Indexes of cardiac performance

It has long been observed that the use of the ejection fraction (EF) to assess the condition of the heart offers serious limitations (1). It is estimated that half of the patients presenting with symptoms of cardiomyopathies and heart failure (HF) have preserved EF defined as EF >50%. It was shown in (2) that the areas under the end-systolic pressure-volume relation (ESPVR) in the heart ventricles are sensitive indexes to reflect the state of the myocardium, a review of some clinical applications of indexes derived from the ESPVR can be found in (3). An objective of the study by Doyle et al. (4) is precisely to show that areas under the ESPVR, or bivariate combination of areas with another index, can be used as a prognostically useful tool for studying cases of women with suspected myocardial ischemia.

The ESPVR is the relation between pressure and volume in the left or right ventricle when the myocardium reaches its maximum state of activation near end-systole (2,3). There have been several studies on the ESPVR (3,5-7), most of these studies have focused on the use of the maximum slope $E_{\text{max}}$ and the volume axis intercept $V_{\text{om}}$ of the ESPVR in order to assess the state of the myocardium. Because of the difficulty to calculate $V_{\text{om}}$, some researchers have tried to neglect $V_{\text{om}}$ and to approximate $E_{\text{max}} \approx (\text{end-systolic pressure}/\text{end-systolic volume})$ (4). Such an approximation can only be justified if it is proven that the results obtained contain useful reliable clinical information. In what follows we introduce some relations that reflect the way the energetic of cardiac contraction is related to the areas under the ESPVR, and how the EF is also influenced by these areas. It may provide some background for the study published in (4).

Mathematical formalism

$PVR$

As in previous publications (8-11), the left ventricle is represented as a thick-walled cylinder contracting symmetrically (Figure 1). A radial active force $D_r$ (force per unit volume of the myocardium) is developed by the myocardium during the contraction phase. The active pressure on the inner surface of the myocardium (endocardium) is given by $\int_a^b D_r \, dr = P_{\text{iso}}$, where $a = \text{inner radius of the myocardium}$, $b = \text{outer radius of the myocardium}$. We neglect inertia and viscous forces since they are relatively small. The equilibrium of forces on the
endocardium can then be expressed in the form:

$$P_{iso} - P = E (V_{ed} - V)$$ \[1\]

$P$ is the left ventricular pressure, $V$ is the corresponding left ventricular volume, $V_{ed}$ is the end-diastolic volume (the largest volume when $dV/dt = 0$). The right-hand side of Equation [1] is the pressure on the endocardium resulting from the elastic deformation of the myocardium. When the elastance $E$ reaches its maximum value $E_{max}$ near end-systole (maximum state of activation of the myocardium), we can write Equation [1] as follows:

$$P_{isom} - P_m = E_{max} (V_{ed} - V_m)$$ \[2\]

We take $V_m \approx V_{es}$ the end-systolic volume when $dV/dt = 0$.

**ESPVR**

Equations [1] and [2] are represented graphically in a simplified way in Figure 2. The ESPVR is a relation between $P_m$ and $V_m$ when the peak isovolumic pressure $P_{isom}$ is kept constant, it is represented by the line $d_1V_m$ with slope $E_{max}$. The changes $\Delta P_{isom}$ and $\Delta P_{isom}$ correspond to $\Delta V_{ed}$ according to the Frank-Starling mechanism.

During a normal ejecting contraction the PVR is represented by the rectangle $V_{ed}d_1V_m$. Equation [2] can be split into the following form:

$$P_m = E_{max} (V_m - V_{om})$$ \[3\]

$$P_{isom} = E_{max} (V_{ed} - V_{om})$$ \[4\]

We can distinguish the following cases described by the ratio $E_{max}/e_{am}$ (maximum ventricular elastance/maximum arterial elastance) and the stroke volume $SV \approx V_{ed} - V_m$ (see Figure 2).

(I) Normal physiological state of the heart, with $d_1$ below $d_5$ on the line $d_3V_{om}$. In this case we have $SV > (V_{ed} - V_{om})/2$, with $E_{max}/e_{am} \approx 2$ and $P_{isom}/P_m \approx 3$. This case corresponds to maximum efficiency for $O_2$ consumption by the myocardium.

(II) Mildly depressed state of the heart, with $d_1$ and $d_5$ coinciding. In this case we have $SV \approx (V_{ed} - V_{om})/2$, with $E_{max}/e_{am} \approx 1$ and $P_{isom}/P_m \approx 2$. The stroke work $SW$ reaches its maximum value $SW_{max}$.

(III) Severely depressed state of the heart, with $d_1$ above $d_5$ on the line $d_3V_{om}$. In this case we have $SV < (V_{ed} - V_{om})/2$, with $E_{max}/e_{am} < 1$ and $P_{isom}/P_m < 2$.

Notice from Figure 2 that in cases (II) and (III) an increase in pressure $P_m$ causes a decrease of the stroke work $SW$, resulting in cardiac insufficiency.

Experimental verification of these results can be found in (5) (left ventricle) and in (6) (right ventricle) for experiments on dogs, and in (7) for results obtained from patients.

We have the following areas under the ESPVR:

(I) $SW = P_m (SV)$, energy delivered to the systemic circulation;

(II) $PE = P_m (V_{om} - V_{ed})/2$, potential energy apparently

![](image.png)
related to the internal metabolism of the myocardium;

(III) \( CW = (P_{\text{isom}} - P_m) \frac{SV}{2} \), energy apparently absorbed by the passive medium of the myocardium;

(IV) \( SWR = SW_{\text{max}} - SW \), stroke work reserve. It is the reserve energy that can be delivered to the systemic circulation when afterload represented by \( P_m \) is increased.

We have \( SW + PE + CW = TW \) the total area under ESPVR. One can derive the following relation for the stroke volume:

\[
SV = (CW/TW)^{1/2} (V_{ed} - V_{om})
\]

Which shows how \( SV \) (and \( EF = SV/V_{ed} \)) is determined by the areas under the ESPVR. When \( CW/TW = 1/4 \) \((d_1 \text{ and } d_2 \text{ coincide in Figure 2})\), we get from Equation [5] \( SV = (V_{ed} - V_{om})/2 \). Experimental verification is shown in Figure 3. We also have:

\[
E_{\text{max}}/e_{\text{am}} = 2 \times CW/SW
\]

Acknowledgements

Disclosure: The author declares no conflict of interest.

References

9. Shoucri RM. Ventriculo-arterial coupling and the areas

![Graphical verification of [5] (left side), and similar relation with the EF = SV/V_{ed} (right side). Experimental data taken from Asanoi et al. (7). Data correspond to three clinical groups: (I) EF ≥ 60% ‘*' ; (II) 40% < EF < 59% ‘o'; (III) EF < 40% ‘x’](image)


Cite this article as: Shoucri RM. Clinical applications of the areas under ESPVR. Cardiovasc Diagn Ther 2013;3(2):60-63.
doi: 10.3978/j.issn.2223-3652.2013.05.05