Effect of Hyperoxia on Left Ventricular Function and Filling Pressures in Patients With and Without Congestive Heart Failure*

Susanna Mak, MD; Eduardo R. Azevedo, MD; Peter P. Liu, MD; and Gary E. Newton, MD

Study objectives: To determine the effects of hyperoxia on left ventricular (LV) function in humans with and without congestive heart failure (CHF).

Design: An acute physiologic study of the effect of hyperoxia on right-heart hemodynamics, LV contractility (peak positive rate of rise of LV pressure \([+\text{dP/dt}]\)), time constant of isovolumic left ventricular relaxation \((\tau)\), and LV filling pressures.

Setting: Bayer Cardiovascular Clinical Research Laboratory at the Mount Sinai Hospital, Toronto, Ontario.

Patients: Sixteen patients with stable CHF and 12 subjects with normal LV function received the hyperoxia intervention.

Interventions: Patients received 21% O\(_2\) by a nonrebreather mask, followed by 100% O\(_2\) for 20 min, and 21% O\(_2\) for a 10-min recovery period.

Results: In response to hyperoxia, there was a 22 \pm 6% increase in LV end-diastolic pressure (LVEDP) in the CHF group and a similar 29 \pm 14% increase in LVEDP in the normal LV function group \((p < 0.05\) for both; mean \pm SEM). Hyperoxia was also associated with a prolongation in \(\tau\) of 10 \pm 2\% in the CHF group \((p < 0.05)\) and 8 \pm 2% in the normal LV function group \((p < 0.05)\). No changes in \(+\text{dP/dt}\) were observed in either group.

Conclusions: Hyperoxia was associated with impairment of cardiac relaxation and increased LV filling pressures in patients with and without CHF. These observations indicate that caution should be used in the administration of high inspired O\(_2\) fractions to normoxic patients, especially in the setting of CHF.

(CHEST 2001; 120:467–473)

Key words: congestive heart failure; hyperoxia; ventricular function

Abbreviations: CHF = congestive heart failure; \(+\text{dP/dt}\) = peak positive rate of rise of left ventricular pressure; LV = left ventricular; LVEDP = left ventricular end-diastolic pressure; NO = nitric oxide; ROS = reactive oxygen species; SVR = systemic vascular resistance; \(\tau\) = time constant of isovolumic left ventricular relaxation; \(\tau_l\) = \(\tau\), logarithmic method; \(\tau_{1/2}\) = \(\tau\), pressure half-time method

The administration of high-concentration supplemental oxygen to the point of hyperoxia can be a frequent occurrence in the hospital setting. It has been long appreciated that hyperoxia has adverse consequences in patients with chronic obstructive lung disease or acute respiratory failure, as gas exchange may be worsened by denitrogenation atelectasis and increased intrapulmonary shunting.\(^1,2\) Over the last 50 years, it has also been demonstrated\(^3,4\) that hyperoxia results in hemodynamic alterations, including increased systemic vascular resistance (SVR) and reduced cardiac output. These effects are of specific relevance to patients with congestive heart failure (CHF), a condition with increasing prevalence and representation in the hospital and intensive care setting. Haque et al\(^5\) observed that hyperoxia was also associated with a reduction in stroke volume and an increase in pulmonary capillary wedge pressure in patients with CHF. This fall in stroke volume raised the possibility

*From the Bayer Cardiovascular Clinical Research Laboratory (Drs. Mak, Azevedo, and Newton), Department of Medicine, Mount Sinai Hospital, and The Toronto Hospital (Dr. Liu), University of Toronto, Toronto, Ontario, Canada.

Drs. Mak and Azevedo are Research Fellows of the Heart and Stroke Foundation of the Heart and Stroke Foundation of Canada. This work was supported by a Grant in Aid from the Heart and Stroke Foundation of Ontario (grant No. NA-3469), and by Bayer Canada, Inc.

Correspondence to: Gary E. Newton, MD, Mount Sinai Hospital, 600 University Ave, Room 1614, Toronto, Ontario, M5G 1X5, Canada; e-mail: gary.newton@utoronto.ca
that high-concentration O₂ impaired cardiac function. Importantly, Haque et al.² also demonstrated that the hemodynamic effects of hyperoxia occurred in a dose-dependent fashion and were detectable at inspired O₂ concentrations as low as 40%. These observations highlight the clinical relevance of examining the cardiovascular effects of hyperoxia, especially in the setting of CHF.

This acute hemodynamic investigation explored the effect of high-concentration O₂ on directly measured left ventricular (LV) hemodynamics and isovolumic indexes of LV contractility and relaxation in patients with CHF and subjects with normal LV function. We tested the hypothesis that hyperoxia would impair LV hemodynamics and function in patients with CHF but not in subjects with normal LV function.

**Materials and Methods**

**Study Population**

Thirty-five patients, separated into three groups, participated in this study. The CHF group (n = 16; mean age, 62 ± 2 years; 15 men and 1 woman) all had stable symptoms (New York Heart Association class II and III) and a LV ejection fraction by radionuclide ventriculography of <35% (mean value, 25 ± 2%). This group included 5 patients with idiopathic dilated cardiomyopathy and 11 patients with coronary artery disease. Medical therapy in this group included diuretics (n = 14), angiotensin-converting enzyme inhibitors or angiotensin II-receptor blockers (n = 14), β-blockers (n = 6), calcium channel blockers (n = 4), and nitrates (n = 5). The normal LV function group (n = 12; mean age, 63 ± 2 years; 10 men and 2 women) included subjects with stable coronary artery disease. Normal LV systolic function was documented by two-dimensional echocardiography or quantitative contrast ventriculography. Medical therapy in this group included diuretics (n = 14), digoxin (n = 7), angiotensin-converting enzyme inhibitors or angiotensin II-receptor blockers (n = 14), β-blockers (n = 6), calcium channel blockers (n = 4), and nitrates (n = 5). The normal LV function group (n = 12; mean age, 63 ± 2 years; 10 men and 2 women) included subjects with stable coronary artery disease. Normal LV systolic function was documented by two-dimensional echocardiography or quantitative contrast ventriculography. Medical therapy in this group included diuretics (n = 14), digoxin (n = 7), angiotensin-converting enzyme inhibitors (n = 2), β-blockers (n = 10), calcium channel blockers (n = 6), and nitrates (n = 7). Finally, the normoxia control group (n = 7; mean age, 61 ± 3 years; five men and two women) also included subjects with normal LV function and stable coronary artery disease. Medical therapy in this group included β-blockers (n = 7), calcium channel blockers (n = 2), and nitrates (n = 3). This protocol was approved by the University of Toronto Ethics Review Committee for experimentation involving human subjects. All patients gave written informed consent.

**Cardiac Catheterization Procedure**

Patients were studied in a nonsedated fasting state following a diagnostic heart catheterization from the femoral approach. For the CHF and normal LV function groups, the following catheters were inserted under fluoroscopic guidance: (1) a pulmonary artery catheter, (2) a 7F micromanometer-tipped catheter (Millar Instruments; Houston, TX) in the LV (11 patients in the normal LV function group and 12 patients in the CHF group), and (3) a 7F coronary sinus thermodilution flow catheter (Webster Laboratories; Baldwin City, CA) from an antecubital vein. For the normoxia control group, a 7F micromanometer-tipped catheter was inserted into the LV.

**Study Protocol**

Following catheter placement, a nonrebreather mask was applied and 21% O₂ was administered for 10 min prior to initial measurements (control). The reservoir bag was emptied of residual air, and 100% O₂ was then administered by the same nonrebreather mask for 20 min, at which time repeat measurements were performed (hyperoxia). A final set of measurements was recorded following a 10-min period during which 21% O₂ was again administered (recovery). Subjects in the normoxia control group received 21% O₂ by face mask instead of 100% O₂. Measurements were made at the same time intervals as described above.

**Hemodynamic Measurements**

Measurements of heart rate, systemic BP, right atrial pressure, and pulmonary artery pressure were acquired on a multichannel chart recorder. At each condition, at least 15 cardiac cycles were averaged for the final value. Cardiac output was measured by the thermodilution technique in triplicate. Coronary sinus blood flow measurements were performed in triplicate according to the method of Ganz et al.⁸

**LV Contractility and Relaxation**

LV pressure and its first derivative (rate of rise of LV pressure) [continuous electronic differentiation] were digitally recorded with a sampling rate of 300 Hz. The measure of contractility used in this study was the peak positive rate of rise of LV pressure (+dP/dt). The measure of relaxation used was the time constant of isovolumic LV relaxation (τ̲) (logarithmic method [τ]) and pressure half-time method (τ₁/₂), which was calculated by two independent methods previously described.⁷,⁸ +dP/dt, τ, and LV end-diastolic pressure (LVEDP) were calculated off-line using a customized software program (Labview version 3.0; National Instruments Corporation; Austin, TX) by a technician blinded to other data in the investigation. These methods are established and validated in our laboratory.⁹

**Blood Samples**

Blood from the femoral artery was analyzed for pH, P₅₀₂, and PO₂ by an automated pH/blood gas analyzer (model 865; Ciba Corning Diagnostics; Medfield, MA). Oxygen saturation was determined with a whole-blood oximeter (Oxicom 3000; Waters Instruments; Rochester, MN). Oxygen content was calculated as follows: O₂ saturation × hemoglobin × 1.34 + 0.0031 × PO₂. Arterial and coronary sinus lactate levels were measured at control and during hyperoxia.

**Statistical Analysis**

All data are presented as mean ± SEM. Analysis was performed with a statistical software package (SigmaStat version 1.0; Jandel Scientific Software; San Rafael, CA). Between-group comparisons of baseline characteristics were made using a Student’s t test. Within-group comparisons of the responses to hyperoxia (control, hyperoxia, and recovery) were made with a one-way repeated-measures analysis of variance. The Student-Newman-Keuls test was used post hoc to identify significant pairwise differences. The relationship between τ and LV pressure responses to the hyperoxia stimulus was determined using simple linear regression and a Pearson correlation statistic. A p value < 0.05 was required for statistical significance.
RESULTS

Baseline Characteristics

The CHF group had significantly elevated heart rate and filling pressures, as well as impaired LV contractility and relaxation, compared to the normal LV function group. Baseline arterial O₂ saturation was similar in the two groups (Table 1).

The Effect of Hyperoxia on Hemodynamics, Blood Gases, and Lactate Levels

In the CHF group, the hyperoxia stimulus was associated with several hemodynamic changes, including an increase in SVR, and reductions in cardiac output, stroke volume, and coronary sinus blood flow (p < 0.05 for all; Table 2). In the normal LV function group, hyperoxia was associated with an increase in SVR and a reduction in coronary sinus blood flow (p < 0.05 for both; Table 3). There were no significant changes in cardiac output and stroke volume in the normal LV function group.

The hyperoxia stimulus resulted in the expected increase in the partial pressure of O₂ (78 ± 3 to 358 ± 21 mm Hg in the normal LV function group and 78 ± 4 to 312 ± 17 mm Hg in the CHF group; p < 0.05 for both). There was no increase in the transcardiac lactate gradient during the administration of high inspired O₂ fraction (~0.5 ± 0.1 to ~0.4 ± 0.1 mmol/L in the normal LV function group and ~0.2 ± 0.1 to ~0.5 ± 0.1 mmol/L in the CHF group; p nonsignificant for both), indicating that myocardial ischemia did not occur despite the significant fall in coronary sinus blood flow.

The Effect of Hyperoxia on LV Hemodynamics, Contractility, and Relaxation

There were no significant changes in LV contractility in response to high inspired O₂ fraction in either group, as measured by +dP/dt (Tables 2, 3). Left ventricular systolic pressure increased significantly in the normal LV function group in response to the hyperoxia stimulus. In the CHF group, there was a similar although nonsignificant trend for an increase in LV systolic pressure.

The 20-min hyperoxia stimulus was associated with a significant increase in LV filling pressures and impairment in LV isovolumic relaxation in both the CHF and the normal LV function groups. In response to hyperoxia, there was a 22 ± 6% increase in LVEDP in the CHF group and a 29 ± 14% increase in the normal LV function group (p < 0.05 for both; Tables 2, 3 and Fig 1). Hyperoxia was also associated with prolongation in the time constant of LV τ (both τ₁ and τ₁/2) in the CHF group and in the normal LV function group (Tables 2, 3 and Fig 1). Neither the rise in LVEDP nor the prolongation in isovolumic LV relaxation returned to control values during the recovery period in both groups. There was a relationship between the prolongation of τ and the rise in LVEDP that was highly significant in the CHF group (r = 0.76; p < 0.01) and in the entire population combined (r = 0.75; p < 0.01; Fig 2).

τ has been reported to be dependent on changes in afterload, especially in the setting of CHF. However, there was no relationship between the prolongation in τ (τ₁) and the change in LV systolic pressure in the CHF group (r = −0.13; p = 0.69) or in the normal LV function group (r = −0.08; p = 0.82). Similarly, there was no relationship between the change in τ₁/2 and changes in LV systolic pressure in either group. No relationships between τ and any measure of afterload, including BP and SVR, were observed in either group.

Normoxia Control Group

There were no significant changes in heart rate, BP, +dP/dt, LVEDP, τ₁, or τ₁/2 in the normoxia control group (data not shown).

Discussion

Our study confirmed that hyperoxia causes systemic vasoconstriction and reduces cardiac output. We have expanded these findings by demonstrating...
that hyperoxia is also associated with prolongation in the time constant of isovolumic LV relaxation, $\tau$, and increases in LVEDP. Therefore, our observations suggest that hyperoxia is associated with disturbances of both early and late phases of LV filling. Furthermore, these effects were observed not only in patients with CHF, but also in subjects with normal LV function and coronary artery disease.

The increase in LVEDP suggests impairment of one or more aspects of ventricular filling. The determinants of LV filling are numerous and include ventricular relaxation, diastolic suction, filling volume, distensibility of the ventricular chamber, pericardial restraint, ventricular interaction, and atrial contribution. The observed relationship between the prolongation of $\tau$ and the increase in LVEDP suggests the possibility that impaired relaxation contributed to abnormal LV filling. A potential mechanism by which relaxation was impaired may relate to the generation of reactive oxygen species (ROS). Increased concentrations of ROS, as likely occurred in response to hyperoxia,[13,14] have negative effects on myocardial function,[15–18] and can impair myocyte calcium homeostasis,[19,20] as well as cardiac β-receptor signaling,[21] both of which may prolong ventricular relaxation. By a similar free-radical mechanism, LV distensibility may have been impaired as a result of consumption of endothelial-derived nitric oxide (NO) by ROS in response to hyperoxia. In vitro studies[25] have confirmed that NO and hyperoxia-

<table>
<thead>
<tr>
<th>Variables</th>
<th>Control</th>
<th>Hyperoxia</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, beats/min</td>
<td>$73 \pm 3$</td>
<td>$72 \pm 3$</td>
<td>$74 \pm 4$</td>
</tr>
<tr>
<td>$F_{Asys}$, mm Hg</td>
<td>$139 \pm 7$</td>
<td>$140 \pm 7$</td>
<td>$138 \pm 9$</td>
</tr>
<tr>
<td>$P_{Aidiast}$, mm Hg</td>
<td>$69 \pm 3$</td>
<td>$72 \pm 2$</td>
<td>$70 \pm 3$</td>
</tr>
<tr>
<td>$R_{AP}$, mm Hg</td>
<td>$8 \pm 1$</td>
<td>$9 \pm 1$</td>
<td>$9 \pm 1$</td>
</tr>
<tr>
<td>$F_{Adiast}$, mm Hg</td>
<td>$40 \pm 3$</td>
<td>$40 \pm 4$</td>
<td>$41 \pm 4$</td>
</tr>
<tr>
<td>$P_{Aidiast}$, mm Hg</td>
<td>$18 \pm 2$</td>
<td>$19 \pm 2$</td>
<td>$20 \pm 2$</td>
</tr>
<tr>
<td>$P_{Vr}$, dyne $\cdot$ s $\cdot$ cm$^{-5}$</td>
<td>$185 \pm 24$</td>
<td>$214 \pm 45$</td>
<td>$239 \pm 50$</td>
</tr>
<tr>
<td>Cardiac output, L/min</td>
<td>$4.6 \pm 0.4$</td>
<td>$4.1 \pm 0.3^{*}$</td>
<td>$4.3 \pm 0.3$</td>
</tr>
<tr>
<td>SV, mL/beat</td>
<td>$64 \pm 6$</td>
<td>$57 \pm 5^{*}$</td>
<td>$58 \pm 51$</td>
</tr>
<tr>
<td>SVR, dyne $\cdot$ s $\cdot$ cm$^{-5}$</td>
<td>$1,626 \pm 148$</td>
<td>$1,901 \pm 181^{*}$</td>
<td>$1,715 \pm 177$</td>
</tr>
<tr>
<td>$CSBF$, mL/min</td>
<td>$94 \pm 6$</td>
<td>$72 \pm 8^{*}$</td>
<td>$84 \pm 6$</td>
</tr>
<tr>
<td>LVEDP, mm Hg</td>
<td>$21 \pm 3$</td>
<td>$25 \pm 3^{*}$</td>
<td>$25 \pm 3^{*}$</td>
</tr>
<tr>
<td>LVSP, mm Hg</td>
<td>$123 \pm 6$</td>
<td>$128 \pm 6$</td>
<td>$128 \pm 8$</td>
</tr>
<tr>
<td>$+dP/dt$, mm Hg/s</td>
<td>$1,050 \pm 84$</td>
<td>$1,020 \pm 79$</td>
<td>$1,021 \pm 80$</td>
</tr>
<tr>
<td>$\tau_1$, ms</td>
<td>$60 \pm 3$</td>
<td>$67 \pm 4^{*}$</td>
<td>$68 \pm 3^{*}$</td>
</tr>
<tr>
<td>$\tau_{1/2}$, ms</td>
<td>$46 \pm 1$</td>
<td>$49 \pm 2^{*}$</td>
<td>$49 \pm 2^{*}$</td>
</tr>
</tbody>
</table>

*Data are presented as mean ± SEM. CSBF = coronary sinus blood flow; see Table 1 for definitions of abbreviations. $^{*}$p value < 0.05 vs control.
generated ROS, specifically the superoxide anion, participate in a reaction that results in the rapid degradation of NO. Previous investigators have demonstrated that NO enhances diastolic LV distensibility. These studies, in humans with normal ventricular function, CHF, and pressure overload demonstrated that the local infusion of NO donors resulted in a fall in LVEDP as well as a shift of the diastolic pressure-volume curve to the right, confirming improved LV distensibility. The persistence of impaired diastolic performance following removal of 100% O₂ in the present study is also consistent with animal experiments demonstrating that ROS-mediated impairment in cardiac function persists much longer than the duration of the initial free-radical insult.

Our observations did not suggest that the increase in LVEDP resulted from increased LV diastolic volume as might have occurred if pulmonary blood flow had increased. Although ventricular volumes were not measured in this study, indirect evidence indicated that pulmonary blood flow did not increase, especially in patients with CHF. In this study and that of Haque et al. cardiac output fell while pulmonary vascular tone did not change or tended to increase. Similarly, there was no indication that LV diastolic volume was altered as a consequence of diastolic ventricular interaction and pericardial constraint, since right atrial pressure, which is a reasonable surrogate for pericardial pressure, did not change in response to high-concentration O₂. Both impaired distensibility and impaired relaxation may have been a consequence of myocardial ischemia induced by the observed fall in coronary blood flow.

![Figure 1](http://publications.chestnet.org/pdfaccess.ashx?url=data/journals/chest/21965/)
in response to hyperoxia. However, this is unlikely as there was no decrease in transcardiac lactate extraction, a sensitive index of myocardial ischemia.

The lack of a fall in \( +dP/dt \) in response to high-concentration \( O_2 \) did not confirm our hypothesis that hyperoxia impairs LV contractile function. Of note, any hyperoxia-mediated reduction in \( +dP/dt \) may have been masked by the concurrent increases in LVEDP that would have tended to augment contractility.\(^{28}\) Another interesting possibility is that hyperoxia may have stimulated cardiac myocyte production of angiotensin I, which is converted to angiotensin II in the blood vessels. Angiotensin II is a potent vasoconstrictor, and also stimulates endothelial cells to secrete endothelin, a major positive cardiac inotropic substance.\(^{29}\) This mechanism has been demonstrated\(^{30}\) in isolated cardiac myocytes and could account for both the fall in coronary blood flow, and the preservation in contractility.

The hyperoxia-associated disturbance in LV filling and LVEDP observed in our study may have important detrimental clinical sequela. Supplemental \( O_2 \) is widely used in the treatment of acute and subacute cardiac conditions, such as acute pulmonary edema and unstable coronary syndromes. In an effort to ensure adequate systemic oxygenation,\(^{31}\) the availability of high-flow enriched \( O_2 \) mixtures likely leads to inadvertent hyperoxia, especially in patients without significant pulmonary disease. In patients with CHF, hyperoxia-associated increase in left-heart filling pressures is of specific concern. The contribution of increased LV filling pressures to pulmonary venous hypertension and pulmonary congestion are well known. Although this study only included CHF patients with stable symptoms based on safety considerations, if a similar rise in LVEDP occurs in response to hyperoxia in decompensated patients, this could exacerbate pulmonary congestion. Admittedly, the degree of hyperoxia that occurs in clinical practice is likely less than that observed in this study since supplemental \( O_2 \) is usually administered at concentrations < 100%. However, Haque et al\(^5\) demonstrated in CHF patients that inspired \( O_2 \) concentration > 21% elicited adverse hemodynamic changes in a dose-dependent manner. Similarly, the negative effects of hyperoxia on relaxation and LVEDP may also occur at lower \( O_2 \) concentrations.

There were limitations in this study with respect to the assessment of ventricular relaxation. The prolongation in the time constant of isovolumic LV relaxation, \( \tau \), in response to hyperoxia occurred in both study groups and was significant by two independent methods. However, the interpretation of this observation is confounded by the increase in LV systolic pressure that also occurred in response to hyperoxia. Increases in afterload are associated with slowing of isovolumic LV relaxation,\(^{10,11}\) although observations from the present study suggest that the prolongation in \( \tau \) was not solely due to changes in LV afterload. There were no relationships between the increases in LV systolic pressure, or any other measure of afterload, and the prolongation in \( \tau \). \( \tau \) was also prolonged in the normal LV function group, despite the relative insensitivity of \( \tau \) to changes in afterload in this population.\(^{32,33}\) Indeed, Starling et al\(^32\) administered methoxamine to normal subjects achieving large increases in LV afterload with no changes in \( \tau \). Despite the lack of a “gold standard” with which to assess isovolumic relaxation, the marked increase in LV filling pressures in response to hyperoxia confirms significant impairment of diastolic events.

In summary, the administration of high-concentration \( O_2 \) was associated with a prolongation of isovolumic LV relaxation and an increase in LV filling pressures both in patients with CHF and in subjects with normal LV function. These adverse effects of hyperoxia on hemodynamics and cardiac function indicate that caution should be used in the administration of high inspired \( O_2 \) fractions to normoxic patients, especially in the setting of CHF.

ACKNOWLEDGMENT: The authors thank the staff of the Bayer Cardiovascular Clinical Research Laboratory of the Mount Sinai Hospital, as well as Drs. John Floras and John Parker for review of the article.
REFERENCES


4. Daly WJ, Bondurat S. Effects of oxygen breathing on the heart rate, blood pressure and cardiac index of normal men, resting, with reactive hyperemia and after atropine. J Clin Invest 1962; 41:126–132


13. Fridovich I. The biology of oxygen radicals: the superoxide radical is an agent of oxygen toxicity; superoxide dismutases provide an important defense. Science 1979; 201:875–890


