Methods for the Evaluation of Right Ventricular Volume Using Ultrasound on a Catheter, in Intensive Care Unit

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ABSTRACT

Hemodynamic monitoring is the main component in intensive care unit (ICU). Patients in ICU are under hemodynamic instability and multi-organ failure for some hours or even some days. Volume-pressure relation constitutes the most reliable method for the estimation of central hemodynamic state and ventricular function. Therefore, the evaluation of intracardiac volume and pressure is necessary. However no available method exists for clinical use that measures the volume of the right ventricular cavity continuously in real time. This paper discusses the methods could be used in measuring the right ventricular volume in the context of an efficient cardiac function evaluation of critical ill patients in ICU, using miniaturised ultrasound on the tip of a Pulmonary Artery Catheter (PAC), which is anyway used on that purpose but evaluates only pressure.

Keywords: Critical Illness, Hemodynamics, Miniaturized Ultrasound, Pulmonary Artery Catheter, Right Ventricle

INTRODUCTION

Scientific community considers that hemodynamic monitoring is a central component of intensive care (Pinsky & Rayen, 2005). Advanced hemodynamic monitoring is an important part of treatment in clinical situations where aggressive, yet guided hemodynamic interventions are required in order to stabilize the patient and optimize outcome. Cardiac Output (CO) and other hemodynamic parameters play an important role in differential diagnosis, establishing the right treatment plan and monitoring and refining it in real-time. Hemodynamic monitoring is the expert collection and analysis of qualitative and quantitative data of cardiopulmonary function. This monitoring includes clinical observation, the use of electri-
cal, photometric, pressure transducing equipment, as well as the application of a number of intravascular catheters. Fluid-filled monitoring systems attach to intravascular catheters and are used for continuous invasive measurement of arterial and cardiac pressures. Periodic measurement of other pressure/flow and gas exchange parameters may also be performed (National Institutes of Health, http://www.cc.nih.gov). Patterns of hemodynamic variables often suggest cardiogenic, hypovolemic, obstructive, or distributive (septic) etiologies to cardiovascular insufficiency, thus defining the specific treatments required.

Current clinical practice guidelines, based on recent clinical trials that failed to demonstrate a beneficial long-term effect of its use on patients’ outcome, recommend the use of Pulmonary Artery Catheter (PAC or Swan – Ganz catheter) only in certain conditions, such as the differential diagnosis between a cardiogenic and a non-cardiogenic pathophysiology in critically ill patients or the evaluation of hemodynamically unstable patients not responding to the applied therapy (Dickstein, 2008). Any delay to obtain the proper treatment for the critically ill patients, might be fatal. To prevent a possible episode, the prognosis is necessary and important with regard to sudden changes in values of right ventricular volumes which signify an oncoming acute pulmonary embolism or ischemic episode (Vonk Noordegraaf & Gallie, 2011). The three most important factors for hemodynamic evaluation are: preload, afterload and contractility. Right ventricular end-diastolic volume (RVEDV) is the best clinical estimate of right ventricular preload and right ventricular end-systolic volume (RVESV) may be used to estimate RV function (Siniscalchi, 2005). In addition the ejection fraction, \[ EF = \frac{EDV - ESV}{EDV} \] is an important index of cardiac performance. EDV is the end diastolic volume and ESV is the end systolic volume. Thus, the calculation of RVEDV and RVESV are of great interest to the clinician.

The PAC is a catheter with length usually at 110cm and external diameter of 7 French (or 2.33mm). In order to access the right heart it enters from a large vein which often is the internal jugular or the subclavian vein and though the superior vena cava enters the right atrium as shown in Figure 1. Through the tricuspid valve is inserted to the right ventricle cavity and then curves in order to enter through the pulmonary valve to the pulmonary artery (Headley, 1989).

The curvature of the catheter in the right ventricle chamber has the form of an arc of a circle and could be considered to be the same in any heart as the location and the distance between the valves is approximately unchanged. Therefore, as a result from the above, if a number of ultrasonic sensors are mounted on the catheter surface with certain geometry, the angle of ultrasound beam from the sensor to the ventricular wall will be constant.

Pulmonary artery catheterization has been used for monitoring the circulation, for measurement of intracardiac pressures and to estimate preload and afterload. However, this technique may not accurately reflect the circulation and simultaneous measurement of volumes would improve patient treatment (Kuehne, 2004). Although, measurement of cardiac volumes especially of the right ventricle is difficult in everyday clinical practice, we argue that the development of a system which will enable prognosis and the effective management of hemodynamic status of critically ill patients and especially those with severe heart failure, will improve significantly the quality of healthcare provided, and will constitute a valuable asset in the hands of the medical personnel.

Even if some of these parameters may be estimated by non-invasive techniques, PAC indications still include patients severely ill in the ICU who present with severe circulatory shock, right ventricular failure, acute respiratory failure due to pulmonary edema not responding to treatment, or require complex fluid management (Vincent, 2012). Furthermore, according to the recently published guidelines for the
diagnosis and treatment of acute and chronic heart failure, pulmonary artery catheterization should be considered in patients i) who are refractory to pharmacological treatment, ii) who are persistently hypotensive, iii) in whom left ventricular filling pressures are uncertain, or iv) who are candidates for cardiac surgery (McMurray, 2012).

In daily practice, PAC is indicated in the diagnostic workup in many conditions, especially in the critically ill patient, where time to decision is short, treatment is often contradictory and subtle manipulation is needed (Table 1). The insertion of PAC may help avoid malpractice, as clinical judgment is often misleading or inadequate. In Table 2, cases of delayed treatment due to absence of hemodynamic monitoring are listed.

Table 3 presents the several existing techniques used in Right Ventricular Volume Measurement with any recorded risk or limitation.

Although intracardiac pressure measurement is obtainable by the commercially available pulmonary artery catheter (PAC), there are

Table 1. Clinical conditions and implications of PAC

<table>
<thead>
<tr>
<th>Clinical Condition</th>
<th>Implication of PAC</th>
</tr>
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</table>
| Cardiogenic shock  | • Assess cardiac output;  
|                    | • Differentiate cardiogenic from non cardiogenic pulmonary edema;  
|                    | • Guide treatment |
| Right Ventricular Infarction | • Guide volume infusion |
| Severe Chronic Heart Failure | • Assess congestion;  
|                                | • Guide treatment (inotropes, vasopressors, vasodilators) |
| Septic (or pseudoseptic) shock | • Guide treatment |
| Reversible causes of cardiogenic shock (fulminant myocarditis, peripartum cardiomyopathy) | • Assess clinical course |
| Pulmonary Hypertension | • Diagnose Primary Pulmonary Hypertension;  
| | • Assess response to treatment |
| Pre-transplantation/Ventricular Assist Device implantation work-up | • Assess vascular resistance;  
| | • Estimate right ventricular function |
no widely available systems to provide ventricular cavity volume estimations for clinical use and the ones available are primarily used for experimental purposes (Hurford & Zapol, 1988; Ghio, 2001; Takala, 2005; Bourantas, 2011). Recent studies suggest that the use of the PAC with its existing pattern (pressure estimation) does not improve patient outcome (Binanay, 2005; Hall, 2005; Schwann, 2011).

So far, ventricular volume evaluation is achieved indirectly using thermodilution, a method which estimates cardiac output (rate of cardiac performance) by measuring the temperature curve. High cardiac output causes rapid change of temperature while low cardiac output can cause slow changes in temperature. However, this method is complex and inherently inaccurate (Iberti, 1990; Espersen, 1995; Critchley & Critchley, 1999; Johnston, 2004; Hein, 2009).

3D echocardiography, CT scanning and cardiac MRI images are the most common non-invasive methods used in RV volume estimation and based on 3D reconstruction of 2D images. Conductance technique, where the volume is calculated by the estimation of electrical conductance of blood in the ventricular cavity and angiography method, in which various geometric models used for RV volume estimation are among the methods that are not frequently used in today’s clinical practice (Linker, 1986; Fritz 2006; Heimann & Meinzer, 2009).

However, there are a few methods for the volume estimation from the internal area of the RV, by means of a catheter. ICUS technique (Vazquez de Prada, 1996) is one of them, where the measurement of several constant distance section areas from the apex to the base of the chamber is performed using a ring ultrasonic transducer and the volume is estimated by applying the Simpson’s formula. Although in all the above methods the RV volume could be measured for general purposes, none of those techniques can estimate the P–V relation since it cannot be easily combined with PAC. Among the previously mentioned methods, magnetic resonance cardiac imaging (MRI) is considered the gold standard for ventricular volume estimation (Mogelvang, 1988; Lorenz, 1995; Niemann, 2007; Brants, 2010). It is a non invasive method and patients are not exposed to radiation. Nevertheless, the use of MRI for constant monitoring in an intensive care unit environment (related with critical patients) is by itself unpractical. MRI equipment is used for diagnosis and intervention but it cannot

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### Table 2. Cases of delayed treatment due to absence of hemodynamic monitoring

<table>
<thead>
<tr>
<th>Clinical Condition</th>
<th>Possible Malpractice without PAC</th>
<th>Measurements</th>
<th>New Diagnosis-Treatment after PAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypotension complicating AMI</td>
<td>IABP/inotropes</td>
<td>Reduced LV preload</td>
<td>RV AMI requiring normal saline infusion</td>
</tr>
<tr>
<td>Acute Pulmonary Edema</td>
<td>Diuretics</td>
<td>Reduced pulmonary vascular resistance</td>
<td>Non cardiogenic pulmonary edema- requiring antibiotics</td>
</tr>
<tr>
<td>Hypotension in a patient with reduced EF</td>
<td>Inotropes</td>
<td>Reduced Vascular resistance</td>
<td>Septic shock requiring mostly vasopressors</td>
</tr>
</tbody>
</table>

AMI: acute myocardial infarction;  
IABP: Intra-aortic balloon counterpulsation;  
LV: left ventricle;  
RV: right ventricle;  
EF: ejection fraction.
Some of the early explorations of intracardiac imaging with phased-array technology and color Doppler were undertaken with miniaturized transesophageal studies for experimental purposes. Higher-frequency rotating catheter probes in the range of 20 to 30 MHz were developed and marketed for intracoronary investigations that yielded new insights into atherosclerosis, vascular response to stents, and coronary remodeling. Lower-frequency (10- to 12.5-MHz) versions of these rotating single-element devices were used for the earliest intracardiac investigations (Pandian, 1990).

The growth of anatomic cardiac transcatheter interventions and increasingly aggressive transcatheter ablative strategies to treat cardiac arrhythmias has stimulated the use of and development of new methods for intracardiac ultrasound (Okumura, 2008).

Table 3. Techniques used in right ventricular volume measurement

<table>
<thead>
<tr>
<th>RV Volume Measurement Technique</th>
<th>Risks and Limitations</th>
</tr>
</thead>
</table>
| Transesophageal Echocardiogram                            | - Breathing and heart rhythm problems, infection of the heart valves, bleeding of the esophagus;  
eg     |
|                                                           | - The patient must follow the ASA NPO guidelines (i.e. usually not eat anything for six hours and not drink anything for two hours prior to the procedure);  |
|                                                           | - It is an instantaneous measurement (cannot be continuous);  
eg     |
|                                                           | - Requires a team of medical personnel;  
eg     |
|                                                           | - Uncomfortable for the patient;  
eg     |
|                                                           | - May require sedation or general anesthesia  
eg     |
| Transthoracic Echocardiogram                             | - It is an instantaneous measurement (cannot be continuous);  
eg     |
|                                                           | - Requires a team of medical personnel;  
eg     |
|                                                           | - The imager can image the RV through various cut planes, resulting possibly in a medium, or smaller dimension  
eg     |
| MRI                                                       | - It is an instantaneous measurement (cannot be continuous);  
eg     |
|                                                           | - Requires a team of medical personnel;  
eg     |
|                                                           | - Not suitable for critical patients, as their movement to the MRI area involves many risks  
eg     |
| Thermodilution                                            | - Average of measurements made over 5–6 minutes and thus do not provide continuous monitoring  
eg     |
| Fick principle applied to carbon dioxide                 | - It requires central venous and arterial catheters;  
eg     |
|                                                           | - Cannot be used in patients ventilated with fractional inspired oxygen greater than 60%;  
eg     |
|                                                           | - Often not applicable in critically ill patients, because they require extreme ventilatory conditions with high fractional inspired oxygen or because their haemodynamic status is unstable;  
eg     |
|                                                           | - Does not provide an instantaneous measure of cardiac output, rather a mean value every 3 min (therefore no real-time monitoring)  
eg     |
| Pulse Contour Method                                      | - Require frequent calibration;  
eg     |
|                                                           | - Need for both arterial and central venous catheters preclude;  
eg     |
|                                                           | - Patients who had poorly defined arterial waveforms or who presented with arrhythmia were always excluded because pulse contour methods cannot provide reliable results in such conditions  
eg     |
The main use of intracardiac ultrasound transducers so far, is the echocardiography in the sense of imaging. In contrast, there are only few cases (not often used in clinical practice) using the intracardiac ultrasound just to calculate a distance from the walls, which is the fundamental function of ultrasounds. However, in both cases, the technology remains the same possibly differing in configuration.

Table 4 presents the last and most common recently used intracardiac ultrasonic devices (Hijazi, 2009).

### ARTIFICIAL NEURAL NETWORKS METHOD

In this study (Toumpaniaris, Skalkidis, Nikolakopoulos, et al., 2010) the data was taken by 120 anonymised Magnetic Resonance Cardiac Images (MRI - PHILIPS INTERA 1.5 TESLA) using a 5-element phased array cardiac coil for signal reception. These images were transferred to a workstation and RVED and RVES volumes were calculated using the conventional method utilized in clinical routine with Segment Cardiac Image Analysis software (MEDVISO, http://medviso.com).

The contour of RV endocardium was designed in the appropriate time of cardiac cycle (end systolic and end diastolic phase), and the 3D model was computed in Cartesian coordinates \((x, y, z)\).

In order to model the pulmonary artery catheterization by the 3D-heart images, an entrance and exit point of the catheter it was defined (i.e tricuspid valve and pulmonary valve), assuming that the same pattern is followed in each subject. In addition, points that represent the ultrasound transducers were assigned.

The two proposed geometries of ultrasound transducers are the cross geometry and the helical geometry.

### Table 4. Intracardiac ultrasonic devices

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Company</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>UltraICE</td>
<td>Boston Scientific</td>
<td>9F nonsteerable rotational motor-driven grayscale only system</td>
</tr>
<tr>
<td>AcuNav</td>
<td>Siemens, Biosense-Webster</td>
<td>Side-looking 64-element phased-array 4-way steerability, 8F and 10F; grayscale, color Doppler, tissue Doppler, 3D localization with Cartosound</td>
</tr>
<tr>
<td>EP Med View Flex Catheter</td>
<td>St Jude Medical</td>
<td>Runs side-looking 64-element catheter on the Viewmate scanner, 10F introducer, 2-way flex color Doppler, grayscale, tissue Doppler 8-2 MHz</td>
</tr>
<tr>
<td>ClearICE</td>
<td>St Jude Medical</td>
<td>Derived from the hockey stick, 64-element side-looking highly steerable 4-way side-looking array with 2 sets of electrodes for integration of 3D localization with NavX; runs on the GE Vivid i scanner; grayscale, tissue Doppler, synchronization mapping, 2D speckle tracking</td>
</tr>
<tr>
<td>SoundStar Catheter</td>
<td>Biosense-Webster</td>
<td>This is a new catheter, just now marketed as a 10F (3.33-mm) device with integrated ultrasound array (like AcuNav) but with the CARTO magnetic sensor in the tip; this is now FDA approved; FDA 510(k) No. is K070242, May 15, 2007</td>
</tr>
</tbody>
</table>
In cross shaped geometry, four points are selected, to be equally distributed on the catheter although the placement of the transducers in the above pattern seems to be quite difficult.

In the helical geometry which is the dominant one, the array of transducers will have a spiral shape along the catheter’s segment which lies in RV cavity.

Also, the same catheter model must be used in any measurement. The catheter and the size of the transducers would not permit the use of more sensors.

Following the distance is measured from any point of catheter to the wall of any ventricle model using the standard distance equation for 3D:

\[ d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \]  

To train the developed artificial neural network (ANN), the distances from catheter to ventricular wall will be considered as the input for the ANN, while the output (the volume) is assigned to be equal to that calculated from the MRIs using the Segment software, as described above. The accuracy of volume calculation algorithm depends on the quantity of RVs that will be used in the ANN.

Keeping in the process the subjects that presents a more realistic view in their measured volumes, the data were finally segregated into 106 end-diastolic volumes and 75 end-systolic available which will be used in two different neural networks ANN.

From 106 diastoles, 100 were used for the design of the first ANN and 6 for simulation.

From 75 systoles, 70 were used for the design of the second ANN and 5 for simulation.

The results showed the optimum performance during the diastolic phase was when used a ANN design with 2 layers and 20 Neurons (R=0.95).

The diastolic volume simulation results were satisfactory, especially if the 15% tolerance from MRI volume will be taken into consideration. The standard error for the diastolic volumes was 8.3±1.6%.

On the contrary the standard error for the end systolic rate was 24.2±3.8%. The end systolic rate is due to the small volume that RV presents during systole and it is quite difficult for the volume to be estimated at this phase even by specialists.

The authors of this study consider that an improvement is necessary in the design of the catheter with the possibility of using a different architecture to add more points or the points to have a better orientation of their simulated beams, inside the cavity.

As the accuracy of the volume measurement system depends on the accurate calculation of distances between the ultrasonic transducers and the corresponding points of the inner ventricular wall surface, this accuracy should be obtained taking into account any possible locality and orientation that an ultrasonic transducer may have within the RV cavity. It is not possible for a physician, during the right heart catheterization procedure, to ensure that always the catheter enters the RV cavity in such a way that any of the transducers having exactly that same position either longitudinal or circularly, related to the cavity. Thus, in order to make sure that the RV volume measurement using ANN is accurate, a precision of the system should be set in 1mm and 15°, and a more complex ANN must be designed according the defined precision, although the displacement between transducers is for example 3mm and 45°.

#### ROTATING SYSTEM

This method (Toumpaniarias, Nikolakopoulos, et al., 2010) is based on a rotating system consisted by two mechanical arms (Figure 2), (primary and secondary). The secondary arm (on which the primary arm is mounted) will be
able to perform a rotation through an angle \( \phi_i \) from 0° to 360°. An ultrasonic sensor is mounted on the tip of the primary arm. The primary arm (where the sensor is mounted) will be able to rotate through an angle \( \theta_j \) from 0° to 180°.

The number of measurements in a complete scan of the chamber depends on the number of steps.

The transducer will measure the radial distance, i.e. the distance from the transducer to the wall of the cavity.

After the assumption that the distance “\( r \)” will be calculated between \( 0 \leq r \leq R(\phi, \theta) \) and several mathematical simplifications, the RV volume will finally calculated using the methods of a) initial point and b) midpoint. Therefore:

1. The method of initial point formula calculates the volume \( (I) \) by the initial point of each rectangle:

\[
I \approx h_y h_x \sum_{k=0}^{n_y-1} \sum_{l=0}^{n_x-1} f(lh_x, kh_y)
\]

\( l : \text{number of partitions in } \phi \)

\( k : \text{number of partitions in } \theta \) (2)

2. The midpoint method, calculates the volume \( (I) \) by the midpoint of each rectangle:

\[
I \approx h_y h_x \sum_{k=0}^{n_y-1} \left[ \sum_{l=0}^{n_x-1} f\left(\frac{(2l+1) \cdot h_x}{2}, \frac{(2k+1) \cdot h_y}{2}\right)\right]
\]

The midpoint method seems to be more reliable since it appears to better approximate the curve.

Due to the difficulties which arising in implementing such a “two miniature rotating arms” device with an ultrasound transducer on it, the test was attempted with simulation on coordinates measured in RV samples acquired by the MRI method. Figure 3 illustrates the cloud of wall points of the simulated right ventricle. Given that each 2D MRI slice consists of \( x, y \) points, using the appropriate algorithms the volume of the cavity could be calculated.

Table 5 presents the results of right ventricular volumes measurement of ten hearts, performed by the two proposed formulae and their comparison with the volume measured by MRI which is considered as gold standard.

According to the Table 5, both methods give similar results but the midpoint method seems to be more accurate, since it provides closer approximation to the volume measured by MRI with an error margin lower than 15%. Although
in this method a single sensor is used, the results show that it is more reliable than the previous one because it performs a more complete scan of the cavity, reducing the probability of a no scanned area. It performs more reliable measurements than thermodilution, as their values are closer to MRI, considering that thermodilution cannot provide measurements with deviation lower than 15% (Nieminen, 2005).

**POLYHEDRA METHOD**

This method (Toumpaniaris, Skalkidis, Markatis et al., 2010) assumes that there are 5 circular dissections on the tube of the catheter. If the total length of the catheter that is inside the RV is \( l \), it could be considered as a part of an arc. There are 5 sections where the ultrasound transducers will be mounted with a separation of \( l/5 \) between them. In each of the 5 points \((O_1, O_2, O_3, O_4, O_5)\) 6 \((A, B, \Gamma, \Delta, E, Z)\) ultrasound transducers will lay rotatively on the surface of the catheter with 60 degrees separation. The beams of the ultrasound transducers of the same point form a hexagon \((A, B, \Gamma, \Delta, E, Z)\). So, 5 hexagonal planes \((u_1, u_2, u_3, u_4, u_5)\) will be formed in the RV wall. The solid created by two consecutive hexagonal planes is considered.

### Table 5. Result of right ventricular volume measurements of ten hearts

<table>
<thead>
<tr>
<th>Sample</th>
<th>V(MRI)(ml)</th>
<th>V (Initial Point) (ml)</th>
<th>Error(%)</th>
<th>V (Midpoint) (ml)</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>80</td>
<td>95.76</td>
<td>19.70</td>
<td>85.8</td>
<td>7.25</td>
</tr>
<tr>
<td>S2</td>
<td>41</td>
<td>32.66</td>
<td>20.34</td>
<td>34.38</td>
<td>16.15</td>
</tr>
<tr>
<td>S3</td>
<td>56</td>
<td>48.23</td>
<td>13.86</td>
<td>50.12</td>
<td>10.50</td>
</tr>
<tr>
<td>S4</td>
<td>164</td>
<td>139.76</td>
<td>14.78</td>
<td>142.56</td>
<td>13.07</td>
</tr>
<tr>
<td>S5</td>
<td>83</td>
<td>76.94</td>
<td>7.30</td>
<td>77.93</td>
<td>6.11</td>
</tr>
<tr>
<td>S6</td>
<td>79</td>
<td>72.64</td>
<td>8.05</td>
<td>74.25</td>
<td>6.01</td>
</tr>
<tr>
<td>S7</td>
<td>121</td>
<td>137.43</td>
<td>13.58</td>
<td>134.25</td>
<td>10.95</td>
</tr>
<tr>
<td>S8</td>
<td>74</td>
<td>84.12</td>
<td>13.68</td>
<td>80.18</td>
<td>8.35</td>
</tr>
<tr>
<td>S9</td>
<td>67</td>
<td>79.16</td>
<td>18.15</td>
<td>76.03</td>
<td>13.48</td>
</tr>
<tr>
<td>S10</td>
<td>166</td>
<td>137.29</td>
<td>17.30</td>
<td>134.49</td>
<td>18.98</td>
</tr>
</tbody>
</table>

Mean Error (Initial Point) = 16.23 ± 1.4%
Mean Error (Midpoint) = 12.45 ± 1.2%

![Figure 3. Cloud of points of the simulated right ventricular wall taken from cardiac MRI slices](image-url)
as the RV volume in this particular sector. Therefore the RV volume between planes $u_1, u_2$ can be calculated using Figure 4.

$$RV_{1,2} = V_{\text{pyramid}}(O_2A_1B_1\Gamma_1\Delta_1E_1Z_1) + V_{\text{tetrahedrons}}(O_2Z_2Z_1A_1 + O_2Z_2A_2A_1 + O_2A_2A_1B_1 + O_2A_2B_2B_1 + O_2B_2B_1\Gamma_1 + O_2B_2\Gamma_1\Delta_1 + O_2\Gamma_1\Delta_1 + O_2\Delta_1E_1 + O_2\Delta_2E_2E_1 + O_2E_2E_1Z_1 + O_2E_2Z_2Z_1)$$ (4)

**Box 1.**

Volume $O_2Z_2Z_1A_1 = \frac{1}{6}$$

$$= \frac{1}{6} \begin{vmatrix}
A_1 & 1 \\
Z_1 & 1 \\
O_2 & 1 \\
Z_2 & 1
\end{vmatrix}
$$

$$= \frac{1}{6} \left( \begin{array}{c}
(\rho + rA_1, 0, 0) \\
(\rho + rZ_1 \cos(-60), rZ_1 \sin(-60), 0) \\
(\rho \cos \varphi, 0, \rho \sin \varphi) \\
(\rho + rZ_2 \cos(-30) \cos \varphi, rZ_2 \sin(-30), (\rho + rZ_2 \cos(-30)) \sin \varphi)
\end{array} \right)$$ (6)
So the total RV volume will be derived by summing up the 4 solid volumes created by the 5 groups of sensors. Namely:

\[ RV_{\text{Total}} = RV_{1,2} + RV_{2,3} + RV_{3,2} + RV_{3,4} \]  \hspace{1cm} (7)

**TRIANGULATION METHOD**

According to this method (Toumpaniaris, 2009) the right ventricle was considered as a random (non-geometric) convex cavity and its volume measurement was based on the triangulation method which is a common method for volume calculation of non-geometric shapes. A spherical transducer which consists of an array of distance sensors mounted on its surface in a constant angle “\( \alpha \)”, is used to transmit ultrasonic beams to the wall of the cavity in order to measure the relative distances “\( r \)” (Figure 5).

The number of sensors on the transducer depends on the angle “\( \alpha \)” which is formed between the sensors. We assume that the sensors are normally distributed on the area of the spherical transducer, two of them pass through the poles and the catheter is connected with the sphere in its two poles. So, the number of sensors in the perimeter of the sphere is \( \frac{360}{\alpha} \) but since the catheter is connected to the poles the final number is \( \frac{360}{\alpha} - 2 \). The sphere consisted by \( \frac{180}{\alpha} \) such perimeters. Therefore, the number of sensors \( n_s \) contained in the spherical transducer is calculated as follows:

\[ n_s = \left( \frac{360}{\alpha} - 2 \right) \times \frac{180}{\alpha} \]  \hspace{1cm} (8)

or:

\[ n_s = \frac{64800 - 360\alpha}{\alpha^2} \]  \hspace{1cm} (9)

where:

\( \alpha \) : The angle between sensors

With the aid of the triangulation method the wall surface is assumed that forming a triangular grid similar to the internal area.

The calculation of the volume, which is based on the Gauss-Ostrogradsky divergence theorem, is given by the following formula (Fritz, 2005; Fritz, 2006):

*Figure 5. Right ventricle’s cross sectional area with the spherical transducer inside*
\[
V = \pm \sum_{i=1}^{m} \left[ \left( y_{i2} - y_{i1} \right) \cdot \left( z_{i3} - z_{i1} \right) - \left( z_{i2} - z_{i1} \right) \cdot \left( y_{i3} - y_{i1} \right) \right] \\
\left( x_{i1} + x_{i2} + x_{i3} \right)
\]

\[ (10) \]

\( m \): The number of triangular surfaces

If above formula will be simulated using the processed MRI images from the rotation device method and compared with the MRI values, it was found to have a Mean Error = 12.87 ± 1.46%.

The main disadvantage of this method is the number of sensors used in order to obtain reliable volume estimation. The volume was computed with angle \( \alpha \) set at 45° and at 30°. The results shown that in the case of 45° there was a huge deviation whereas the results in the case of 30° would be considered satisfactory. In conclusion, the maximum suitable angle between sensors might be a few degrees above 30°, because as the angle approaches 45° the method tends to be inaccurate. From the above formula this corresponds to 40 - 60 sensors.

CONCLUSION

As Moon (2002) presented, there is a huge range of normal RV volume values which renders any statistical application challenging. However, if it becomes necessary for a heart to be qualified as normal or pathologic from just one value, the tolerance must be high. Under these conditions, a deviation of up to 15% or even 20% might be considered acceptable. The above rate (15-20%) was extrapolated from the value range presented by Moon et al., solely for creating an effective tolerance ratio of the normal values range but, on the same time, minimize overlapping with pathological values.

Because of the complex shape of right ventricle it is difficult to define a method that fulfills all the requirements and limitations that arise in order to measure its volume, as the volume should be measured by the distances taken from ultrasonic sensors mounted along the PAC.

A thorough effort is been paid to the appropriate layout geometry of the ultrasonic sensors as they will build along the pulmonary artery catheter’s surface, so that the RV volume could be measured.

As the MRI method is considered to be a gold standard in ventricles volume measurement, a comparison of cardiac MRI with any method in this field is suggested.

In a potential clinical application, since the human heart is a moving cavity and all its dimensions change constantly, it is essential to couple the above methods with ECG gating in order to “freeze” the cardiac motion and acquire measurable RV volumes in different cardiac phases. A retrospective gating technique, similar to the one established in MR cardiac imaging, could be applied to the stream of data provided by the moving sensor. Consequently, by using a retrospective ECG gating technique, the measurements acquired in different time points could be matched with the respective ECG phase and eventually create sets of data referring to a certain cardiac phase. By introducing the necessary spatial data to each one of the points in the time sets, the total RV volume could be correctly calculated in several distinct cardiac phases.

Taking into account that RV volume is perfectly measured by MRI, the proposed method might be considered to perform satisfactory measurements. Thus, any potential errors, should be related to what is been described as pathologic. As the range of normal and pathological values is huge and overlapping, there is no significance in a scalar approximation. The diagnosis is not obtainable by just one number. The proposed methods are intended for real time volume measurement performance and they are not related with a particular pathology, but could be used as a monitor for oncoming pathology, like liquid overfilled – pulmonary
edema, pulmonary hypertension, heart failure etc. Although the RV volume measurement using this particular method could have a relative accuracy in regard to MRI, for higher accuracy in value, it might be necessary to include a constant un-measured volume (even it is too small) which perhaps not measured by the method due to its particular characteristics and could be neglected.

FURTHER WORK

A big step ahead will be undoubtedly the development of a non-invasive smart system for continuous volume and pressure measurement, in real time using a matrix of miniature sensors on the top of the skin. It will constitute a challenge in both sensors technology and cardiac function evaluation in critical illness, as the measurement of the right ventricular volume, is difficult in everyday clinical practice.

It will improve the quality of healthcare services, constituting a precious asset in the hands of the medical community.

This device will be a wearable smart system with a matrix of miniature sensors using an embedded technology. It will be able to evaluate the volume and the pressure in the right ventricular cavity of the heart, measuring the shape dimensions and the velocity in the cardiac cavities and vessels as well as the cardiac rate. On the other hand, as this technique reduces morbidity and mortality is of a significant socioeconomic impact.

REFERENCES


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