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How Does the Left Ventricle Work? Ventricular Rotation as a New Index of Cardiac Performance

Jae-Kwan Song, MD

Division of Cardiology, Asan Medical Center, University of Ulsan College of Medicine, Seoul, Korea

ABSTRACT

Although simple cylindrical or ellipsoidal left ventricular (LV) geometry with transverse or circumferential muscle contraction has been traditionally used to estimate LV performance, the estimated LV ejection fraction (EF) with muscle fiber shortening up to 20% is less than 50% of maximum, which is lower than the normal EF observed in routine clinical practice. Thus, oblique fiber orientation and LV rotation, in addition to radial thickening and longitudinal shortening, is predicted as an essential component of effective LV pumping. This was confirmed by animal experiments using surgically implanted markers or invasive sonomicrometry. Demonstration of the muscle band extending from the pulmonary artery to the aorta, which connects the ventricular myocardium, both right ventricle and LV as a continuous band (muscle band theory) provides an anatomical backbone of helical configuration of the cardiac muscle band with descending and ascending segments wrapping the LV apex. Moreover, sequential, non-simultaneous, activation and contraction of the helicoids muscle band contributes to LV rotation or twist motion. Recently, magnetic resonance imaging and speckle tracking echocardiography (STE) techniques have provided an excellent noninvasive way to measure LV rotation and twist, which is expected to contribute to a more thorough evaluation of both LV systolic and diastolic function. Initial animal experiments showed that quantification of apical rotation or LV twist using STE is more accurate for estimating LV systolic function than conventional EF under a variety of LV inotropic conditions, irrespective of coronary ligation. As de-rotation or the untwisting rate can also be measured by STE, the role of ventricular untwisting as a temporal link between LV relaxation and suction can be addressed. Further clinical investigations are needed to determine the real clinical impact of these new indices of LV mechanical function. **(Korean Circ J 2009;39:347-351)**

KEY WORDS: Ventricular function; Rotation; Echocardiography.

In routine clinical practice, assessment of left ventricular (LV) contractility is probably one of the most important tasks during evaluation of cardiac function. Quantitative indices of LV systolic function, such as ventricular volumes, ejection fraction (EF), and fractional shortening, are believed to mainly reflect radial thickening and longitudinal shortening of transverse or circumferential muscle fibers. Simultaneous activation without any dys-synchrony has been regarded as a hallmark of a normally functioning LV. However, recent animal and clinical investigations documented both the structural anisotropy and the regional heterogeneity of mechanical shortening and lengthening sequences in the LV wall, which result in a highly efficient global function of the normal heart.

Correspondence: Jae-Kwan Song, MD, Division of Cardiology, Asan Medical Center, University of Ulsan College of Medicine, 388-1 Pungnap-dong, Songpa-gu, Seoul 138-736, Korea
Tel: 82-2-3010-3150, Fax: 82-2-486-5918
E-mail: jksong@amc.seoul.kr

Pump Function and Fiber Orientation: The Fallacy of the Simple Sliding Theory

The major function of the heart is to pump an adequate amount of blood, and this is critically dependent on execution of the contraction-relaxation cycle. The major molecules involved in the contraction-relaxation cycle are the two chief contractile proteins, the thin actin filament and the thick myosin filament. During contraction initiated by increased concentrations of calcium, the filaments slide over each other without the individual molecules of actin or myosin actually shortening. As they slide, they pull together the two ends of the fundamental contractile unit, the sarcomere. During relaxation, the two overlapped filaments slide back to their original positions, as a decreased calcium level fails to interact with the troponin complex, which inhibits the binding of actin and myosin. This 'sliding theory' remains the most reliable mechanism for explaining systolic radial thickening or longitudinal shortening of the LV, which we observe with various cardiac imaging modalities in daily routine clinical practice. The resultant changes in LV volumes during the cardiac cycle is used to calculate the EF, which has been the most popular index for representing LV pump function in clinical practice.

EF is higher than 50% in the normal human LV and the importance of fiber orientation in maintaining normal EF has been an interesting and challenging physiologic issue. Preparations of isolated papillary muscle rarely, upon stimulation, exhibit shortening in excess of 20%. Using various mathematical models of LV geometry, estimated EF is less than 50% when only circular or constrictor fibers are considered to constitute the LV (Fig. 1).[1)2)] For example, 20% shortening of circular muscle fibers corresponds to an EF of only 36% for the ellipsoid or cylinder model and 48.8% for the spherical model. To have a normal EF >50% with less than 20% shortening of muscle fibers, a different fiber orientation is needed. The most effective fiber orientation is a helical or spiral one, with which virtually any EF is possible depending on the LV geometry and the pitch angle of the spiral fiber. Thus, rotating movements of the helical fibers, rather than simple thickening or shortening of longitudinal or circular fibers, is a fundamental mechanism of LV contraction, and, more than 400 years ago, it was postulated that myocardial contraction could be compared to the wringing motion of a wet linen cloth to squeeze out the water.[3)4)]

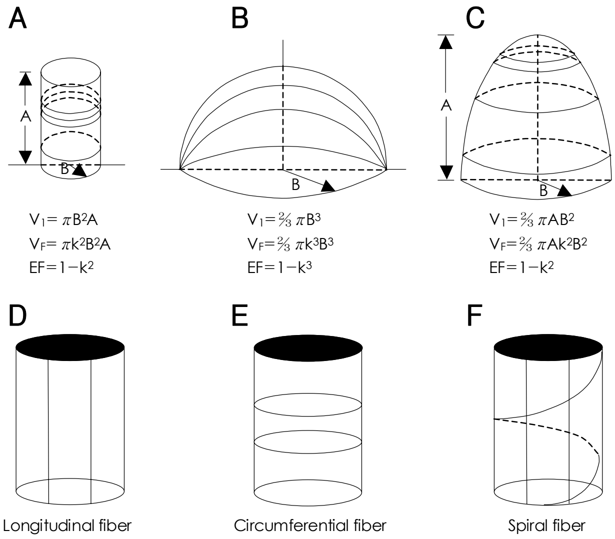

Fig. 1. Diagrams showing various fiber geometries and mathematical models of the left ventricle for calculation of ejection fraction (EF). Upon stimulation, uniform shortening of the individual fibers to k times their initial lengths results in a radius change from B to kB with the indicated EF. If k=0.8 in circular fibers, which corresponds to a 20% shortening, this corresponds to an EF of only 0.36 for the cylinder (A) or ellipse of revolution (B) and 0.488 for the sphere (C). In a cylindrical model with longitudinal fibers (D), 15% fiber shortening results in only a 15% reduction in chamber volume, whereas with circumferential fibers (E), 15% fiber shortening results in only a 30% reduction in volume. Depending only upon the cylinder dimensions and the pitch angle of the spiral fibers (F), virtually any ejection fraction (up to and including 100%) could be generated from spiral fibers capable of shortening only 15% (modified from references 1 and 2).

Muscle Band Theory and Sequential Muscle Contraction

Recently, it has been proposed that the ventricular myocardium, both right ventricle and LV, exists as a continuous muscle band.[5)] Careful anatomic studies have established the way the cardiac band should be unrolled and this unique anatomy and spatial configuration of the myocardial muscle determine the way ventricular ejection and filling take place. Unwrapping occurs easily, with least resistance, along a natural cleavage plane, which includes the anterior interventricular sulcus and the cleavage plane defined by two muscular strata, the fibers of the descending segment and the fibers of the ascending segment (Fig. 2). In this way, the muscle band extends from the pulmonary artery to the aorta. Helical configuration of the cardiac muscle band can be easily appreciated in the schematic drawing in Fig. 2. This unique spatial configuration provides apical and basal loops, and an anatomical backbone for effective ventricular performance based on LV rotation or twist.

Recent sophisticated electrophysiologic and cine-angiographic studies have demonstrated the physiologic nonuniformities of regional LV performance.[6-9)] Tradi-

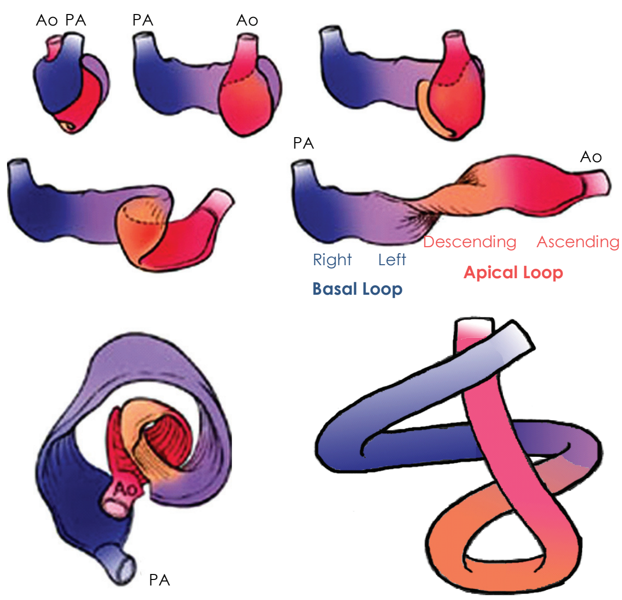

Fig. 2. Representative illustrations demonstrating the muscle band extending from the pulmonary artery (PA) to the aorta (Ao) which connects the ventricular myocardium, both right ventricle and LV, as a continuous band. This band provides an anatomical backbone of helical configuration of the cardiac muscle band with descending and ascending segments wrapping the LV apex. The helical configuration of the cardiac muscle band results in two loops at the cardiac base and apex (modified from reference 5). LV: left ventricular.

tionally, simultaneous contraction of the whole LV, or synchrony, has been regarded as a hallmark or an important prerequisite for normal LV performance. However, LV muscle does not contract simultaneously at all, and the actual sequence of mechanical ventricular activation closely follows the helicoids trajectory of the myocardial band.[10] It is conceivable, therefore, that sequential contractile activity of the peculiar helicoids structure of the ventricular myocardium allows upward and downward movements as well as rotation. The initial segment to be activated is the basal region of the ventricle, first the RV segment and then the LV, making a characteristic clockwise rotation of the basal loop. Subsequent contraction of the descending segment pulls the ventricular base downward, thereby shortening the long axis of the ventricular cavity, reducing its volume and allowing ventricular ejection. Contraction of the ascending segment then results in an increase in the longitudinal axis of the ventricles and an upward displacement of the base of the heart, which increases the ventricular volume. The helical spatial orientation of the descending and ascending segments winding around the LV apex contributes to the counter-clockwise rotation of the LV apex during systole. Thus, during ventricular contraction, two opposite basal and apical rotations result in LV twist, which leads to LV wringing or torsional deformation during systole, and this action is believed to generate the required pumping power.

Left Ventricular Torsion in Clinical Practice

Noninvasive measurement of LV twist or rotation has been possible by magnetic resonance imaging or speckle-tracking echocardiography (STE) (Fig. 3). Traditionally, counter-clockwise apical rotation angles are illustrated as positive values, and clock-wise basal rotation as negative values. Twist is defined as the net difference of these two rotation angles and LV torsion can be calculated as LV twist divided by LV size.

There are several clinical fields where noninvasive assessment of LV twist or rotation could be applied. One is assessment of LV systolic function. Animal and clinical experiments using invasive surgically implanted markers or sonomicrometry or noninvasive magnetic resonance imaging showed that LV rotation is sensitive to changes in both regional and global LV function.[11-14] Thus, quantification of LV rotation or twist is expected to be useful for assessing LV systolic function. In an open chest canine model, apical rotation, not basal rotation, exhibited dose-dependent changes in response to pharmacological modulation of inotropic status. Moreover, apical rotation and LV twist measured by STE were highly correlated with dP/dt_{max}, an invasive index of LV contractility, under a variety of LV inotropic conditions, irrespective of coronary ligation. A comparison of the R^2 values demonstrated that a more accurate measure of LV contractility is provided by LV twist or apical rotation alone, rather than LVEF (Fig. 4).[15] These observations suggest that STE measurement of apical rotation alone provides a noninvasive assessment of LV contractility. This is an important finding as there is a major concern about the feasibility of doing LV twist or torsion measurements in clinical practice due to the tremendous difficulty in obtaining reliable measurements of basal rotation.[16] Longitudinal motion of the LV causes the myocardium to move in and out of the image plane, and this is more pronounced at the LV base. The clini-

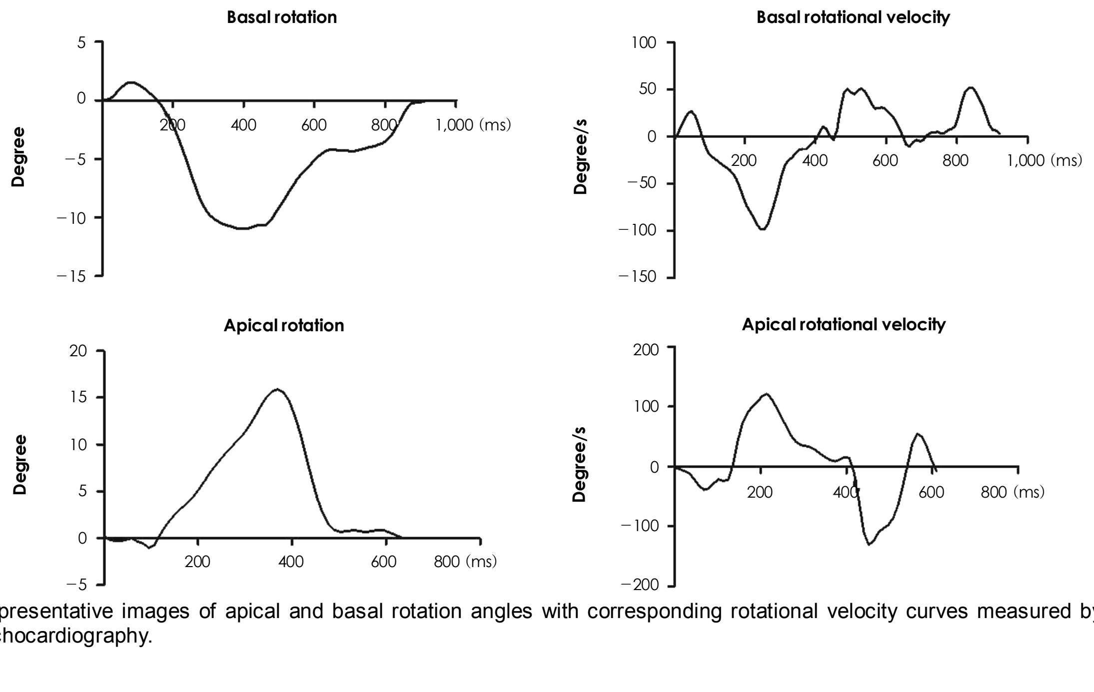

Fig. 3. Representative images of apical and basal rotation angles with corresponding rotational velocity curves measured by speckle tracking echocardiography.

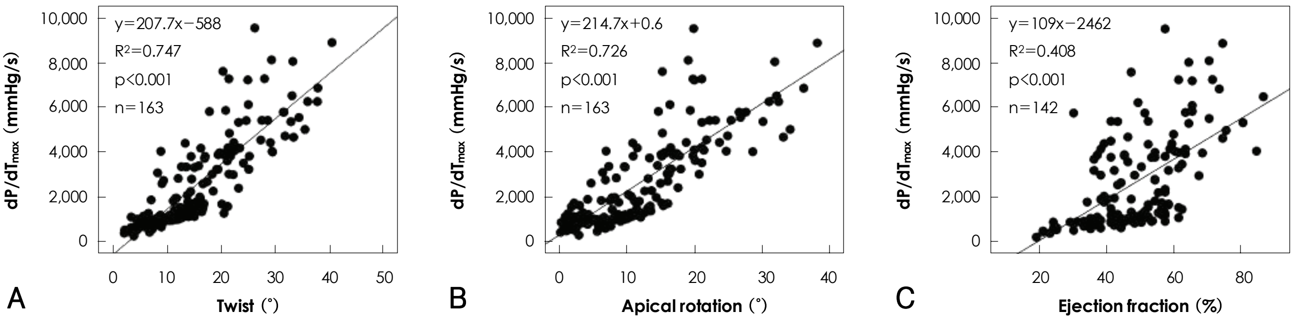

Fig. 4. Association between dP/dt_{max}, an invasive gold standard of LV contractility and left ventricular twist (A), apical rotation (B) and ejection fraction (C)(modified from reference 15). LV: left ventricular.

cal impact of apical rotation as a more accurate measure of LV contractility compared to conventional LV-EF needs to be determined.

Diastology is another potential area for clinical application of LV twist or rotation, and LV twist/rotation is expected to contribute to our understanding of LV relaxation and suction. LV systolic twisting deformation is one mechanism by which potential energy is stored during ejection, to be better released during diastole and contribute to the creation of suction. In systole, as the base and apex of the heart rotate in the opposite direction and generate twisting of the heart muscle, part of the energy used in contraction is stored within the extracellular collagen matrix and compressed within the myocytes. During relaxation, this energy is promptly released and manifested by LV untwisting. About 40% of the LV untwisting occurs during isovolumic relaxation, and its rate correlates with the time constant of LV pressure decay (tau). As de-rotation or the untwisting rate can be easily measured by STE, the role of ventricular untwisting as a temporal link between LV relaxation and suction can be addressed. In an animal experiment, it was found that the start of LV untwisting coincided with the beginning of relaxation and preceded suction-aided filling that results from elastic recoil.[17] The untwisting rate may be a useful marker of diastolic function or even serve as a therapeutic target for improving diastolic function.

Conclusions

Recent noninvasive imaging techniques provide us with a totally new window for estimation of different aspects of LV mechanical function. Assessment of rotation/de-rotation or twist/untwist seems to be essential in a thorough understanding of both systolic and diastolic LV function. Further clinical investigations are needed to determine the real clinical impact of these new indices of LV mechanical function.

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