Pulmonary Hypertension

Oxidative Stress Is Associated With Increased Pulmonary Artery Systolic Pressure in Humans

Nima Ghasemzadeh, Riyaz S. Patel, Danny J. Eapen, Emir Veledar, Hatem Al Kassem, Pankaj Manocha, Mohamed Khayata, A. Maziar Zafari, Laurence Sperling, Dean P. Jones, Arshed A. Quyyumi

Abstract—Oxidative stress contributes to the development of pulmonary hypertension in experimental models, but this association in humans is unknown. We investigated the relationship between pulmonary artery systolic pressure measured by echocardiography and plasma aminothiol oxidative stress markers, with the hypothesis that oxidative stress will be higher in those with pulmonary hypertension. A group of 347 patients aged 65±12 years from the Emory Cardiovascular Biobank underwent echocardiographic assessment of left ventricular ejection fraction and pulmonary artery systolic pressure. Plasma aminothiols, cysteine, its oxidized form, cystine, glutathione, and its oxidized disulphide were measured and the redox potentials (E₅₀) of cysteine/cystine and glutathione/oxidized glutathione couples were calculated. Non-normally distributed variables were log transformed (Ln). Univariate predictors of pulmonary artery systolic pressure included age (P<0.001), sex (P=0.002), mitral regurgitation (P<0.001), left ventricular ejection fraction (P<0.001), left atrial size (P<0.001), diabetes mellitus (P=0.03), plasma Ln cystine (β=9.53; P<0.001), Ln glutathione (β=−5.4; P=0.002), and E₅₀ glutathione (β=0.21; P=0.001). A multivariate linear regression model adjusting for all confounding variables demonstrated that Ln cystine (β=6.56; P=0.007), mitral regurgitation (β=4.52; P<0.001), statin use (β=−3.39; P=0.03), left ventricular ejection fraction (β=−0.26; P=0.003), and age (β=0.17; P=0.003) were independent predictors of pulmonary artery systolic pressure. For each 1% increase in plasma cystine, pulmonary artery systolic pressure increased by 16%. This association persisted in the subgroup with preserved left ventricular ejection fraction (≥50%) and no significant mitral regurgitation. Whether treatment of oxidative stress will improve pulmonary hypertension requires further study. (Hypertension. 2014;63:1270-1275.)

Key Words: cystine ▪ hypertension, pulmonary ▪ oxidative stress

Pulmonary hypertension (PH) is defined as persistent elevation of mean pulmonary artery pressure >25 mm Hg.¹ Although group 1 PH is a rare and progressive life-threatening disease, mild to moderate PH secondary to a variety of cardiac and pulmonary disorders is far more common.² ³ Underlying pathophysiologic changes include pulmonary arterial smooth muscle proliferation, endothelial dysfunction, oxidative stress (OS), and inflammation.⁴ OS is also associated with aging and several chronic ailments, including cardiovascular disease,⁵ diabetes mellitus,⁶ and chronic pulmonary disease.⁷ In experimental models, OS characterized by increased levels of reactive oxygen species contributes to the development of PH and subsequent right ventricular remodeling.⁸ ¹¹ Similarly, increased intracellular calcium flux, mediated by higher OS, leads to smooth muscle contraction and higher pulmonary artery systolic pressure (PASP),¹² and improvement of OS decreases PASP and improves right ventricular dysfunction.⁴ ¹³⁻¹⁵ However, few human studies have explored the link between OS and PH.¹⁶ ¹⁷ Aminothiol compounds play a crucial role in redox signaling and can be quantified in plasma to assess OS burden in vivo.¹⁸ Of these, cysteine constitutes the major extracellular thiol pool, which reacts readily with oxidants to form its disulphide cystine, which is an abundant and sensitive indicator of systemic oxidant burden.¹⁹ Intracellularly, glutathione is a major antioxidant that helps eliminate peroxides and maintain redox state.²⁰ The Nernst equation may be used to calculate the redox potentials of both the glutathione and the cysteine pools. Increased OS, measured as lower levels of glutathione and higher levels of cysteine or a more oxidized redox potential, is associated with cardiovascular disease risk factors, cardiovascular disease, subclinical vascular disease, and importantly with adverse outcomes.²¹⁻²⁸

To investigate the association of plasma aminothiols with PASP, we measured plasma levels of aminothiols and estimated PASP using surface echocardiography, with the hypothesis that increased OS, characterized as a higher cystine level, will be associated with increased PASP in humans.
Methods

Study participants were recruited as part of the Emory Cardiovascular Biobank, consisting of 347 patients aged between 53 and 77 years enrolled before undergoing cardiac catheterization for confirmed or suspected CAD across 3 Emory Healthcare sites between 2004 and 2008. Subjects with connective tissue disease, HIV infection, liver disease, congenital heart disease, sickle cell disease, or other systemic inflammatory conditions were excluded. Patients’ demographic characteristics, medical history, and behavioral (lifestyle) habits were collected on interview. Risk factor prevalence was determined by physician diagnosis and treatment for hypertension, hyperlipidemia, and diabetes mellitus. Smoking was classified as nonsmoker or ever smoked if there was a lifetime history of smoking ≥100 cigarettes. Medical records were reviewed to confirm self-reported history of cardiovascular or pulmonary diseases. The study was approved by the Emory University Institutional Review Committee and all subjects provided informed consent.

Each subject underwent transthoracic echocardiographic assessment of left ventricular ejection fraction (LVEF), mitral regurgitation (MR), left atrial (LA) size, and estimation of PASP. Echocardiographic measurements were all performed according to the American Society of Echocardiography recommendations.29 PASP was estimated using the velocity of the tricuspid regurgitant jet based on the simplified Bernoulli equation (PASP = 4V2 + right atrial pressure), where Vr is the peak velocity of the tricuspid regurgitant jet measured by continuous-wave Doppler.30 Estimation of the severity of MR was performed by assessment of vena contracta using color Doppler echocardiography with values <0.3 mm, corresponding to mild MR, 0.3 to 0.69 mm as moderate MR, and >0.7 mm as severe MR by personnel who were blinded to the OS data. Severity of coronary artery disease was assessed by the Gensini score with 2 operators who independently evaluated all coronary angiograms. This score uses a point system for the degree of luminal narrowing along with a multiplier for specific coronary tree locations, thereby weighting each lesion score for prognostic significance. The total of the lesion scores is summed to give a final Gensini score.31

Measurement of Plasma Aminothiol Levels

Plasma levels of cysteine, its oxidized form, cystine, glutathione, and its oxidized disulphide were measured, and the ratios of cysteine/cystine and glutathione/oxidized glutathione were calculated and expressed as redox potentials, Eh cysteine and Eh glutathione, respectively, where a more oxidized value has a more positive numeric value. Detailed methods for the measurements of aminothiols in plasma have been described previously.34,26,52,33 Briefly, samples were collected directly into specially prepared tubes containing a preservative to retard auto-oxidation, centrifuged, and the supernatant frozen at −80°C, which shows no significant loss for 1 year. Analyses by high-performance liquid chromatography were performed after dansyl derivatization on a 3-aminopropyl column with fluorescence detection. Metabolites were identified by coelution with standards and quantified by integration relative to the internal standards, with validation relative to external standards. Issues of sample collection, stability, analysis, and standardization have been extensively studied, and the method has been used in several clinical studies.34

Statistical Analysis

Means±SD and proportions are used to describe continuous and dichotomous variables, respectively. Spearman correlation test was used to determine bivariate correlations between aminothiols and PASP. Kolmogorov–Smirnov test was used to determine normality. Where data were not normally distributed, natural logarithm (Log) transformation was performed. Multivariate linear regression, including all variables with P≤0.20 in univariate analyses, was used to determine independent predictors of PASP. Regression coefficients are presented as point estimates with 95% confidence intervals. Binary logistic regression was performed to investigate independent predictors of PH as defined by PASP≥50 mm Hg. Only P values ≤0.05 were considered significant. Analyses were performed using the SPSS 20.0 software (SPSS Inc, Chicago, IL).

Results

A total of 347 subjects undergoing coronary angiography, 61% men and mean age 65±12 years, with and without coronary artery disease were enrolled (Table 1). Subjects had multiple risk factors; 15% presented with acute myocardial infarction and 5% had a history of chronic lung disease.

Relationship of Plasma Aminothiols With Cardiovascular Risk Factors

Plasma cystine, glutathione, and Eh glutathione significantly correlated with age (r=0.32, P=0.0001; r=−0.12, P=0.02; and r=0.13, P=0.01, respectively). Patients with diabetes mellitus had significantly higher levels of cystine (117±40 versus 102±29 μmol/L; P=0.0008) and lower glutathione (1.18±0.6 versus 1.3±0.6 μmol/L; P=0.04) when compared with those with non–diabetes mellitus. History of hypertension was associated with higher cystine (112±36 versus 94±22 μmol/L; P=0.0001). We observed no difference in plasma aminothiol levels between men and women.

Plasma cysteine level correlated with glutathione (r=−0.13; P=0.01), cysteine (r=0.39; P<0.001), and Eh glutathione (r=0.17; P=0.01) levels. Plasma aminothiols did not correlate

Table 1. Baseline Characteristics

<table>
<thead>
<tr>
<th>Predictors</th>
<th>All (n=347)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>65±12</td>
</tr>
<tr>
<td>Male sex, %</td>
<td>61</td>
</tr>
<tr>
<td>Black, %</td>
<td>16</td>
</tr>
<tr>
<td>BMI, kg/m2</td>
<td>26±11</td>
</tr>
<tr>
<td>Hypertension, %</td>
<td>71</td>
</tr>
<tr>
<td>Diabetes mellitus, %</td>
<td>34</td>
</tr>
<tr>
<td>Acute myocardial infarction</td>
<td>15</td>
</tr>
<tr>
<td>Smoking, %</td>
<td>12</td>
</tr>
<tr>
<td>Pulmonary disease, %</td>
<td>5</td>
</tr>
<tr>
<td>Statin use, %</td>
<td>70</td>
</tr>
<tr>
<td>β-blocker use, %</td>
<td>71</td>
</tr>
<tr>
<td>Mitral regurgitation, %</td>
<td>84</td>
</tr>
<tr>
<td>Mild</td>
<td>66</td>
</tr>
<tr>
<td>Moderate</td>
<td>23</td>
</tr>
<tr>
<td>Severe</td>
<td>11</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>50±15</td>
</tr>
<tr>
<td>LA size, cm</td>
<td>4.2±0.8</td>
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<tr>
<td>LV hypertrophy, %</td>
<td>15</td>
</tr>
<tr>
<td>Gensini score</td>
<td>52±70</td>
</tr>
<tr>
<td>Cystine, μmol/L</td>
<td>107±23±33.7</td>
</tr>
<tr>
<td>Cysteine, μmol/L</td>
<td>13.4±5.8</td>
</tr>
<tr>
<td>Glutathione, μmol/L</td>
<td>1.27±0.62</td>
</tr>
<tr>
<td>GSSG, μmol/L</td>
<td>0.03±0.03</td>
</tr>
<tr>
<td>Eh glutathione, mV</td>
<td>−136.1±11.7</td>
</tr>
<tr>
<td>Eh cysteine, mV</td>
<td>−75.3±9.1</td>
</tr>
<tr>
<td>CRP, mg/L</td>
<td>9±17.5</td>
</tr>
</tbody>
</table>

Data presented as mean±SD. BMI indicates body mass index; CRP, C-reactive protein; GSSG, oxidized glutathione; LA, left atrium; LV, left ventricular; and LVEF, left ventricular ejection fraction.
with serum C-reactive protein (CRP) levels ($r=-0.01; P=0.77$


to cystine). Relationship Between Aminothiol Markers of OS and PASP

Using linear regression, univariate predictors of PASP included Ln cystine ($P<0.001$), Ln glutathione ($P=0.002$), and Eh glutathione ($P=0.001$) with Ln cysteine ($P=0.06$) trending toward significance (Table 2; Figure 1). In addition, PASP was higher in women ($P=0.005$), in those with MR ($P<0.001$) with a trend toward higher PASP in patients with diabetes mellitus ($P=0.06$). Other univariate correlates of PASP were age ($P<0.001$), LA size ($P<0.001$), and LVEF ($P<0.001$; Table 2).

A multivariate linear regression model that included age, sex, diabetes mellitus, statin use, presence of MR, LVEF, LA size, Gensini score, CRP, as well as Ln cystine, Ln glutathione, and Eh glutathione, revealed Ln cystine ($P=0.007$), MR ($P<0.001$), statin use ($P=0.03$), LVEF ($P=0.003$), and age ($P=0.003$) as independent predictors of PASP (Table 2). Ln cysteine was not included in the multivariate model given its high collinearity with Ln cystine.

Table 2. Univariate and Multivariate Correlates of PASP

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Univariate Linear Regression</th>
<th>Multivariate Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$</td>
<td>$P$ Value</td>
</tr>
<tr>
<td>Age</td>
<td>0.27</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Male sex</td>
<td>$-4.38$</td>
<td>0.005</td>
</tr>
<tr>
<td>Black</td>
<td>1.22</td>
<td>0.55</td>
</tr>
<tr>
<td>Hypertension</td>
<td>0.40</td>
<td>0.81</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>2.94</td>
<td>0.06</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>$-0.007$</td>
<td>0.92</td>
</tr>
<tr>
<td>Acute MI</td>
<td>$-0.68$</td>
<td>0.74</td>
</tr>
<tr>
<td>Smoking</td>
<td>$-2.26$</td>
<td>0.33</td>
</tr>
<tr>
<td>Pulmonary disease</td>
<td>0.33</td>
<td>0.92</td>
</tr>
<tr>
<td>Statin use</td>
<td>$-1.92$</td>
<td>0.20</td>
</tr>
<tr>
<td>$\beta$-blocker use</td>
<td>0.47</td>
<td>0.76</td>
</tr>
<tr>
<td>LA size</td>
<td>4.71</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Mitral regurgitation</td>
<td>5.02</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>LVEF</td>
<td>$-0.26$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Gensini score</td>
<td>0.015</td>
<td>0.18</td>
</tr>
<tr>
<td>CRP, mg/L</td>
<td>0.06</td>
<td>0.18</td>
</tr>
<tr>
<td>Ln cystine, μmol/L</td>
<td>9.53</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Ln cysteine, μmol/L</td>
<td>3.76</td>
<td>0.06</td>
</tr>
<tr>
<td>Ln glutathione, μmol/L</td>
<td>$-5.43$</td>
<td>0.002</td>
</tr>
<tr>
<td>Ln GSSG, μmol/L</td>
<td>0.175</td>
<td>0.87</td>
</tr>
<tr>
<td>Eh cysteine, mV</td>
<td>$-0.03$</td>
<td>0.664</td>
</tr>
<tr>
<td>Eh glutathione, mV</td>
<td>0.219</td>
<td>0.001</td>
</tr>
</tbody>
</table>

BMI indicates body mass index; CRP, C-reactive protein; GSSG, oxidized glutathione; LA, left atrium; LVEF, left ventricular ejection fraction; and MI, myocardial infarction.

Subgroup Analysis

Association of OS Markers With PASP in Patients With Normal LVEF and Insignificant MR

To investigate the effects of OS on PASP without the confounding effects of low LVEF and MR that may also be associated with OS, we analyzed patients with normal LVEF ($\geq$50%) and those free of moderate or severe MR. In this subset of 217 subjects, a multivariate linear regression model controlling for age, sex, diabetes mellitus, statin use, LA size, Gensini, CRP, as well as Ln cystine, Ln glutathione, and Eh glutathione, revealed only Ln cystine as an independent OS marker predicting PASP ($\beta=6.82; P=0.009$). Moreover, Ln cystine was significantly higher in patients with PASP $\geq$50 mm Hg when compared with those with PASP between 26 and 49 mm Hg and those with PASP $\leq$25 mm Hg ($P=0.003$).

Association of OS Markers With PASP in Patients Without Chronic Lung Disease

To investigate whether the observed association of OS markers exists even in those without a diagnosis of chronic lung disease, we excluded these subjects (n=19; 5%). Linear regression model adjusting for the aforementioned variables revealed an independent association between Ln cystine and PASP ($\beta=5.6; P=0.03$) in the remaining subjects.

Discussion

Herein, we report that a higher level of plasma aminothiols, representing nonfree radical OS burden, is associated with higher PASP assessed by echocardiography, independent of other clinical and echocardiographic risk factors, including MR and left ventricular dysfunction. Every 1% increase in plasma cystine level was associated with a 16% increase in PASP independent of other OS, we analyzed patients with normal LVEF ($\geq$50%) and those free of moderate or severe MR. In this subset of 217 subjects, a multivariate linear regression model controlling for age, sex, diabetes mellitus, statin use, LA size, Gensini, CRP, as well as Ln cystine, Ln glutathione, and Eh glutathione, revealed only Ln cystine as an independent OS marker predicting PASP ($\beta=6.82; P=0.009$). Moreover, Ln cystine was significantly higher in patients with PASP $\geq$50 mm Hg when compared with those with PASP between 26 and 49 mm Hg and those with PASP $\leq$25 mm Hg ($P=0.003$).

Inflammatory and oxidative changes are present in the lung vasculature in PH, and patients with systemic inflammatory conditions, such as lupus or scleroderma, are at risk for PH. Patients with established PH have upregulation of inflammatory mediators, such as intracellular adhesion molecule-1 and endothelial leukocyte adhesion molecule-1, and anti-inflammatory therapy has been invariably associated with decreases in PASP in experimental models.

The putative role of OS in the pathophysiology of PH is supported by experimental data. Remin overexpressing rats have higher intrapulmonary NADPH oxidase activity and higher right ventricular systolic pressure. Conversely, reduction in NADPH oxidase activity in the gp91(phox) knockout mice decreases hypoxia-induced generation of reactive oxygen species and abolishes pathophysiological changes in the pulmonary artery. Furthermore, xanthine oxidase–mediated increase in reactive oxygen species expression in neonatal rats...
exposed to chronic hypoxia has been shown to result in PH. In lung tissues from patients with pulmonary arterial hypertension, increased nitrotyrosine and 8-hydroxyguanosine activities have been noted. Finally, in a murine model of PH, lower superoxide dismutase (SOD2) activity was reported, findings similar to those observed in lung tissue harvested from patients with PH at autopsy. Increased proliferation of pulmonary artery smooth muscle cells was ameliorated by SOD2 augmentation. These data along with our findings of an independent association of OS markers with PASP, even in early stages of PH, suggest a pathophysiologic role for OS in the development of human PH.

Plasma aminothiols are reliable measures of systemic oxidative burden, with glutathione representing intracellular and the cysteine/cystine pools reflecting extracellular oxidative burden. Although we did not observe any significant independent association with glutathione or its redox potential, Eh glutathione—the oxidized disulfide cystine—was independently associated with PASP.

We have previously shown that aminothiol markers of OS are associated with cardiovascular risk factors, including hypertension, endothelial dysfunction, increased systemic arterial stiffness, increased carotid wall thickness, even in relatively healthy subjects without risk factors, and with worse long-term outcomes. This study extends our findings to hypertension in the pulmonary circulation. To ensure that risk factors for atherosclerosis were not responsible for our observed association, we controlled for all known and measured risk factors, including medications, and found that the association of PASP with OS persisted. Similarly, we adjusted for the presence of significant MR, left ventricular dysfunction, and significant coronary artery disease, all known to be associated with PH. Thus, even in the subset with absence of significant MR and left ventricular dysfunction, plasma cystine was a predictor of PASP independent of other risk factors, including systemic inflammation, measured as plasma CRP level. A PASP of 38 mm Hg is considered the best discriminatory cutoff value, corresponding to mean pulmonary artery pressure of 25 mm Hg for diagnosis of PH. We chose a higher cutoff of 50 mm Hg in this study to reduce the potential of false-positive high PASP readings with echocardiography further. We found that plasma cystine is significantly higher in those with PASP ≥50 mm Hg than those with PASP <25 and PASP between 26 and 49 mm Hg.

Despite a large body of evidence on the association of OS with PH especially in animal models, it remains uncertain whether antioxidant therapy would be a useful therapeutic modality in patients with PH. This may have been partly secondary to the lack of well-designed randomized controlled clinical trials with therapies targeted to OS pathways because almost all studies to date have investigated the effect of non-targeted antioxidant compounds in experimental models of PH with overall mixed results.

Future studies need to validate our results and investigate whether plasma cystine can predict PH and be used to monitor the severity of the disease.

**Strengths and Limitations**

This is the first study to demonstrate an independent association between readily available plasma markers of systemic oxidant stress and PASP.

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**Figure 1.** Relationship between aminothiol levels and pulmonary artery systolic pressure (PASP). A–C, Bivariate correlations of PASP with Ln cystine, Ln glutathione, and Eh glutathione, respectively.

**Figure 2.** Differences in aminothiol levels in subjects with normal pulmonary artery systolic pressure (PASP; ≤25 mm Hg), and mild or moderate pulmonary hypertension.
OS with PASP. A limitation of our study is the potential inaccuracy in measuring PASP with echocardiography. However, it remains the most widely used method for noninvasive screening of PH that is highly correlated with direct pressure measurements during right heart catheterization with a pooled sensitivity and specificity of 83% and 72%, respectively.\textsuperscript{43,47,48} We may have underestimated the prevalence of chronic lung disease because this diagnosis was obtained from the history and chart review. Nonetheless, the independent association between PASP and cystine persisted even after excluding subjects with chronic lung disease. We acknowledge that findings from this study might not be generalizable to all subcategories of PH.\textsuperscript{49}

**Conclusions**

Increased plasma OS burden, estimated as increased circulating levels of cystine, is associated with increased PASP.

**Perspectives**

In this study, we have shown for the first time that novel plasma aminothiol markers of OS are associated with PASP independent of traditional cardiovascular risk factors, as well as the presence of chronic lung disease, significant MR, and depressed left ventricular systolic function. Whether treatment of PH can be monitored using aminothiol markers and whether targeted treatment of OS that normalizes aminothiol levels will improve PH requires further investigation. Future studies are also needed to investigate the association of these aminothiol markers with PASP in different subcategories of PH.

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**Disclosures**

None.

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**Novelty and Significance**

**What Is New?**

- To our knowledge, this is the first study in humans to investigate the association between readily measurable plasma markers of systemic oxidative stress and pulmonary hypertension. Every 1% increase in plasma cysteine level was associated with a 16% increase in pulmonary artery systolic pressure.

**What Is Relevant?**

- Whether these measurements can be used to titrate therapy and whether antioxidants that normalize amino acid levels will be therapeutic for pulmonary hypertension needs to be investigated.

**Summary**

Plasma cysteine is associated with pulmonary artery systolic pressure independent of other risk factors and even in those with normal left ventricular systolic function and no significant mitral regurgitation.
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