RC time constant of single lung equals that of both lungs together: a study in chronic thromboembolic pulmonary hypertension

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1Department of Pulmonary Diseases and 2Department of Physics and Medical Technology, Institute for Cardiovascular Research, VU University Medical Center, Amsterdam; 3Department of Physiology, VU University, Amsterdam; 4BMEYE, Academic Medical Center, University of Amsterdam, Amsterdam, The Netherlands; and 5Laboratory of Hemodynamics and Cardiovascular Technology, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

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Saouti N, Westerhof N, Helderman F, Marcus JT, Stergiopulos N, Westerhof BE, Boonstra A, Postmus PE, Vonk-Noordegraaf A. RC time constant of single lung equals that of both lungs together: a study in chronic thromboembolic pulmonary hypertension. Am J Physiol Heart Circ Physiol 297: H2154–H2160, 2009. First published October 2, 2009; doi:10.1152/ajpheart.00694.2009.—The product of resistance, R, and compliance, C (RC time), of the entire pulmonary circulation is constant. It is unknown if this constancy holds for individual lungs. We determined R and C in individual lungs in chronic thromboembolic pulmonary hypertension (CTEPH) patients where resistances differ between both lungs. Also, the contribution of the proximal pulmonary arteries (PA) to total lung compliance was assessed. Patients (n = 23) were referred for the evaluation of CTEPH. Pressure was measured by right heart catheterization and flows in the main, left, and right PA by magnetic resonance imaging. Total, left, and right lung resistances were calculated as mean pressure divided by mean flow. Total, left, and right lung compliances were assessed by the pulse pressure method. Proximal compliances were derived from cross-sectional area change ∆A and systolic-diastolic pressure difference ∆P (∆A/∆P) in main, left, and right PA, multiplied by vessel length. The lung with the lowest blood flow was defined “low flow” (LF), the contralateral lung “high flow” (HF). Total resistance was 0.57 ± 0.28 mmHg·s⁻¹·ml⁻¹, and resistances of LF and HF lungs were 1.57 ± 0.2 vs. 1.00 ± 0.1 mmHg·s⁻¹·ml⁻¹, respectively, P < 0.0001. Total compliance was 1.22 ± 0.11 ml/mmHg, and compliances of LF and HF lung were 0.47 ± 0.11 and 0.62 ± 0.12 ml/mmHg, respectively, P = 0.01. Total RC time was 0.49 ± 0.2 s, and RC times for the LF and HF lung were 0.45 ± 0.2 and 0.45 ± 0.1 s, respectively, not different. Proximal arterial compliance, given by the sum of main, right, and left PA compliances, was only 19% of total lung compliance. The RC time of a single lung equals that of both lungs together, and pulmonary arterial compliance comes largely from the distal vasculature.

Compliance: pulmonary hypertension; resistance and capacitance time; resistance

In contrast to the systemic circulation, in the pulmonary circulation compliance (C) and resistance (R) were shown to be inversely related in health and in various types of pulmonary hypertension i.e., their product, RC time, is constant for both lungs together (17, 19, 23). This means that, in patients with low resistance, compliance is high and vice versa. Why resistance and compliance are coupled in the total pulmonary arterial system is not clear. Two possible explanations exist. 1) The constant RC time is an intrinsic property of each lung, similar to what is found to both lungs together. 2) The lungs, hemodynamically acting in parallel, may compensate for each other’s changes, i.e., with increased resistance in one lung, the compliance in the other lung increases with the overall RC time unaltered, but with different RC times in the two lungs.

Also in contrast to the systemic arterial system, where compliance is mainly located in the (proximal) aorta (28, 30, 34), it is not known how compliance of the pulmonary arterial tree is distributed over the system. If explanation 1 is more likely, it is to be expected that the pulmonary arterial compliance is distributed over the whole pulmonary arterial bed, and it does not matter which part of a lung is obstructed. If in a lung segment the resistance increases by a partially obstructing clot than automatically, the compliance of this same segment will be lost and the RC product will remain about the same.

To investigate the RC time in individual lungs, we studied a group of chronic thromboembolic pulmonary hypertension (CTEPH) patients with different resistances between left and right lung. To obtain resistances and compliances, we measured main pulmonary artery (PA) pressure (right heart catheterization) and flows and diameters in the main PA and left and right PA [magnetic resonance imaging (MRI)]. To determine the contribution of proximal arteries to total arterial compliance, we determined area compliance of the main and left and right PA with their lengths to derive proximal volume compliance. This last test should provide information on the distribution of compliance over the pulmonary vascular bed: Is it mainly from the proximal arteries (as in the systemic circulation), or more equally distributed? If a more equal distribution were found, then this provides a mechanism for the constancy of RC time in each lung, irrespective of the degree of obstruction.

METHODS

Patient Population

Twenty three patients suspected for CTEPH were referred to our hospital for a diagnostic work up between March 2008 and December 2008. All patients had a documented history of pulmonary embolism, a high probability V/Q scan, and echocardiographic evidence for pulmonary hypertension.

The study protocol was approved by the institutional ethics committee, and informed consent was obtained from all subjects. All patients underwent, as part of the diagnostic procedure, pulmonary angiography to assess the operability of the thromboembolic lesions according to current guidelines (9, 14). Pressure was measured with a fluid-filled, single-lumen, 7-Fr or 5-Fr Grollman catheter (Cordis, Roden, the Netherlands) in the main PA. Four patients turned
out to have no pulmonary hypertension and were considered “normals.” Thus data are presented of 19 patients plus four normals.

MRI Protocol

Within 24 h before or after pulmonary angiography and right heart catheterization, patients received MRI scan for the purpose of this study. MRI was performed using a 1.5-T whole body system (Siemens Avanto; Siemens Medical Solutions, Erlangen, Germany) equipped with a circularly polarized phased-array body coil.

Flow measurements. Instantaneous pulmonary flows were measured by MRI, using phase-contrast flow quantification (13, 15) in the main, left, and right PA. This imaging was performed during breath hold using a gradient echo MRI sequence, with velocity encoding perpendicular to the imaging plane and a velocity sensitivity of 120 cm/s. This flow sequence was run with the following parameters: orientation = orthogonal to the PA, slice thickness = 6 mm, field of view = 240 × 320 mm², matrix size = 140 × 256, echo time = 4.8 ms, repetition time = 11 ms, temporal resolution = 22 ms, and flip angle = 25°.

After the three flow measurements were acquired, a phantom was imaged with identical imaging parameters, to serve as correction for the background phase error in the main, left, and right PA (3).

Cross-sectional Area Measurements

The image plane for measuring area change (mm²) was chosen orthogonal in the middle of the main, right, and left PA as previously published (7). The magnitude images, as obtained with the above-mentioned flow measurements, were used to measure the arteries’ cross-sectional areas at peak systole (maximal area) and end-diastole (minimal area), see Fig. 1. The vessel cross section could accurately be delineated through all phases of the cardiac cycle and was obtained by automatic delineation of the vessel wall (main, left, and right PA).

Fig. 1. Top: Transversal magnetic resonance imaging (MRI) of main pulmonary artery (PA). Middle: cross section of right PA. Bottom: cross section of left PA. In all panels, the arrow in the first image shows the minimal area and in the second image the maximal area of the PA.
with in-house developed software in MATLAB 7.0, R14 (The Mathworks, Natick, MA) based on a study of Li et al. (18).

**Data Analysis**

**Resistances.** Total pulmonary resistance was calculated from mean PA pressure, and mean flow in main PA. The resistances of individual lungs were calculated from the mean PA pressure divided by the mean flow to that lung. Thus we assume that the pressure in the MPA is identical to the pressures in the proximal left and proximal right PA. The resistance in right and left lung were summed (as parallel resistances) and compared with the total resistance measured in the MPA.

**Compliances.** Total arterial compliance (i.e., compliance of both lungs together) was assessed with the pulse pressure method (PPM). The PPM uses the two-element Windkessel model with flow waveform and resistance as inputs to estimate the compliance value that best predicts systolic and diastolic pressures (26, 30). This method has been shown to produce more accurate data than the calculations on the basis of the three-element Windkessel (26). Compliances of the individual lungs were also assessed with the PPM with the resistance and flow waveform of the individual lungs as input variables.

In each patient, we defined the lung with the lowest pulmonary blood flow as “low flow” (LF) lung, and the other lung as “high flow” (HF) lung.

**Local Compliances**

From the area variation between systole and diastole, ΔA, and the pulse pressure, ΔP, we calculated (local) area compliance \( C_A = \frac{\Delta A}{\Delta P} \). Area compliance, \( C_A \), times artery length gives local volume compliance, \( C \), of the main, left, and right PA. Artery length was assumed to be 2 cm for the main PA, and 3 cm for right as well as left PA, based on measurements in a subset of patients. Total proximal volume compliance was taken as the sum of the three compliances of the main, left, and right PA.

For each patient, the product of resistance and compliance, \( RC \), was calculated for both lungs together, as well as for the LF and HF lung separately.

**Statistics**

Values presented are means ± SD. The group averages were compared using one-way analysis of variance with a Bonferroni multiple-comparison adjustment. An association between mean PA pressure and \( RC \) was calculated for both lungs together, as well as for the HF and LF lung separately.

**Table 1. Baseline parameters of patients with CTEPH and CTE-non-PH**

<table>
<thead>
<tr>
<th>Variable</th>
<th>CTEPH (n = 19)</th>
<th>CTE-non-PH (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>60±12</td>
<td>58±8</td>
</tr>
<tr>
<td>Female-to-male ratio (n)</td>
<td>10/9</td>
<td>2/2</td>
</tr>
<tr>
<td>Functional class I, II, III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>or IV per NYHA (n)</td>
<td>0.4,13.2</td>
<td>1,3,0</td>
</tr>
<tr>
<td>RAP, mmHg</td>
<td>5.5±3.8</td>
<td>3.2±2</td>
</tr>
<tr>
<td>mPAP, mmHg</td>
<td>40±12</td>
<td>16.2±2</td>
</tr>
<tr>
<td>TPR, mmHg·s⁻¹·ml⁻¹</td>
<td>0.64±0.28</td>
<td>0.19±0.06</td>
</tr>
<tr>
<td>Cardiac index, l/min·cm⁻²</td>
<td>2.7±0.5</td>
<td>3.7±0.6</td>
</tr>
<tr>
<td>SvO₂, %</td>
<td>62.8±8.5</td>
<td>75±4.5</td>
</tr>
</tbody>
</table>

Values presented as means ± SD and ranges; n, no. of subjects. CTEPH, chronic thromboembolic pulmonary hypertension; NYHA, New York Heart Association; RAP, right atrial pressure; mPAP, mean pulmonary artery pressure; TPR, total pulmonary resistance; SvO₂, mixed venous oxygen saturation. Note: 1 mmHg·s⁻¹·ml⁻¹ = 1.33 × 10⁸ dyn·s⁻¹·cm⁻³.

**RESULTS**

We studied 19 patients with confirmed CTEPH and 4 with angiographic lesions but without PH (CTE-non-PH). The gender was equally distributed between males and females. The PH patients had pulmonary hypertension with a mean PAP of 40 ± 12 mmHg (range 28–63 mmHg) and a cardiac index (CI) of 2.7 ± 0.5 l/min·m⁻². The four non-PH patients had a mean PAP of 16 ± 2 mmHg (range 15–19) and a CI of 3.7 ± 0.6 l/min·m⁻². Table 1 summarizes the baseline pulmonary hemodynamics of both groups.

Examples of flows in main, right, and left PA are shown in Fig. 2.

The LF lung with the smallest flow had the highest resistance, and this resistance was significantly higher than in the HF lung. The averaged resistance data are presented in Fig. 3A, 1.57 ± 0.2 vs. 1.00 ± 0.1 mmHg·s⁻¹·ml⁻¹, \( P < 0.0001 \). The parallel addition of the resistances of the HF and LF lung was 0.57 ± 0.28 mmHg·s⁻¹·ml⁻¹; when plotted as a function of measured total resistance, the relation is tight with a slope not different from unity (\( r^2 = 0.94 \), \( P < 0.0001 \); Fig. 3B). This proves that the sum of resistances of individual lungs equals total resistance.

The compliance was lower in the LF lung compared with the HF lung (0.47 ± 0.11 vs. 0.62 ± 0.12 ml/mmHg, \( P = 0.01 \); Fig. 3C). Again, the sum of individual compliances was compared with total arterial compliance (1.22 ± 1.1 ml/mmHg), and it is tightly related (\( r^2 = 0.99 \), \( P < 0.0001 \); Fig. 3D). This proves that the sum of compliances of individual lungs equals total arterial compliance.

**Relation Resistance and Compliance**

The total resistance was inversely related with total compliance of both lungs together (\( r^2 = 0.81 \)). The average \( RC \) time was 0.49 ± 0.15 s (Fig. 4A). The resistance and compliance in
the LF and the HF lung were also inversely related ($r^2 = 0.63$ and $r^2 = 0.85$, respectively; Fig. 4, B and C). The average $RC$ times for the LF and the HF lung were $0.45 \pm 0.15$ s and $0.45 \pm 0.14$ s, respectively, and were not different ($P = \text{not significant (NS)}$; Fig. 5). $RC$ times of individual lungs were also not different from total $RC$ time (both lungs together, $P = \text{NS}$).

**Relation Diameter and Area Compliance With Pressure**

To investigate how much the three most proximal vessels contribute to total compliance, we derived area compliances and multiplied them with vessel length. The proximal arterial volume compliances of the main, right, and left PA were $0.056 \pm 0.02$, $0.048 \pm 0.03$, and $0.049 \pm 0.02$ ml/mmHg, respectively. Their sum, i.e., total proximal arterial compliance ($0.804 \pm 0.29$ ml/mmHg).

The proximal compliance was $15 \pm 3\%$ of total compliance in the non-PH and $19 \pm 6\%$ of total compliance in the CTEPH patients ($P = \text{NS}$).

Volume compliance of the main, left, and right PA (or actually main, HF, and LF PA) showed the same inverse relation with mean PAP (Fig. 6).

**DISCUSSION**

The present study shows that the product of resistance and compliance, $RC$, is similar in each lung, whether the vascular bed is more (LF) or less (HF) affected, and in both lungs together. The similar $RC$ time constant per lung implies an intrinsic phenomenon and that changes in one lung do not compensate for the other. In other words, each lung has a reciprocal relation between resistance and compliance, regardless of the magnitude of resistance in a lung. To the best of our knowledge, this is the first study where resistance and compliance are measured within single lungs and both lungs together in healthy individuals and pulmonary hypertensive patients.

The average product of $R$ and $C$ (i.e., $RC$ time), which describes the exponential decay of the PAP during diastole, in our study is $0.49$ s. Other studies have reported constant $RC$ times in healthy subjects, idiopathic pulmonary arterial hypertension, and CTEPH, but the values of $RC$ time differ. The main reason for the differences is the way compliance is derived. Reuben (23) found a constant $RC$ time of $0.38$ s obtained with the exponential decay of the diastolic PA pressure wave method. Other studies have shown that the various ways to estimate volume compliance may differ by $>50\%$, with the PPM giving the smallest compliance values and thus
the shortest RC times (17, 26). If we use the compliance estimates reported by Lankhaar et al. (11, 17) obtained with the PPM, the average RC time is \(0.42\) s, a value close to the one found in our present study.

Therefore, we conclude, on the basis of the similar RC times of single and both lungs, that the constant RC time is an intrinsic property of each lung.

It has been shown on many occasions that increased intravascular pressure distends the arteries and causes increased stiffness of arteries (8, 10, 12, 24, 32) due to their nonlinear distensibility (1, 4). The observation in this study that area compliance was similarly related to mean pressure in left and right (or “HF” and “LF”) PA results from the fact that proximal pulmonary arteries are exposed to the same pressure and material properties are assumed equal.

Both total arterial compliance and area compliance decrease with increasing pressure. Thus, in patients with increased pressure, compliance is decreased. This may, in part, explain our findings that, with increased resistance, compliance is decreased. Another, speculative, explanation could be that functional removal of part of the arterial system, a consequence of vessel obstruction and/or hypoxic vasoconstriction, also causes a decrease in compliance along with an increase of resistance.

The latter part of the explanation is consistent with our observation that pulmonary compliance is distributed over the distal pulmonary vascular bed. This is a characteristic that differs from the systemic circulation where compliance is mainly located in the proximal aorta (28, 30, 34). To explore the distribution of compliance, we measured the local area compliances of right and left PA with MRI as previously described by others (2, 6, 7, 21, 25, 31, 33). By multiplying the area compliance with the length, we obtain volume compliance of the proximal vessels. Interestingly, the contribution of proximal compliance to overall pulmonary arterial compliance was small (19%). Thus we conclude that an important part of the compliance is located in the pulmonary arteries distal to the proximal left and right PA.

Patel et al. (20) have shown that approximately one-third of the stroke volume can be stored in the main PA, which means...
that two-thirds of the stroke volume can be stored in the more distal pulmonary arteries, also suggesting that a large part of the total compliance is distributed over the pulmonary arterial vasculature. Normal pulmonary arteries have thinner walls than their systemic counterparts (27); therefore, it has been suggested that the vascular distensibility extends to medium-sized arteries of 1 mm size, and hence probably contribute to total arterial compliance (29). This seems also to be confirmed by the study of Engelberg and DuBois (5), who studied the pressure-volume characteristics of different anatomic portions of the vascular bed in isolated rabbit lungs. Their results showed an almost equal distribution of compliance over the entire arterial vascular bed. In addition, the study of Wiener et al. (35), who studied the pressure and flow propagation in the pulmonary circulation of a dog, also seems to confirm this. They used a model of the pulmonary system to calculate, among other things, the compliance of each arterial segment from the main PA down to the capillary level. Their results demonstrate that the major part of total compliance is present in the arterioles and precapillary arteries. Furthermore, other studies have also shown that the distensibility (fractional diameter change/mmHg) of pulmonary arteries is constant and independent of size and location in the pulmonary circulation (16, 22). These studies all support the hypothesis that compliance is distributed over the entire pulmonary circulation, even in the precapillary vessels. However, this distribution of compliance in the human pulmonary arterial system needs further research.

Thus, with considerable compliance located in the distal pulmonary arterial system, we can explain that the RC time is constant in the pulmonary circulation in all categories of patients with PH and over a wide range of resistances; in other words, resistance and compliance are inseparably connected to each other, because they share the same distribution over the pulmonary vascular bed.

Limitations

A limitation of this study is that pressure and flow were not measured simultaneously. Potentially, this can result in pressure and flow measurements in different hemodynamic states. We think this effect to be small, since we performed the MRI within 24 h after or before catheterization. Also, the difference in heart rate between MRI and right heart catheterization during pulmonary angiography was <5%.

The pressure wave form obtained by fluid-filled catheters can be distorted by the dynamic response of the catheter. However, if used properly (flushing, etc.), errors are small, and reliable pressure curves can be obtained, especially since the PA pressure does not contain high frequencies.

We used main PA pressure for left and right artery pressure as well. The distance between these locations is so small that errors in pressure are negligible. Womersley’s theory states that the longitudinal impedance predicts the pressure difference between two close sites, and this impedance is extremely small (36).

In conclusion, we have shown that the RC time constant applies for each lung separately in CTEPH, despite differences in resistances. This is consistent with our observation that the pulmonary vasculature distal to the main, right, and left PA contributes for an important part to total arterial compliance.

GRANTS

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DISCLOSURES

No conflicts of interest are declared by the authors.

REFERENCES


