in normal individuals under resting conditions such as existed during this experiment, and with the limb at heart level, a linear relationship exists between pulsatile electrical impedance blood flow determination and direct measurement of total flow by electromagnetic flowmeter has been demonstrated (11).

This study suggests that very little of the previously observed (19) increase of nonrenal nonhepatic blood flow change during TM or ordinary rest could be accounted for by change of muscle and/or skin blood flow and is therefore consistent with preliminary indication of TM-induced increased cerebral blood flow (18). This conclusion assumes that forearm blood flow changes are representative of skin and skeletal muscle blood flow changes in other parts of the body, an assumption supported by comparisons between blood flow changes in arms and calf (5, 32) and comparison between systemic and forearm circulatory changes (1).

The present study does not establish the mechanism by which decreased forelimb oxygen extraction occurs. Electromyographic evidence, however, indicates decreased muscle tone during TM (4), which supports contribution of decreased muscle metabolism in the decline of limb metabolism. Another possibility to explain narrowing of arteriovenous forearm oxygen difference during TM is redistribution of forearm blood flow to less active metabolic sites such as skin. However, estimates of skin blood flow under room temperature conditions, such as apply here, indicate that the skin accounts for only about 15% of forearm blood flow at rest and has about 15% of the metabolic rate of muscle (2, 7). Therefore, skin blood flow would be required to more than triple, and an associated extreme decline in muscle blood flow would be required to account for the observed increase of venous oxygen concentration. Normally, skin
flow is under sympathetic vasoconstrictor control and forearm skin blood flow is little increased by local sympathetic (28); hence, such a large increase of forearm skin blood flow due to a behavioral intervention seems unlikely. Recently, Benson and colleagues reported that, during an advanced Tibetan Buddhist meditation technique, known as g Turmo yoga, practiced for the alteration of body temperature in cool-cold ambient temperatures, finger and forearm temperatures can rise several degrees, possibly by the mechanism of vasodilation (6). However, vasodilation of skin forearm and fingers during the procedure of TM (31), practiced in comfortable room temperature conditions, seems unlikely, because galvanic skin resistance (GSR) measured on the hand increased markedly (31), inconsistent with major increase in skin temperature (22). Additionally, Kanellakos and Lukas (20) reported no consistent change of hand temperature during TM practice, and Bagchi and Wenger (3) noted a 1°C decline of forearm temperature during a yogic meditation technique. Therefore, muscle metabolism apparently declines despite little change of muscle blood flow. This study is therefore consistent with the hypothesis of significant contribution of muscle relaxation to the overall decline of metabolic rate in TM (12).

The finding of 10% stage I sleep during TM and 14% stage I sleep during ordinary rest plus the lack of correlation between sleep time and forearm oxygen consumption do not support a significant contribution of sleep to the physiological effects of TM, in agreement with previous findings in this laboratory (16, 19).

The observed decrease of arteriovenous oxygen difference and, therefore, oxygen consumption (Eq. 3) might also only be apparent, i.e., due to a shift of the oxygen-hemoglobin saturation curve to the right, so that oxygen release was increased greatly. However, such disturbance of normal Po2 saturation relationship seems unlikely, because measured and calculated arterial and venous saturation and content values were almost identical.

REFERENCES