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Original Citation:

Three-dimensional reconstruction of the functional strain-line pattern in the left ventricle from 3-dimensional echocardiography / J. O. Mangual; A. De Luca; L. Toncelli; F. Domenichini; G. Galanti; G. Pedrizzetti. - In: CIRCULATION. CARDIOVASCULAR IMAGING. - ISSN 1941-9651. - STAMPA. - 5:(2012), pp. 808-809. [10.1161/CIRCIMAGING.112.979385]

Published version:
DOI: 10.1161/CIRCIMAGING.112.979385

Three-Dimensional Reconstruction of the Functional Strain-Line Pattern in the Left Ventricle From 3-Dimensional Echocardiography

Jan O. Mangual, PhD; Alessio De Luca, MD; Loira Toncelli, MD; Federico Domenichini, PhD;
Giorgio Galanti, MD; Gianni Pedrizzetti, PhD

Advances in 3-dimensional (3D) echocardiography offer a rapid, effective imaging technique with adequate temporal and spatial resolution for left ventricular motion assessment. 3D multidirectional tracking of the endocardial left ventricular layer has shown that the functional pattern of directional strain arrangement during cardiac contraction closely relates with the structural architecture of the myocardial helical muscle fiber orientation.[1] In a similar manner, we carried out segmentation tracking of the endocardial-epicardial layers in 10 healthy young athletes (nonprofessional athletes, enrolled at the Sport Medicine Center of the University of Florence, Italy, training 2–3 days a week for 2 hours daily; all exhibiting an excellent echographic window) to evaluate the 3D strain pattern over the whole myocardium thickness and to compare with the hypothesized underlying fiber architecture. An echocardiographic 3D full-volume image of the left ventricular was recorded by a Philips IE33 machine (frame rate, 15–30 Hz). Imaging data were processed by 3D feature tracking (4DLVA 3.0; TomTec Gmbh, Unterschleissheim, Germany), and the endocardial and epicardial tracked surfaces were exported for the following principal strain analysis.[1]

Principal strain analysis allows to define the direction along which the main contractile strain (S1) develops, accompanied by a secondary strain (S2) that is typically of much lower intensity and by a thickening (positive strain, S3, that is a consequence of tissue incompressibility $S1+S2+S3\approx 0$). The analysis identifies the directions along which such strains act, such that, relative to such directions, shear deformations are absent. Therefore, this approach gives a physics-based synthesis of the overall 3D deformation pattern into 1 principal strain (S1) and 1 secondary strain (S2), with the third strain following from incompressibility.

Figure 1 depicts the principal end-systolic strain pattern on the subendocardial, subepicardial layers and short axial slices along the left ventricle (left and right images, respectively; see also Video I in the online-only Data Supplement for the time course). All the images are an average of the volunteers to reduce the noise that results from the echography and the inaccuracies of the 3D echocardiography tracking. Besides noise, individual cases within this homogeneous group did not deviate much from the shown pattern. Results show similar directions of the principal end-systolic strain to those reported by magnetic resonance diffusion tensor imaging.[2] The principal strain lines showed a remarkable relation with the reported orientation and activation sequence of the muscle fibers reported with combined displacement encoding with stimulated echoes and cine strain encoding DENSE-SENC imaging,[3] thus suggesting that the contraction is predominantly driven by shortening along 1-dimensional muscular fibers (see Video II in the online-only Data Supplement for time sequence of the primary strain) with minor connectivity along the transversal directions (see Video III in the online-only Data Supplement for time sequence of the secondary strain). It must be noted that the functional direction of contraction must not necessarily coincide with the anatomic direction of the fibers; the 2 entities are complementary and integrative, the former reveals how the activation of the latter contributes to the reduction of cavity volume. It is interesting to see how contraction is initially driven along similar contractile paths about the endocardium and epicardium levels; during the cardiac cycle, the subepicardial layer maintains a mostly circumferential strain path, whereas the subendocardium has regions of longitudinal and circumferential shortening.

The time profiles of the 3 principal strains are plotted in Figure 2. The curves represent the average on the 10 subjects, with bars representing the SD. The direction of the most positive strain (S3) on the short axial plane was verified to exhibit a dominant radial direction (thickening) as reported,[4] supporting a strong validation of this approach using 3D echocardiography. The principal strain (S1) is directly driven by the result of shortening of fibers. The small entity of secondary strain (S2), instead, transversal to the principal strain, evidences the anisotropic character of contraction. In synthesis, the principal strain reflects an effective measure of

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Received July 31, 2012; accepted October 17, 2012.

From the Department of Civil and Environmental Engineering (J.O.M., F.D.) and Sport Medicine Center (A.D.L., L.T., G.G.), University of Florence, Florence, Italy; Department of Engineering and Architecture, University of Trieste, Trieste, Italy (G.P.); and Department of Cardiology, Mount Sinai School of Medicine, New York, NY (G.P.).

The online-only Data Supplement is available at http://circimaging.ahajournals.org/lookup/suppl/doi:10.1161/CIRCIMAGING.112.979385/-/DC1.

Correspondence to Jan O. Mangual, PhD, Department of Civil and Environmental Engineering, University of Florence, Via S. Marta 3, 50139 Florence, Italy. E-mail jmangual@dicea.unifi.it

(*Circ Cardiovasc Imaging.* 2012;5:808-809.)

***Circ Cardiovasc Imaging* is available at http://circimaging.ahajournals.org** **DOI: 10.1161/CIRCIMAGING.112.979385**

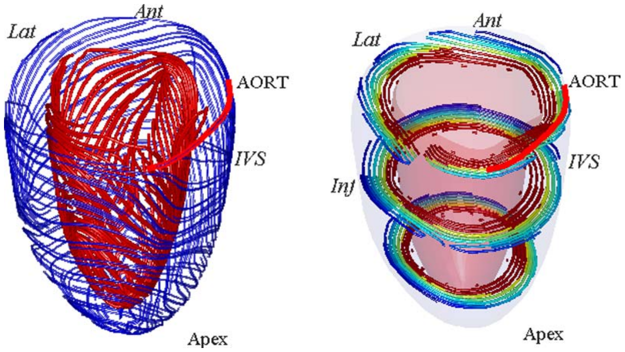

Figure 1. Three-dimensional principal strain-line patterns over the myocardium at end systole. **Left**, the epicardial layer with blue stream lines and the endocardial layer with red stream lines. **Right**, the short axial view of 3 anatomic planes (basal, mid, and apical), with streamline color pattern changing from blue at the subepicardium to red at the subendocardium. Ant indicates anterior; Lat, lateral; AORT, aorta; IVS, intraventricular septum (which extends along the red line shown on the endocardial layer); and Inf, inferior.

tissue contractility, with minor transversal connectivity and consequent radial thickening. The peculiar small contribution of the secondary strain suggests that it may represent a sensible indicator of initial contractile alterations during early stages of a disease. Its spatial distribution (Video III in the online-only Data Supplement) shows that S2 exhibits regional dilation during contraction along the principal direction.

These results are subjected to several limitations because of the 3D echocardiography technology and the 3D tracking method. Care was taken to verify that end-systolic global longitudinal strain values were comparable with values obtained by 2D echocardiography, sometime requiring multiple refinements of the 3D tracking procedure. This analysis was possible as a result of the very good image quality of this special group of subjects and may not be generally applicable. Nevertheless, the finite region required for tracking implies that results from endocardium and epicardium are reciprocally influenced and sharp transmural changes are not detectable. The benefits of such application are the ease and quick acquisition of echocardiography imaging in the clinical setting. The analysis of strain in terms of patterns may be useful in verifying wall motion abnormality at early stages, ie, specifically in the case of postinfarction remodeling where myocardial fibers disarray.

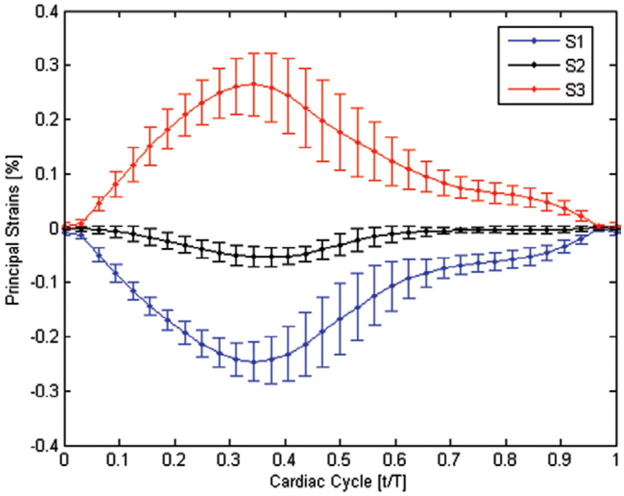

Figure 2. Time evolution of the 3 global principal strains (averaged over the entire myocardium) obtained from the 10 athletes analyzed. Data correspond to the mean data value (**solid lines**) with its corresponding SD (**error bars**). S1 corresponds to the principal contractile strain, S2 is the secondary contractile strain, and S3 is the positive strain mostly represented by thickening along the radial direction.

Sources of Funding

J.O.M. is supported by the Whitaker International Scholars Program.

Disclosures

None.

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Key Words: left ventricle 3D strain ■ 3D echocardiography ■ principal strain ■ fiber orientation ■ contractile function