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Left Ventricular Twist in Cardiomyopathy

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1. Introduction

Merely 50 years ago, Inge Edler and Helmut Hertz were the first to use an ultrasound transducer, borrowed from a local shipyard where it was used for the detection of cracks in metal plates, to record the motion of cardiac structures. Ever since then, the clinical use of echocardiography has steadily increased. Echocardiography is an attractive imaging modality for several reasons. It is highly available, relatively inexpensive, it does not involve ionising radiation, and images are displayed in realtime allowing prompt diagnosis. However, despite a staggering technical progress in echocardiography, regional myocardial function was, until recently, still assessed by visual analysis of wall motion, a relatively inaccurate and poorly reproducible manner.

During the last 10 years, tissue Doppler imaging has been developed to quantify regional myocardial function [1]. Initially formatted as a one-dimensional method for measurement of regional longitudinal myocardial velocity profiles, tissue Doppler imaging has been further developed to allow measurements of one-dimensional regional strain [2]. This index measures local deformation as opposed to (passive and active) motion and thereby better reflects regional myocardial function. However, tissue Doppler imaging is inextricably limited by the angle-dependency of the technique. Because of this limitation, it is not clinically feasible to measure myocardial deformation in directions not parallel to the direction of the Doppler beam, such as left ventricular rotation. Although some have tried to override this limitation by applying complex algorithms [3], measurement of left ventricular rotation by echocardiography has only recently become clinically feasible by the development of speckle tracking echocardiography.

1.1. Left ventricular twist

In the 16th century, Leonardo daVinci already described the rotational motion of the left ventricle [4,5] and in 1669, Richard Lower observed that myocardial contraction could be compared with 'the wringing of a linen cloth to squeeze out the water' [6]. The mechanistic basis for this wringing motion or twist lies in the complex spiral architecture of the left ventricle as revealed by the anatomical studies of Streeter et al. [7] and Greenbaum et al. [8] The left ventricle consists of obliquely oriented muscle fibres that vary from a smaller-radius, right-handed helix at the subendocardium to a larger-radius, left-handed helix at the subepicardium. The functional consequence of this three-dimensional helical structure is a cyclic systolic twisting deformation, resulting from clockwise basal rotation and counterclockwise apical rotation (as seen from the apex). Left ventricular twist plays a pivotal role in the mechanical efficiency of the heart, making it possible that only 15% fibre shortening results in a 60% reduction in left ventricular volume [9]. Moreover, diastolic untwisting of the left ventricle plays a crucial role in diastolic suction [10]. In the last decades, left ventricular twist has mainly been studied with tagged magnetic resonance imaging (MRI). However, lack of availability, limited temporal resolution, and the time-consuming and complex data analysis have precluded its use in routine clinical practice. More recently, it became possible to study left ventricular twist with tissue Doppler techniques and two-dimensional speckle tracking echocardiography. As mentioned before, this latter technique offers the opportunity to track myocardial deformation independently of both cardiac translation and the insonation angle.

1.2. Assessment of left ventricular twist

Ever since the description of the rotational motion of the left ventricle by Leonardo da Vinci [4,5] in the 16th century, left ventricular twist has intrigued clinicians and researchers in their quest to understand the performance of the human heart. In the early 1960s, Harrison et al. [11] developed a method to measure external ventricular wall dimensions during the cardiac cycle. Silver tantalum clips were sutured into the human epicardium during cardiac surgery and these markers were viewed by calibrated cineradiographs. Ingels et al. [12] further developed this technique and studies of left ventricular twist continued throughout the 1980s. Unfortunately, progress was limited due to the invasive nature of the technique with its inherent limitations; the surgical implantation of the clips frequently led to local inflammation, hemorrhage and fibrosis, possibly affecting left ventricular twist. In addition, implantation of the clips could only be done in surgically accessible areas, which limited the left ventricular areas studied. In 1990, Buchalter et al. [13] described for the first time the non-invasive assessment of left ventricular twist with MRI. A tagging technique was employed to label specific areas of the myocardium prior to image acquisition. Tagging is achieved by selective radio-frequency excitation of narrow planes and appears as black lines on the image acquisition. Using dedicated software, displacement of these tagging lines can be monitored, allowing quantification of left ventricular deformation. However, the limited availability, the poor temporal resolution, and the time-consuming and complex data analysis have precluded its use in routine clinical practice.

More recently, assessment of left ventricular twist by speckle tracking echocardiography has become available. The fundamental principle of deformation imaging by speckle tracking echocardiography is simple. A certain segment of myocardial tissue is shown in an ultrasound image as a pattern of gray values caused by the interference of ultrasound reflected by the tissue. Such a pattern, resulting from the spatial distribution of the gray values, is commonly referred to as a speckle pattern. If the position of the myocardial segment within the ultrasound image changes, one can presume that the position of the speckle pattern will change accordingly. Since each region of the myocardium has its own rather unique speckle pattern, the speckle pattern can serve as a fingerprint of the region of interest of the myocardium. Furthermore, given a sufficiently high frame rate, it can be assumed that particular speckle patterns are preserved between subsequent image frames [14]. Thus, tracking of the speckle pattern during the cardiac cycle allows one to follow the motion of this myocardial segment within the two-dimensional ultrasound image. Several studies have shown [15,16] that twist data derived from commercially available speckle tracking software correlated well with tagged MRI. To be able to evaluate serial studies of left ventricular twist by speckle tracking echocardiography in the same patient, the technique needs to be reproducible as well. Van Dalen et al. [17] studied the feasibility and variability of left ventricular twist measurement and found that the method is feasible in approximately two thirds of subjects and has good intraobserver, interobserver and temporal reproducibility, allowing to study changes over time in left ventricular twist in an individual patient.

In this chapter, the important physiological role of left ventricular twist and untwist will be explained. Furthermore, cardiomyopathies may show striking alterations of left ventricular twist. The pathophysiological background and potential clinical role of these changes is discussed.

2. Physiology of left ventricular twist

According to the Hippocratic treatise "On the Heart", the heart is shaped like a pyramid, has a deep crimson colour, and is an extremely strong muscle. From the top of the heart, rivers that irrigate the "mortal habitation" flow into the body. If these rivers dry up, then the person dies [18]. Leonardo da Vinci's investigations of the heart and circulation began nearly 18 centuries later, in the 1490s. Da Vinci made a number of advances in the understanding of the heart and blood flow. For example, he showed that the heart is indeed a muscle, that it has four chambers and he linked the pulse in the wrist with left ventricular contraction. Furthermore, as mentioned before, Da Vinci was the first to describe the rotational motion of the left ventricle [4,5]. However, it lasted until the late 1960s before left ventricular twist was described in more detail by Streeter et al. [7] following a study of post-mortem canine hearts. Using a rapid method of fixation, they were able to analyze these hearts in either systole, begin diastole or end-diastole. Fibre angle, representing the angle between the myofibres as projected onto the circumferential-longitudinal plane and the circumferential axis, was introduced for quantification of fibre orientation. This angle changed continuously from the subendocardium to the subepicardium, typically ranging from +60 degrees at the subendocardium to -60

degrees at the subepicardium. Left ventricular twist is supposed to originate from the dynamic interaction between these oppositely wound subepicardial and subendocardial myocardial fibre helices, whereby the direction of left ventricular twist is governed by the subepicardial fibres, mainly owing to their longer arm of movement [19]. Left ventricular twist plays a pivotal role in the mechanical efficiency of the heart, making it possible that only 15% fibre shortening results in a 60% reduction in left ventricular volume [20]. Furthermore, mathematical models have shown that the counterdirectional arrangement of muscle fibres in the heart is energetically efficient and important for equal redistribution of stresses and strain in the heart [21]. However, controversy remains present. The group of Buckberg published in 2005 a comprehensive compendium, "Rethinking the cardiac helix; a structure function journey", of the Liverpool meeting: "New concepts of cardiac anatomy & physiology" [22]. Buckberg et al. believe that, based on anatomical studies by Torrent-Guasp [23] the heart is a helix that contains an apex, and that sequential contraction of the basal, descending, and ascending loop of the helix leads to the physiological pattern of myocardial contraction [24]. Although interesting, other anatomical studies have failed to reproduce the findings of Torrent-Guasp, and during the past few years this latter theory seems to gradually lose appreciation as compared to the theory of dynamic interaction between oppositely wound subepicardial and subendocardial myocardial fibres [25]. Taber et al. [19] used a theoretical model to underscore the importance of the arrangement of myocardial fibres for left ventricular function. Peak systolic twist approximately doubled with a change in de epicardial / endocardial fibre angles from +90 degrees / -90 degrees to +60 degrees / -60 degrees. The importance of fibre orientation for left ventricular twist was highlighted in clinical context as well [26]. Left ventricular sphericity index was found to have an independent positive linear relation with peak systolic twist in dilated cardiomyopathy patients. Even in dilated cardiomyopathy patient with similar left ventricular ejection fraction, left ventricular sphericity index remained positively correlated to left ventricular twist. Interestingly, in normal hearts the left ventricular sphericity index had a parabolic relation with apical peak systolic rotation and peak systolic twist. A left ventricular sphericity index of about 2.1 was associated with the highest peak systolic twist, lower and higher sphericity indices were associated with less peak systolic twist. The findings of this study seem to support the hypothesis by Taber et al. that alterations in fibre-orientation influence left ventricular peak systolic twist. Furthermore, the curvature of the left ventricular wall is related to wall tension. Since deformation of myocardial fibres is known to be inversely related to wall tension, changes in cardiac shape may also lead to changes in left ventricular twist by means of alterations in wall tension [21].

In 1995, Moon et al. [27] investigated the effects of load and inotropic state on left ventricular twist. They studied 6 cardiac transplant recipients 1 year after heart transplantation. At the time of surgery 12 radiopaque midwall left ventricular myocardial markers were implanted. The authors claimed that pressure and volume loading did not affect left ventricular twist. However, in more recent tagged MRI studies by MacGowan et al. [28] and Dong et al. [29] it has been shown that afterload changes do affect left ventricular twist. Dong et al. also investigated the influence of preload and contractility. An isolated increase in preload resulted in an increase in left ventricular twist. From a multiple linear regression analysis, they concluded that the effect of preload on left ventricular twist was about two-thirds as great as that of

afterload. Since left ventricular twist is critically dependent on the arrangement of fibres in the myocardium, the dependence of left ventricular twist on pre- and afterload-induced changes in left ventricular volumes is intuitive. Dong et al. also observed that dobutamine increased left ventricular twist, even at identical pre- and afterload, indicating that there is a direct inotropic effect on left ventricular twist that is not mediated through changes in volume, but through changes in force.

Finally, several groups investigated the influence of aging on left ventricular twist [30-32]. Nakai et al. [30] and Takeuchi et al. [31] reported increased left ventricular twist with aging. Because left ventricular peak systolic twist is calculated as the maximal value of *instantaneous* left ventricular apical rotation minus left ventricular basal rotation, any difference between the timing of left ventricular basal and apical peak systolic rotation (defined as rotational deformation delay) will result in less left ventricular peak systolic twist. In a study by Van Dalen et al. [32] it was shown that the increase of left ventricular twist with aging results not only from an increase in apical peak systolic rotation but also from a decrease in rotational deformation delay. The function of subendocardial fibres declines with age, even in normal hearts [33,34]. Loss of the opposed action of subendocardial fibres will allow the subepicardial fibres to cause more pronounced left ventricular apical rotation and thereby left ventricular twist. Time-to-peak left ventricular basal rotation remained relatively unchanged with aging, whereas left ventricular apical peak rotation occurred later in systole with advancing age, approaching time-to-peak basal rotation and thereby decreasing rotational deformation delay. Although the increase in time-to-peak left ventricular apical rotation may be caused by an increase in collagenous tissue in the conduction system with advancing age [34], this would implicate an increase in time-to-peak left ventricular basal rotation as well, leaving rotational deformation delay unchanged. The increase in time-to-peak left ventricular apical rotation with advancing age may also be explained by prolonged contraction duration, which was previously found in aged myocardium of animals [35,36]. This prolonged contraction duration results from a prolonged active state rather than changes in passive properties or myocardial catecholamine content [37]. Whether this is the true explanation of the increase in time-to-peak left ventricular apical rotation with advancing age, and why time-to-peak left ventricular basal rotation would not be influenced by this phenomenon, still needs to be clarified. Nevertheless, both increased left ventricular apical rotation and decreased rotational deformation delay seem to be characteristics of "physiological cardiac aging", and may contribute to the preservation of left ventricular ejection fraction in the elderly.

3. Physiology of left ventricular untwist

Untwisting starts after the peak of left ventricular twist, just before the end of systole. The twisting deformation of the left ventricle during systole results not only in ejection of blood but also in storage of potential energy. During the isovolumic relaxation period the twisted fibres behave like a compressed coil that springs open while abruptly releasing the potential energy. This process may be actively supported by still depolarized subendocardial fibres that are – in contrast to the systolic period – now not opposed by active contraction of the subepi-

cardial fibres [38]. However, the effective force of contraction of myocardial fibres is expected to be minimal during this part of the cardiac cycle. Nevertheless, dissimilarities of apparent stiffness of the endocardium and epicardium caused by differences in breakdown of actin-myosin cross-bridges may be of influence. The group of Shapiro and Rademakers was one of the first to investigate the physiology of left ventricular untwisting in more detail with MRI [39]. They found, in an open-chest canine model, that left ventricular untwisting and filling are dissociated in time. In the normal resting heart about 40% of left ventricular untwisting occurs during isovolumic relaxation. Dobutamine enhanced the extent of left ventricular untwisting before mitral valve opening and further accentuated the dissociation between left ventricular untwisting and filling. The untwisting rate, the mean left ventricular untwisting velocity during the isovolumic relaxation phase, is proportional to the rate of isovolumic pressure decay [40]. In addition, left ventricular untwisting precedes and is a strong predictor of the intraventricular pressure gradient, a marker of diastolic suction during early left ventricular filling. This may be caused by a temporal dispersion between basal and apical de-rotation, the diastolic reversal of systolic rotation [41]. At the left ventricular apical level there is faster de-rotation, as compared to the basal level, which may be explained by the relatively increased systolic apical rotation, and thus stored potential energy. Interestingly, at the left ventricular basal level there is still a profound de-rotation from mitral valve opening until the peak of early left ventricular filling velocity. This may be explained by the temporal dispersion in basal and apical repolarization. Since the basal endocardial fibres are the latest to be repolarized (repolarization progresses from the apex to the base of the heart and from the epicardium to the endocardium, and takes approximately 150ms), an extra de-rotating force may still be present during this period at the basal level. Furthermore, there is a brief episode of re-rotation at the basal level from the peak to the end of the early left ventricular filling velocity that may partially be explained by the sudden omission of the de-rotational forces of the endocardial fibres, at the moment of complete cardiac repolarization. In contrast, during this period continuing de-rotation is seen at the left ventricular apical level. Since rotation is related to an increase and de-rotation to a decrease in left ventricular pressure, this phenomenon may facilitate blood flow all the way to the apex. Thus, left ventricular untwisting provides a temporal link between two crucial diastolic phenomena, relaxation and diastolic suction.

In adolescents and young adults, there may be a marked contribution of active left ventricular relaxation to left ventricular filling, resulting in an accentuated early diastolic filling velocity with a short deceleration time, resembling restrictive left ventricular filling at Doppler echocardiography ('pseudo-restrictive' left ventricular filling pattern). Very rapid left ventricular untwisting plays a pivotal role in this physiological rapid early diastolic filling [42]. In contrast, in dilated cardiomyopathy patients, untwisting is delayed and this impairment to utilize suction may impair left ventricular filling [42].

Marked changes in left ventricular diastolic function are known to occur in healthy elderly [43,44]. As described before, with advancing age left ventricular twist increases, probably due to both a decrease in rotational deformation delay and subendocardial dysfunction leading to loss of the counteraction of the subendocardial fibre helix. The early diastolic release of

increased potential energy stored during this augmented systolic twisting deformation may be the cause of preserved peak diastolic untwisting velocity and untwisting rate with aging. A strong age-independent relation between left ventricular peak systolic twist and peak diastolic untwisting velocity and untwisting rate supports this hypothesis. Nevertheless, although peak diastolic untwisting velocity and untwisting rate do not change significantly with advancing age, both parameters are significantly impaired when normalized for the increased extent of left ventricular twist. This results in a progressive delay in relative left ventricular untwisting and in the time-to-peak diastolic untwisting velocity with aging. This may reflect the increased stiffness known to occur in aging. In addition, the same subendocardial dysfunction that is supposed to lead to increased left ventricular twist with aging, may also lead to loss of the active part of untwisting normally caused by in early diastole still depolarized subendocardial fibres. Relatively reduced and delayed left ventricular untwisting may help to explain the increased duration of isovolumic relaxation in the elderly. Because left ventricular untwisting generates the left ventricular pressure gradient that helps filling the left ventricle [10], impediment of left ventricular untwisting may lead to delayed generation of this pressure gradient, and thereby to delayed opening of the mitral valve.

4. Left ventricular twist in cardiac disease

4.1. Subendocardial dysfunction

As mentioned before, left ventricular twist originates from the dynamic interaction between oppositely wound subepicardial and subendocardial myocardial fibres. The direction of left ventricular twist is governed by the subepicardial fibres, mainly owing to their longer arm of movement. Subendocardial ischemia with loss of contraction of the counteracting subendocardial fibres will lead to increased left ventricular twist. Therefore, left ventricular twist, and in particular changes within one patient, may provide an easily assessable marker of subendocardial ischemia. Increased left ventricular twist has been described in aging healthy subjects (as discussed previously), and in patients with hypertrophic cardiomyopathy (HCM), aortic stenosis (AS), or diabetes.

In HCM patients, left ventricular twist is increased [45,46]. Actually, in particular left ventricular basal rotation is augmented [46]. The increased basal rotation may be explained by loss of counteraction of the subendocardial fibre helix, caused by endocardial ischemia due to microvascular dysfunction [47,48]. Also, larger radius differences between the subepicardium and subendocardium in hypertrophic muscle may increase the dominant action of the subepicardial fibres and increase basal rotation. Interestingly, left ventricular apical rotation and twist are dependent on the pattern of left ventricular hypertrophy. In patients with a sigmoidal septal curvature, left ventricular apical rotation and twist are increased as compared to patients with a reverse septal curvature. This may be partly explained by the degree of subendocardial ischemia, since patients with a sigmoidal septal curvature more often have left ventricular outflow tract obstruction. The extravascular compressive forces caused by

gradients due to the outflow obstruction may lead to more extensive microvascular dysfunction and subendocardial ischemia.

AS patients are consistently found to have increased left ventricular twist, mainly due to increased left ventricular apical rotation [49-51]. Furthermore, left ventricular apical rotation and twist correlate positively to the severity of AS. This underlines the potential role of subendocardial ischemia as the cause of increased left ventricular apical rotation and twist in AS since the severity of subendocardial ischemia is known to be related to the severity of AS [52]. In addition, left ventricular apical rotation and twist are highest in AS patients with symptoms (angina) or electrocardiographic signs (strain) compatible with subendocardial ischemia [53]. However, deformation of myocardial fibres is known to be inversely related to wall tension. Since increased afterload in AS leads to increased endocardial wall tension, increased left ventricular twist in AS may also be caused by decreased endocardial deformation as a result of increased endocardial wall tension, independently of ischemia.

Increased left ventricular twist was also described in diabetics with a normal left ventricular ejection fraction [54-56]. Several potential mechanisms for the supposed loss of counteraction of the subendocardial fibres have been mentioned, including metabolic disturbances triggered by hyperglycemia, increased free fatty acid oxidation, altered calcium homeostasis, myocyte death, fibrosis, small-vessel diseases, and cardiac autonomic neuropathy.

In all the above mentioned examples, increased left ventricular twist may serve as a compensatory mechanism to balance loss of left ventricular myocardial contraction in other directions, which with subendocardial dysfunction is usually a loss of contraction in the longitudinal direction, and thereby preserve left ventricular ejection fraction.

4.2. Diastolic dysfunction

The need for objective evidence of left ventricular diastolic dysfunction has led to an extensive search for accurate, noninvasive, load-independent methods to quantify its severity. Takeuchi et al. [57] examined whether left ventricular hypertrophy adversely affects left ventricular untwisting in hypertension patients. Patients with moderate to severe left ventricular hypertrophy had reduced and delayed left ventricular untwisting as compared to patients without left ventricular hypertrophy, which may contribute to the left ventricular relaxation abnormality seen in these patients.

In both HCM [58] and AS [51], the untwisting rate, the mean untwisting velocity during the isovolumic relaxation phase, is decreased and untwisting is delayed. Subendocardial ischemia may lead to loss of active untwisting normally caused by the subendocardial fibres during early diastole. In addition, the impaired compliance of the left ventricles of these patients will prevent optimal transformation of the potential energy stored in systolic left ventricular twisting into kinetic energy. However, *peak* diastolic untwisting velocity is decreased in HCM patients, whereas it is increased in AS patients. In AS patients, systolic left ventricular twist is clearly increased as compared to controls. The increased potential energy stored in this more twisted left ventricular will be released after all, which may lead to increased, but delayed, peak diastolic untwisting velocity, that may serve as a compensatory mechanism to help left

ventricular filling. Conversely, in HCM patients systolic twist is only moderately increased, which may thwart this phenomenon. This hypothesis is supported by the fact that increased peak diastolic untwisting velocity have been found in a subgroup of HCM patients with mild diastolic dysfunction, who had increased systolic twist. It has been suggested that increased untwisting might be a compensatory mechanism, preventing the need to increase left atrial pressure.

4.3. Noncompaction cardiomyopathy

Noncompaction cardiomyopathy (NCCM) is a myocardial disorder characterized by excessive and prominent trabeculations associated with deep recesses that communicate with the ventricular cavity but not the coronary circulation [59]. Although NCCM was included in the 2006 World Health Organization classification of cardiomyopathies [60], it remains subject to controversy owing to lack of consensus on its aetiology, pathogenesis, diagnosis, and management [61]. The final stage of the development of myocardial architecture is characterized by the formation of compact myocardium and development of oppositely wound epicardial and endocardial myocardial fibre helices [62,63]. Since NCCM is probably caused by intrauterine arrest of this final stage of cardiac embryogenesis [64], it may be anticipated that left ventricular twist characteristics are altered, beyond that seen in patients with impaired left ventricular function and normal compaction. This has been confirmed in a clinical study. NCCM patients were found to show left ventricular rigid body rotation, that is predominantly instantaneous rotation at the basal and apical level in the same direction, with near absent left ventricular twist. In a subsequent, larger study left ventricular rigid body rotation was confirmed to be an objective, quantitative, and reproducible criterion with a good predictive value for the diagnosis of NCCM as established by expert opinion [65]. Interestingly, all familial NCCM patients showed rigid body rotation. Since the diagnosis of NCCM seems most certain in patients with familial NCCM, this finding underscores the excellent sensitivity of solid body rotation for NCCM. Of additional interest was the finding that NCCM patients who were first-degree relatives from one family had identical left ventricular rotation patterns, suggesting a genetic-functional relationship in NCCM.

4.4. Cardiac resynchronization therapy

Although a significant reduction of left ventricular twist was observed in patients with advanced heart failure, left ventricular twist did not improve after resynchronization therapy, despite significant gains in left ventricular global and short-axis function in responders. In fact, non-responders showed further reduction of left ventricular twist [66]. However, in a more recent study, subendocardial and subepicardial left ventricular twist were investigated separately, which did lead to identification of prognostic value of left ventricular twist in the population undergoing resynchronization [67]. At 6-month follow-up, 53% of the patients showed favorable outcomes after resynchronization therapy. In a multivariate logistic regression analysis, only the immediate improvement of subepicardial left ventricular twist was independently related to favorable outcomes. Furthermore, the immediate improvement of subepicardial left ventricular twist had incremental value over established parameters.

Several reasons may explain this finding. First, subepicardial left ventricular twist may reflect the positive effects of cardiac resynchronization therapy better than subendocardial left ventricular twist, because the subepicardial layer is the major determinant of left ventricular twist. Second, left ventricular pacing in cardiac resynchronization therapy is applied from the epicardial surface, which may be more closely related to mechanical changes in the subepicardial than the subendocardial left ventricular layer.

4.5. Ischemic heart disease

Sun et al. [68] subjected 7 pigs to myocardial infarction by occlusion of the left anterior descending coronary artery. After 8 weeks, left ventricular twist was decreased significantly in the left anterior descending coronary artery territory areas, whereas there was no change in twist in adjacent and remote left ventricular areas. Therefore, the authors proposed that left ventricular twist may be suitable for noninvasive quantification of left ventricular regional function in ischemic heart disease. Kroeker et al. [69], using an optical device coupled to the left ventricular apex in 16 open-chest dogs, also found a decrease of left ventricular apical rotation with ischemia caused by occlusion of the left anterior descending coronary artery. Interestingly, in the first 10 seconds of occlusion, there was a paradoxical increase in left ventricular apical rotation, which was attributed to isolated subendocardial ischemia leading to loss of the counteractive action of the subendocardial helix of myofibres.

In clinical studies in patients with a prior anterior myocardial infarction it was found that, although left ventricular basal rotation was preserved, left ventricular apical rotation was decreased, leading to decreased left ventricular twist [70]. In patients with a left ventricular aneurysm, left ventricular apical rotation was nonexistent or even inverted, leading to severely decreased left ventricular twist.

4.6. Congenital heart disease

In the majority of left ventricular twist studies in congenital heart disease, investigators focused on patients with a congenital transposition of the great arteries. In patients operated with atrial switch, the systemic right ventricle shows absence of twist, whereas the subpulmonary left ventricle shows reduced twist [71,72]. Furthermore, there are regional differences of apical rotation of the subpulmonary left ventricular, whereas apical rotation is homogeneous in a normal left ventricle [73,74]. In a theoretical model of situs inversus totalis, and in 8 patients with this condition [75,76] it was shown that, although gross anatomy is mirror imaged, this is not the case for left ventricular systolic deformation. Both the left ventricular base and apex rotated in a counterclockwise direction, whereas the midventricular section exhibited hardly any rotation. These findings may be explained by the arrangement of myofibres in these patients. Anatomical studies have revealed that in situs inversus totalis arrangement of myofibres is normal in the apical regions leading to normal counterclockwise rotation, whereas at the basal level a partly mirror-imaged pattern of the normal transmural change in fibre angle is seen.

5. Conclusion

Even though left ventricular twist is indispensable for proper left ventricular function, little is known about it in “the cardiology community”. Mainly due to the development of speckle tracking echocardiography, allowing accurate, reproducible and rapid bedside assessment of left ventricular twist, interest in this important mechanical aspect of left ventricular deformation has been rapidly increasing.

Although the vital physiological role of left ventricular twist is indisputable, the clinical relevance of assessment of left ventricular twist in cardiomyopathies still needs to be confirmed. Nonetheless, left ventricular twist evaluation has already provided significant pathophysiological insight in a broad variety of cardiomyopathies. It has become clear that increased left ventricular twist in for example HCM, AS, and diabetics, but also in a healthy ageing population, may serve as a compensatory mechanism to preserve ejection fraction. Furthermore, demonstration of left ventricular rigid body rotation in NCCM may provide a unique way to objectively confirm this difficult diagnosis. Diastolic left ventricular untwisting represents the elastic recoil caused by the release of restoring forces that have been generated during the preceding systolic left ventricular twist and has an important contribution in left ventricular filling through suction generation. Measurement of left ventricular untwisting may become an important element of diastolic function evaluation in cardiomyopathies in the future.

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