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A new approach to assessment of the left ventricle

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A B S T R A C T

Cardiac motion is a continuous process; however most measurements to assess cardiac function are taken at brief moments in the cardiac cycle. Using functional data analysis, repeated measurements of left ventricular volume recorded at each frame of a continuous image measured with cardiac ultrasound (echocardiography) were turned into a function of volume over time. The first derivative of the displacement of volume with respect to time is velocity; the second derivative is acceleration. Plotting volume, velocity, and acceleration against each other in a 3-dimensional plot results in a closed loop. The area within the loop is defined by the kinematics of volume change and so may represent ventricular function.

- We have developed an approach to analyzing images of the left ventricle that incorporates information from throughout the cardiac cycle.
- Comparing systolic and diastolic areas within a loop defined by volume, velocity, and acceleration of left ventricular volume highlights imbalances in the kinematics of the two phases, potentially indicating early sub-clinical disease.
- Substantially more information about left ventricular function may be derived from a non-invasive clinically available tool such as echocardiography.

A R T I C L E I N F O

Method name: Functional data analysis

Keywords: functional data analysis, dynamics, kinematics, left ventricle, sub-clinical dysfunction, imaging, echocardiography

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Method details

Rationale

Cardiac motion is a continuous process; however most measurements to assess cardiac function are taken at brief moments in the cardiac cycle. Systole (contraction) and diastole (relaxation) are interrelated yet they are rarely considered collectively, oversimplifying the interplay of forces through the cardiac cycle. In clinical practice, the contractile function of the main pumping chamber of the heart, the left ventricle (LV), is typically quantified by the ejection fraction (EF), which is calculated from LV volumes at the two brief moments of end-systole and end-diastole. But it provides no information about the motion or duration of the systolic phase itself. All of the current clinically available non-invasive measures of cardiac function extrapolate overall performance from brief moments in time only, and do not incorporate the full phases of systole and diastole.

The LV exhibits periodic motion, with each cardiac cycle starting with the same blood volume at which the previous cycle ended. The net effect of ventricular contraction is displacement of blood, thus LV volumetric changes may be used as a surrogate for global LV motion.

The endocardial border of the LV can be traced and tracked throughout the cardiac cycle. Existing software estimates the volume contained within the endocardial border. This volume can be extracted for each frame of the continuous image, resulting in a dataset of volume measurements every 3-6 milliseconds (depending on the acquisition frame rate). Functional data analysis (FDA) replaces the repeated measurements at discrete moments in time with a function of that measurement over continuous time [1]. The first derivative of the displacement of volume with respect to time is velocity, or the rate of change in volume. The second derivative of displacement with respect to time is acceleration. This represents the addition or removal of forces that produce the change in volume. If the rate of change in volume displacement (velocity) is of interest then it follows that what causes that change (acceleration) is also of interest.

In mechanical systems, plotting volume against one or more of its derivatives creates a plot in 'phase space' – a space that represents a measurement and the rates of change of that measurement [1,2]. Plotting the volume data with either method results in a closed loop because the motion of the heart is a periodic process. The area within the loop is defined by the kinematics of volume change and so may represent ventricular function. Zero velocity defines the border between systole and diastole, allowing areas to be calculated separately for the two phases under the same loading conditions.

Force-frequency studies on tissue samples from failing ventricles have found that along with a decrease in systolic force, diastolic force increases as the rate of stimulation increases [3,4]. Cellular transport mechanisms become impaired in failing myocardium [4,5] and chronic diabetes [6]. As a result of slowed decay of the intracellular calcium transient there is a deleterious accumulation of intracellular calcium, which is associated with a rise in diastolic force. The rise in force is from persistent activation of contractile proteins during diastole, requiring greater energy at rest and as rate increases. Comparing the systolic to diastolic area in our loops would highlight imbalances in the kinematics of the two phases, potentially indicating early sub-clinical disease, where early changes to myocardial function due to impaired glucose metabolism, for example, are thought to affect the diastolic phase before the systolic.

Thus the relationship between systolic and diastolic kinematics derived from a non-invasive clinically available tool such as echocardiography, may tap into findings that have previously only been able to be assessed in explanted tissue samples.

Method

1. The volume data are replaced by a sum of periodic Fourier components. This sum specifies the form of the volume curve over time as a function. Numerical approximations to the first and second order derivatives are then calculated, representing velocity and acceleration respectively.
2. The dataset of time, volume, velocity and acceleration are each centred on their means so that the loop lies close to the projected plane, decreasing the risk of overestimation.