STRAIN ENERGY RELATED INDICATOR AS AN INDEX OF LEFT VENTRICLE CONTRACTILITY

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INTRODUCTION

The contractile state of the left ventricle (LV) is a decisive factor in the recovering after mitral valve repairment. Currently at the Fundacion CardioInfantil Institute of Cardiology, LV contractility is estimated from physiological values as the ejection fraction (EF) and geometrical ventricular parameters. A new quantitative methodology to estimate ventricular contractile state is designed and applied in this study. The proposed methodology is based on the theory of material characterization, basically on the concepts of Young Modulus and the strain energy related to the area between the stress-strain curve. The methodology was successfully applied to two clinical cases and the obtained indicator seems to be related to contractile state. The methodology and its computational tools are established for a future validation of the obtained indicator.

When the conditions under which the heart works are changed for long periods [i.e. preload, after load, and valve behavior], the contractility of the heart is altered. This physiological alteration responds to the actual working conditions and may become permanent. The measurement of this contractility stage has always been an issue due to the impossibility of making direct in-vivo measurements of the involved variables. In response to this, researches have proposed different approaches to the problem of measuring the heart's contractility [1-3]. These approaches result on indicators derived from invasive or non-invasive diagnostic tools, some indicators are more accurate than others but are mainly affected by the heart's conditions.

The purpose of this work is to develop and apply a methodology to infer an indicator directly related to the heart's ability to contract based on the mechanical properties and energy of the contracting the myocardium. The study aims to combine the magnitude of mechanical stress and deformation of the heart's wall, and the after load to infer an indicator of the mechanical properties of the heart related to its contractility. To obtain the magnitudes of the mechanical stresses and deformation of the heart's wall, a mathematical model [4] fed by physiological variables measured as pressure, dimensions and wall movement of the heart will be used. It is expected that the resulting indicator will be related to the heart's contractile state, once its dependency on the after load is eliminated.

METHODOLOGY

The methodology proposed to obtain the new contractility indicator is schematically described in Figure 1 and explained in the following paragraphs.

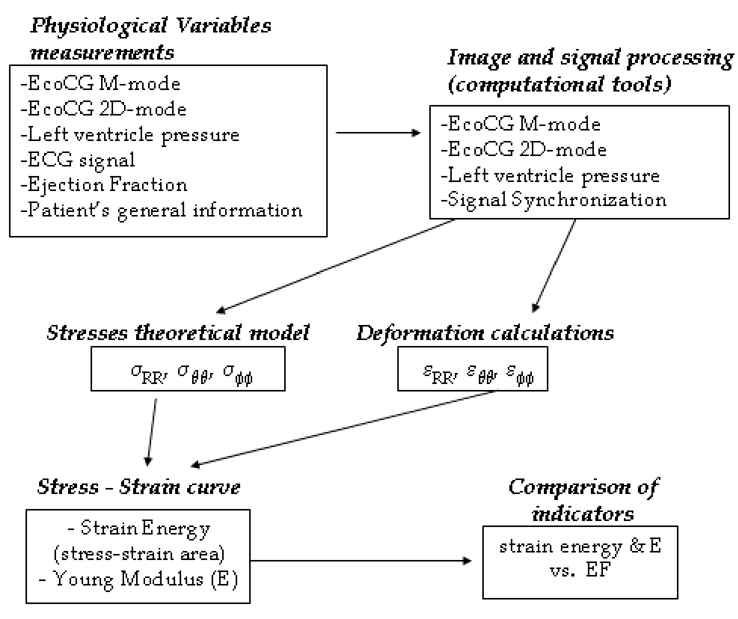

Figure 1. Flow chart of the methodology

The new indicator will be inferred from clinical measurements of physiological variables such as: intra ventricular pressure, ventricular dimensions, LV wall thickness and deformation and ECG signals. These variables are taken from standard clinical diagnostic procedures such as ventricular catheterization and echocardiography (EcoCG).

The diagnostic images given by the EcoCG and the catheter pressure register are manipulated in a computational tool designed in Matlab® (Mathworks) for the quantification, normalization and synchronization of the variables, resulting into the numerical values of the variables for 54 points in a complete cardiac cycle. This tool is divided into four modules "EcoCG M-mode", "EcoCG 2D-mode", "LV Pressure", and "Signal synchronization", as seen on the second block of Figure 1.

Having the numerical values of pressure and ventricular dimensions through the complete cardiac cycle ("LV Pressure" and "EcoCG 2D-mode" modules), an algorithm from the theoretical model of heart streses proposed by Wong [4], is applied and three-dimensional ventricular stresses are found. Ventricular wall strain is calculated from the numerical values of the position of the heart's walls through the cardiac cycle ("EcoCG M-mode" module).

Having the values of stress and strain of the LV in a complete cardiac cycle (54 points), stress is plotted versus strain for all the points of the cycle. The area under this curve is calculated and it represents the energy that was consumed by the ventricle to overcome pressure and strain in the cardiac contraction and relaxation. This area is divided by the maximum intra ventricular pressure in order to eliminate its dependency on after load. This result is the proposed indicator of the heart's contractility, named N-indicator.

Using the theoretical definition of radial strain from Wong's [4] stresses' model and the measured radial strain from the "EcoCG M-mode" module, a value of Young's Modulus is found for each point of the cardiac cycle. Young's Modulus or Modulus of Elasticity (E) is related to the amount by which a material stretches or deforms when a force or stress is applied [5]. E is commonly used in the engineering practice to characterize the stiffness of materials. In this study E is found to observe its behaviour in the myocardium material through the cardiac cycle.

RESULTS

To make a preliminary evaluation of the proposed methodology, it was successfully applied in two clinical cases and the N-indicator was calculated for both. The clinical cases will be referred to as Case 1 and Case 2. N-indicator is later compared to a reference contractility state, measured in standard EcoCG examination, the Ejection Fraction (EF):

$$EF= (DD-DS)*100/DD \tag{1}$$

DD= end of diastole LV diameter, DS= end of systole LV diameter.

This descriptive comparison will have into account the pathological conditions of the examined hearts. The pathological condition of the patient of Case 1 was Coarctation of Aorta (CoAo) with a pressure gradient lower than 20 mmHg. The condition of the patient of Case 2 was Intra ventricular Communication (IVC). Reference parameters and general patient's information are shown in Table 1.

Table 2 shows the indicator found in the developed methodology.

In Case 2 the reference parameter EF is higher than it is in Case 1, while N-Indicator and the maximum deformation are lower. Given the condition of Case 2 (IVC), the higher EF can be related to the fact that this heart has to pump an extra amount of blood that is returning to the right ventricle (RV) through the IVC. Even though this heart is pumping more blood, it is not necessary pumping it at a higher energy of contraction; it does not have high pressures to overcome. On the contrary, part of the blood is exiting at the RV low pressure.

Table 1. Reference Parameters

Parameter	Case 1	Case 2
Ejection Fraction (EF)	38.9%	58.8%
Maximum LV Volume	14.53 ml/ m^2	6.28 ml/ m^2
Maximum LV Pressure	142 mmHg	115 mmHg
Age	7 years	6 months
Height	112 cm	66 cm
Weight	18 Kg	6.5 Kg
Body Surface	0.75 m^2	0.35 m^2

Table 2. New Indicators

Parameter	Case 1	Case 2
Stress-Strain Area	19.2 mmHg	6.7 mmHg
Maximum Deformation	43 %	27 %
N-Indicator	13.5 %	5.8 %

The situation in Case 1 can be seen as opposite, the heart is pumping a lower percentage of blood but it is doing it at a higher energy cost. The pressure inside the LV has to overcome an augmented pressure in the aorta; it is using more energy to do so.

By these observations one can see that the contraction energy related to Indicator-N could give a better sign of the capacity of the LV to contract and of its contractile state than the percentage of blood expelled (EF).

COMMENTS AND CONCLUTIONS

The proposed methodology was successfully applied into two clinical cases. The designed computational tools are effective and time-saving in the quantitative processing of diagnostic images and registers. This methodology and tools are available for its future clinical validation.

The behaviour of the Indicator-N and the maximum deformation seems to be directly related to the contractile stage given the pathological conditions in the two cases. These preliminary observations need future clinical validation.

The curves of Elasticity Modulus vs. cardiac cycle timing do not give yet any quantifiable information about the characterization of the stiffness of the myocardium. Even though they show an irregular pattern of this modulus, showing the non-linear behaviour of the material; situation opposed to the theoretical model of stresses assumptions.

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