Blood-Gas Changes and Pulmonary Hemodynamics following Acute Myocardial Infarction

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SUMMARY
Arterial and mixed venous oxygen tensions were measured in 24 patients following acute myocardial infarction while they were breathing air and 100% oxygen. Total venous admixture and the right-to-left shunt during 100% oxygen breathing were calculated. These data were related to the pulmonary arterial diastolic pressure, the cardiac index, and the central blood volume.

Patients with myocardial infarction that was not complicated by congestive failure had blood gases, pulmonary shunts, and pulmonary arterial diastolic pressures comparable to control patients who were at rest in bed.

When congestive failure complicated myocardial infarction, arterial blood oxygen tension was lower, pulmonary shunting was increased, and the pulmonary arterial diastolic pressure was elevated. Cardiac index and central blood volume were usually normal.

The present data quantitate the contribution of anatomic shunting to the hypoxemia observed in myocardial infarction. Hypoxemia and increased anatomic shunting are closely correlated to the degree of elevation of pulmonary arterial diastolic pressure. The interrelationships of arterial hypoxemia, venous admixture, arterial-alveolar oxygen gradient, and pulmonary arterial diastolic pressure suggest that pulmonary venous congestion is an important determinant of the hypoxemia and shunting observed in patients with acute myocardial infarction.

Additional Indexing Words: Pulmonary arterial diastolic pressure
Right-to-left shunt in lung
Oxygen breathing
Pulmonary vascular congestion

In the past 5 years, arterial hypoxemia has been recognized as a common occurrence during the first few days of hospitalization after acute myocardial infarction.\(^1\)\(^{10}\) Recently, the magnitude of the hypoxemia has been related to the clinical condition of the patient.\(^10\) Arterial oxygen tension is most abnormal in patients with clinical evidence of heart failure or shock and returns toward normal as the condition improves. Mechanisms postulated for the hypoxemia of myocardial infarction have been lucidly discussed in a recent symposium.\(^11\) Several previous studies have attempted to assess the role of pulmonary shunts in this hypoxemia.\(^1\)\(^{6}\)\(^9\) Included in our concept of anatomic shunts are capillaries which are completely unventilated.

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(e.g., fluid-filled or collapsed), anatomic vascular communications, bronchial venous flow, thebesian venous drainage, and collapsed terminal airways. The extent to which shunting contributes to the total arterial unsaturation has been estimated indirectly from arterial oxygen mixtures. 1-6,9 “Anatomic shunting” may be more precisely measured by administration of 100% oxygen and analysis of mixed venous and systemic arterial blood samples. 10,12 However, in previous studies 100% oxygen has not always been utilized and samples of venous blood from the pulmonary artery were not often obtained. Thus, reported shunt calculations have usually been based on reasonable estimates rather than actual measurements. Furthermore, the blood-gas measurements and calculations of shunt flow have not been correlated with hemodynamic measurements.

In the present study we quantitated the magnitude of right-to-left “anatomic shunting” of blood through the lungs in a group of patients with acute myocardial infarction. Both arterial and mixed venous oxygen tensions were measured before and after the breathing of 100% oxygen. The results have been related to the clinical findings and certain hemodynamic parameters, including the pulmonary arterial diastolic pressure, the cardiac index, and the central blood volume, in an attempt to elucidate some of the interrelationships of pulmonary and cardiovascular derangements which may accompany acute myocardial infarction.

Methods

Blood-gas and hemodynamic data were obtained from 24 patients with definite acute myocardial infarction within 24 hours of their admission to the Myocardial Infarction Research Unit of the New York Hospital. The diagnosis of acute myocardial infarction was established according to criteria previously published. 14 The ages of the patients ranged from 44 to 79 years (mean, 62.7 years). Nineteen were men. In nine of the patients, studies were done on successive days. Five control studies were obtained in four patients hospitalized for investigation of spontaneous angina pectoris. None of these four had clinical evidence of congestive heart failure. Patients on whom the diagnosis of infarction was considered but not proved were not included in either group. None of the patients was grossly obese. All 28 subjects were supine in bed with one or two pillows for comfort during the procedure. Some had received analgesics within 4 hours of our sampling, but all were fully alert and cooperative. No relation was apparent between the level of sedation and the presence of heart failure.

The various maneuvers were carried out in a calm and efficient manner, and the subjects appeared to be in a steady state. The nature and purpose of the study was explained to each patient prior to initiation of the procedures, and informed consent was obtained. The principles of the Declaration of Helsinki were strictly followed.

An indwelling nylon arterial catheter (i.d., 1.0 mm; o.d., 1.4 mm) was inserted via the Seldinger technic. In 19 patients a similar catheter was advanced from an antecubital vein into the pulmonary artery while the intravascular pressure pulse was monitored to substantiate the location of the catheter tip. After insertion of the catheter, the patient relaxed for at least 20 min in order to return to a steady state prior to measurements. Patients were asked to breathe quietly and to refrain from taking deep breaths so that the measurements would better reflect the actual clinical state.

Arterial and mixed venous blood samples were drawn into heparinized plastic syringes while the patient was breathing room air. After administration of 100% oxygen for 20 min, additional samples were obtained. The oxygen was supplied through a mouthpiece and a nonrebreathing valve while the nose was occluded. A 10-inch length of wide-bore rubber tubing was attached to the exhaust limb of the valve to prevent backflow of air through the valve during the initial moments of inspiration.

Blood samples were iced and taken immediately to the laboratory where they were analyzed for oxygen tension, carbon dioxide tension, and pH within 10 min of collection. Determinations were performed with a Radiometer pH meter no. 27 with a gas monitor. The arterial (Pao2) and mixed venous (Pmvco2) oxygen tensions were measured with an oxygen electrode calibrated according to the anticipated oxygen tension: for mixed venous samples a gas mixture with known oxygen tension in the range of 30 to 35 mm Hg was used; for arterial samples during air breathing, the known mixture used was in the range of 80 to 85 mm Hg. For arterial samples obtained during oxygen breathing, calibration was accomplished with humidified oxygen. Selection of the calibrating gas according to the anticipated oxygen tension diminishes the problem of alinearity occasionally encountered with the polarographic method.

Circulation, Volume XLV, March 1972
Ten 5-ml samples of blood exposed to 100% oxygen in a rotating tonometer for more than 30 min and handled exactly as the patients' specimens yielded oxygen tension of 611 ± 21 mm Hg. This result is 102 mm Hg lower than predicted. A value lower than that theoretically postulated for blood oxygen tension when wet gas calibration is used has been found and this finding has been discussed by others.15, 16 The discrepancy is probably due to errors in both handling and measuring samples with high O₂ tensions. We have not attempted to correct for these variable methodologic errors in calculating our results. An approximate correction factor would have reduced the calculated anatomic shunt by less than 1% and the alveolar-arterial O₂ difference (A-aDO₂) by approximately 60 to 100 mm Hg.

The A-aDO₂ was calculated by subtracting the arterial oxygen tension measured during oxygen breathing from the theoretical alveolar oxygen tension. Alveolar oxygen tension was assumed to be equal to the barometric pressure less the combined tensions of alveolar CO₂ (presumed equal to the measured arterial Paco₂) and water vapor at 37.8°C.

Oxyhemoglobin saturation was obtained from a Severinghaus blood-gas calculator* using the measured values for oxygen tension and pH. From the oxygen tension, saturation, and hemoglobin concentration (cyanmethemoglobin method), the total venous admixture while the patient was breathing room air was calculated according to the formula:

\[
\frac{Cc - Ca}{Cc - Cmv} = \frac{Qs}{Q}.
\]

Cc represents the pulmonary end-capillary blood oxygen content. Alveolar oxygen tension was assumed to be 104 mm Hg. Ca and Cmv represent the respective arterial and mixed venous blood oxygen contents. Qs represents the portion of the total cardiac output (Q) that is shunt flow. The anatomic shunt was calculated in the same manner, using the results from the corresponding samples obtained during oxygen breathing.

Pulmonary arterial diastolic pressure (PADP) and cardiac output were measured during quiet air breathing a few minutes subsequent to the oxygen studies. Pressures were measured with a Statham 23 Db transducer. Zero reference level was 10 cm below the sternal angle as determined with a carpenter's spirit level. Cardiac output (CO) was measured by the indicator-dilution method,17 using indocyanine green as an indicator, a Waters X302 Densitometer, and an Electronics for Medicine photographic recorder. Indicator-dilution curves were integrated by manual methods after reploting on semilog paper. The mean of three separate curves was accepted as the output. Central blood volume (cbv), the content of the intravascular space between the pulmonary arterial injection site and the sampling site in the proximal aorta, was calculated from the dye curves by the formula:

\[
\text{cbv} = \frac{\text{arrival time} + \text{mean transit time}}{60} \times \text{CO}.
\]

The results were expressed in relation to the body surface area.18

**Results**

**Blood-Gas Findings**

Results obtained from analysis of blood gases are listed in table 1. Mean arterial oxygen tension while the patient was breathing air was 78 ± 12 (SD) mm Hg in the absence of heart failure but fell to 59 ± 14 mm Hg (P > 0.001), when failure was detected clinically. The decrease in arterial oxygen tension associated with heart failure resulted in a rise in the mean venous admixture (calculated from the data obtained while the patient breathed air) from 12.2 ± 7.8% without congestive failure to 21.2 ± 10.5% (P > 0.05) with it.

Breathing oxygen for 20 min raised the PaO₂ to 528 ± 55 mm Hg in patients without failure. The response to oxygen breathing was significantly lower, 376 ± 104 mm Hg (P > 0.001), when failure was present. As a result, calculated A-aDO₂ was significantly increased in the presence of heart failure, averaging 317 ± 115 mm Hg in the patients with congestion and 138 ± 58 in those without it (P > 0.001). In the patients with pulmonary edema, PaO₂ decreased still further to 221 ± 105 mm Hg. The abnormal response to O₂ breathing associated with heart failure resulted in a significant increase in the calculated anatomic shunt. Thus, the anatomic shunt rose from 5.4 ± 2.9% of the cardiac output in patients at rest in bed without failure to 9.2 ± 3.7% when failure was present (P > 0.02).

The calculated venous admixture is greater than the anatomic shunt. The difference

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*The London Company, Westlake, Ohio.

*Circulation, Volume XLV, March 1972
between these two calculations represents the combined contribution of ventilation-perfusion imbalances and of possible diffusion disturbances to the hypoxemia, and like the anatomic shunt is significantly larger, 13.1 ± 6.5% when failure is present compared to 6.8 ± 5% without failure (P > 0.02).

Data obtained from the five control studies in patients who had coronary artery disease but no evidence of acute infarction or heart failure were not significantly different from those obtained in the 12 patients with acute myocardial infarction and no heart failure.

Mean values for P_{aCO_2} during air breathing was 39.1 ± 3 mm Hg in patients with acute infarction without heart failure compared to 40.3 ± 3 mm Hg in those with congestive failure. Mean arterial pH was also similar in the two groups, averaging 7.42 ± 0.03 without, and 7.41 ± 0.04 with, heart failure. Carbon dioxide tensions in both groups during oxygen breathing were within ±2 mm Hg of the values during air breathing and attest to the steady state of the patients during the present study.

**Hemodynamic Findings**

The hemodynamic data are recorded in table 2. Mean pulmonary arterial diastolic pressure of 8.8 ± 3.6 mm Hg in patients without cardiac failure did not differ significantly from the value observed in patients without infarction. Clinical evidence of heart failure was associated with a significantly higher pulmonary arterial diastolic pressure, 16.6 ± 7.0 mm Hg (P > 0.005). There was no significant difference in pulmonary arterial pulse pressure. The two patients with the highest pulmonary arterial diastolic pressures both went into cardiogenic shock several days after the studies and eventually died.

The cardiac index was nearly identical in patients with and without congestive failure. Calculated central blood volume was significantly higher in patients with failure, 709 ± 186 ml, compared to 560 ± 119 in those without cardiac failure (P > 0.05).

**Hemodynamic and Blood-Gas Relationships**

Arterial oxygen tension, measured while the subjects were breathing room air varied inversely with the pulmonary arterial diastolic pressure. The data for all subjects are plotted in figure 1; the coefficient of correlation is r = −0.78. Although the data are analyzed on the basis of a postulated linear relationship, the plot suggests the possibility of a two-component curve with a break at a pulmonary...
Table 2

Mean Values for Hemodynamic Data

<table>
<thead>
<tr>
<th></th>
<th>No myocardial infarction</th>
<th>Myocardial infarction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No CHF</td>
<td>CHF</td>
</tr>
<tr>
<td>No. of observations</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Pulmonary arterial diastolic pressure (mm Hg)</td>
<td>7.3 ± 1.7</td>
<td>8.8 ± 3.6*</td>
</tr>
<tr>
<td>Pulmonary arterial pulse pressure (mm Hg)</td>
<td>9.0 ± 0.8</td>
<td>13.1 ± 3.7</td>
</tr>
<tr>
<td>Cardiac index (liters/min/m²)</td>
<td>2.05 ± 0.05†</td>
<td>2.76 ± 0.52†</td>
</tr>
<tr>
<td>Central blood volume (ml/m²)</td>
<td>520 ± 2</td>
<td>560 ± 119†</td>
</tr>
</tbody>
</table>

* Difference between means significant, P < 0.005.
† Difference between means significant, P < 0.01.
‡ Difference between means significant, P < 0.05.

Abbreviation: CHF = congestive heart failure.

Arterial diastolic pressure of 15 mm Hg. A similar inverse relationship was observed between the arterial oxygen tension achieved during inhalation of 100% oxygen and the pulmonary arterial diastolic pressure, \( r = -0.85 \) (fig. 2). The calculated anatomic shunt varied directly with the pulmonary arterial diastolic pressure (fig. 3). The largest shunts were recorded in patients with the highest pulmonary arterial diastolic pressure (\( r = 0.71 \)).

The A-aDO₂ (\( r = 0.80 \)) and the venous admixture \( (r = 0.72) \) also were significantly correlated with the pulmonary arterial diastolic pressure. Neither the cardiac index nor the central blood volume could be significantly related to pulmonary arterial pressures.

When congestive heart failure was present, the arterial oxygen tensions achieved during both air and oxygen breathing were lower, while the venous admixture, the anatomic shunt, the alveolar-arterial oxygen gradient, and the pulmonary arterial pressures were higher than in the patients who were not in failure (fig. 4).
Serial Observations

Figure 5 illustrates the serial changes in a patient who was initially studied during cardiogenic shock and gradually improved to recovery on the fourth hospital day. At the time of the initial study, arterial PaO₂ was 43 mm Hg during air breathing and 102 mm Hg during administration of 100% oxygen. As the patient improved clinically, the A-aD₂O gradient gradually fell and the value of PaO₂ rose.

Discussion

Work from this laboratory¹⁰ and by others¹⁻⁹ has established that hypoxemia is a common accompaniment of acute myocardial infarction. Four mechanisms for this hypoxemia have been postulated. These include: (1) decreased alveolar ventilation, (2) ventilation-perfusion imbalances, (3) diffusion abnormalities, and (4) increased pulmonary arteriovenous shunting.

Since arterial carbon dioxide tension is almost always normal or diminished following acute myocardial infarction,¹⁻⁴,¹⁰ it is likely that overall alveolar hypoventilation is not a significant contributor to the hypoxemia, except perhaps in severe cardiogenic shock.¹¹

It has been shown that the ratio of dead space to tidal volume is elevated in most patients with acute myocardial infarction, and

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**Figure 3**

Anatomic shunt plotted in relation to the pulmonary arterial diastolic pressure.

**Figure 4**

Anatomic shunt distributed in accord with the clinical findings of congestive failure. Although there is considerable scatter, note the definite trend toward increased shunting in the presence of congestive failure. Horizontal lines indicate mean values for each group. MI = myocardial infarction; CHF = congestive heart failure.

**Figure 5**

Serial oxygen tensions during progressive recovery from cardiac shock. Plotted are the arterial oxygen tensions, obtained while the patient breathed room air and then 100% oxygen, and the alveolar-arterial gradient. Arterial oxygen tensions rose and the alveolar-arterial gradient decreased as left ventricular failure diminished.
that the physiologic dead space is usually increased.\textsuperscript{1-3} Thus, some portion of the observed hypoxemia is attributable to ventilation-perfusion imbalances.

The presence and importance of diffusion abnormalities remain unsettled. Hardy and associates\textsuperscript{4} reported that steady-state carbon monoxide diffusing capacity was normal following myocardial infarction, even in the presence of congestive failure. On the other hand, Valencia and Burgess\textsuperscript{5} used the single-breath carbon monoxide technic and reported that, when heart failure was not evident clinically, the pulmonary diffusing capacity ($D_{L\text{CO}}$) ranged from 51 to 122\% of predicted value. With congestive failure, $D_{L\text{CO}}$ was between 67 and 100\% of the predicted value for their laboratory. The reasons for these disparate results are not apparent and await clarification.

The contribution of intrapulmonary shunting to the total venous admixture may be quantitated by administering 100\% oxygen.\textsuperscript{12, 13} After a suitable period (usually 10 min is sufficient in the absence of intrinsic lung disease) nitrogen is no longer present in the alveoli, and even the most inadequately ventilated lung units contain $O_2$, $CO_2$, and $H_2O$ vapor. Sampling and analysis of arterial and mixed venous blood allow calculation of the percentage of the blood flow which is shunted from the pulmonary to the arterial circulation without undergoing gas exchange. It is assumed that at this high alveolar oxygen tension there is no appreciable diffusion barrier.\textsuperscript{11, 19}

The present data clearly indicate that anatomic shunting as measured by the administration of 100\% oxygen contributes to the hypoxemia observed in acute myocardial infarction. Furthermore, this shunting is increased when congestive failure and pulmonary edema develop (figs. 3 and 4). These findings are in accord with the results of Higgs,\textsuperscript{2} but they are at variance with those of Sukumalchantra and associates,\textsuperscript{9} who found no difference in the magnitude of shunting in patients with uncomplicated myocardial infarction, those with left ventricular failure, and those in shock. The reasons for these divergent results are not apparent, but may be due in part to the fact that most of the subjects in the latter study did not receive 100\% oxygen and that the samples of mixed venous blood were obtained from the vena cava or right atrium rather than the pulmonary artery. While it is often claimed that the former sampling sites adequately represent mixed venous blood, this has not been documented in acutely ill patients, especially when shock is present.

The method we have employed to determine the magnitude of shunting within the lung does not define the anatomic site(s) of the shuntlike effect. Possibilities include blood perfusing the capillaries of completely unventilated (e.g., fluid-filled) or atelectatic alveoli, anatomic vascular communications, bronchial venous flow, and thebesian venous drainage. We did not measure the effects of deep breathing. This maneuver opens temporarily collapsed terminal airways and would almost certainly have transiently altered arterial blood oxygen. Collapsed airways most likely contribute to the anatomic shunt in the patient with myocardial infarction. However, we attempted to maintain a uniform steady state and did not induce deep breathing.

The analytical errors inherent in collecting and measuring blood samples containing high oxygen tensions total approximately 100 mm Hg. This increases the numerator of the shunt equation by approximately 0.3 ml $O_2$/100 ml of blood and leads to a small (less than 1\%) overestimate of the shuntlike effect. The results do not materially affect the interclass differences that we are reporting. Arterial oxygen tensions achieved in our patients during oxygen breathing are comparable to those reported by others.\textsuperscript{1-6}

Pulmonary arterial end-diastolic pressure is closely correlated with a commonly accepted indicator of left ventricular failure, the left ventricular end-diastolic pressure.\textsuperscript{20} It is somewhat lower than left ventricular end-diastolic pressure measured directly, especially when the latter is greatly increased. In the absence of pulmonary vascular disease, however,

\textit{Circulation, Volume XLV, March 1972}
elevated pulmonary artery diastolic pressure reflects left ventricular dysfunction. Correlation between mean pulmonary arterial wedge pressure and pulmonary arterial diastolic pressure in patients with acute myocardial infarction has been noted by others.\(^{21}\) In our patients the pulmonary arterial pulse pressure was not increased, and it is not likely that changes in pulmonary vascular resistance influenced the relationship between left ventricular and pulmonary arterial pressures.

The correlations between arterial oxygen tensions and pulmonary arterial diastolic pressures both when the subject was breathing air (fig. 1) and oxygen (fig. 2) suggest to us that gas exchange is influenced to a considerable degree by pulmonary venous pressure, even in the absence of clinically recognizable congestive heart failure. We believe that this vascular congestion and the concomitant defects in gas exchange occur as a continuous and interrelated distribution in acute myocardial infarction. A similar correlation, between the arterial oxygen tension and the pulmonary arterial (capillary) wedge pressure, has recently been noted by another group.\(^{21}\)

While the blood-gas measurements were well correlated with the elevation of pulmonary arterial diastolic pressure, cardiac output and central blood volume were poorly correlated with this indicator of ventricular function. Cardiac output depends upon many factors, including metabolic demand, preload, contractility, and afterload. Preload, or ventricular filling pressure, influences pulmonary function, but it is only one of the many factors regulating cardiac performance. It is not surprising, therefore, that the level of blood flow cannot be related to arterial oxygenation.

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