3D Echocardiographic Optimization of Residual Native Myocardial Function in Patients with Left Ventricular Assist Devices

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Abstract

Preservation of native left ventricular (LV) function in patients supported with left ventricular assist device (LVAD) may be beneficial to attain optimal hemodynamics and theoretically enhance potential recovery. Currently, LVAD speed optimization is based on hemodynamic parameters, without considering residual native LV function. We hypothesized that, alternatively, LV rotational mechanics can be quantified by 3D echocardiography (3DE), and may help preserve native LV function while optimizing LVAD speed. We sought to: (1) test the feasibility of quantifying the effects of LVAD implantation on LV rotational mechanics, and (2) determine whether conventional speed optimization maximally preserves native LV function. We studied 55 patients with LVADs, who underwent transthoracic 3DE imaging (Philips) and quantitative analysis of LV twist (TomTec). Thirty patients were studied before and after LVAD implantation. The remaining 25 patients were studied during hemodynamics ramp studies. The pump speed at which LV twist was maximal was compared with the hemodynamics based optimal speed. LV twist decreased following LVAD implantation from 4.2±2.7 to 2.3±1.9° (p<0.01), reflecting the constricting effects on native function. During the lower speeds of the ramp studies, no significant changes were noted in LV twist, which peaked at a higher pump speed. In 11/25 (44%) patients, the conventional hemodynamic+2DE methodology and 3DE assessment of maximal residual function did not indicate the same optimal conditions, suggesting that at a higher pump speed would have better preserved native function. Quantitative 3DE analysis of LV rotational mechanics provides information, which together with hemodynamics may help select optimal pump speed, while better preserving native LV function.

1. Introduction

As heart failure (HF) develops, the left ventricle undergoes adverse remodeling that includes changes in chamber size and shape, systolic and diastolic function, and rotational mechanics. LVADs are increasingly used in patients with end-stage HF as a bridge to heart transplantation, destination therapy and as a bridge to recovery [1-3]. Despite the frequent improvement in cardiovascular hemodynamics achieved by the use of these devices, it is possible that LVAD may adversely affect the rotational mechanics of the ventricle. Moreover, it is increasingly recognized that preserving native LV function in patients on mechanical support is beneficial for both optimal hemodynamics and potential recovery.

Although we previously described a systematic protocol for LVAD speed optimization using hemodynamic and 2DE ramp tests, the identification of optimal LVAD settings remains a challenging clinical task [4-6]. Also, these ramp tests fail to quantify residual native LV function, because conventional ejection phase indices, such as ejection fraction (EF), are not useful in patients with LVADs.

With the advent of speckle-tracking echocardiography (STE), LV rotational mechanics can now be easily assessed. The strengths of 2D STE include the ability to detect subtle changes in myocardial deformation that precede changes in LV EF [7]. Furthermore, because 3DE has a better capacity to accurately track myocardial motion independently of the imaging plane [8], 3D STE has recently emerged as the preferred modality for measuring LV rotation.

We hypothesized that 3DE assessment of LV rotational mechanics during ramp studies may provide additional information on residual native LV function. This study was designed to: (1) test the feasibility of quantifying the effects of LVAD implantation on LV rotational mechanics, and (2) determine whether conventional speed optimization choices during ramp studies coincide with maximally preserved native LV function.

2. Methods

We prospectively studied 55 patients (age 56±13, males 68%, 76% destination therapy) with LVADs (35 Heart Mate II (HMII); 20 HeartWare (HVAD)) who underwent transthoracic 3DE imaging (Philips EPIQ) and

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quantitative analysis of 3D LV twist (TomTec). The study included two protocols. In Protocol 1, 30 patients were studied before and after LVAD implantation. In Protocol 2, 25 patients underwent simultaneous 3DE imaging and right-heart catheterization during a ramp study [4, 5]. This protocol included analysis of rotational deformation at 5 increasing pump speeds. The speed at which it was maximal was compared with the hemodynamics-based optimal speed. This was done to determine whether the conventional speed optimization protocol results in maximally preserved residual native deformation, as a surrogate of LV function.

In Protocol 1, we enrolled 58 patients with end-stage HF who underwent clinically indicated transthoracic echocardiograms before and 1-2 months after LVAD implantation. From this group, 30 patients (51.7%) were selected based on quality of both pre- and post-implantation transthoracic 3DE images that were used to measure parameters of LV rotational mechanics, which were compared between pre- and post-implantation phases.

In Protocol 2, we enrolled 48 patients undergoing clinically indicated LVAD speed optimization using the ramp protocol that included simultaneous transthoracic echocardiography and right heart catheterization. The ramp test protocol has been previously described [4-6]. Briefly, LVAD speed was initially set at the lowest range for each pump and then gradually increased to the highest range. Hemodynamic and 2DE parameters were measured at each speed (up to 10 speeds). The acquired data were then reviewed by a HF specialist to determine the optimal pump speed. At the conclusion of the test, the device was set at the speed targeting a central venous pressure <12 mmHg, pulmonary capillary wedge pressure <18 mmHg and cardiac index >2.2 L/min by the indirect Fick's method, while trying to maintain less than moderate mitral regurgitation and intermittent aortic valve opening.

In addition to the conventional ramp protocol, 3DE images were obtained at every other speed and used to measure parameters of LV rotational mechanics that were also compared between protocol phases to independently determine the speed that resulted in maximally preserved native rotational function. All 3DE analyses were performed by a reader blinded to speed settings and hemodynamic data. After excluding 23/48 patients due to either poor 3D image quality or for not completing the full ramp protocol, the remaining 25 patients were used for analysis.

Transthoracic imaging was performed by an experienced sonographer using the IE33 or EPIQ system (Philips) and an X5-1 phased-array transducer. Images were optimized for endocardial visualization. Image acquisition included a wide-angled, 4-beat, "full-volume" 3DE datasets from the apical position during a single breath-hold. Care was taken to include the entire left ventricle within the 3DE images. Settings were optimized to obtain the highest possible frame rate (Figure 1, top left), resulting in an average of 24±6 Hz.

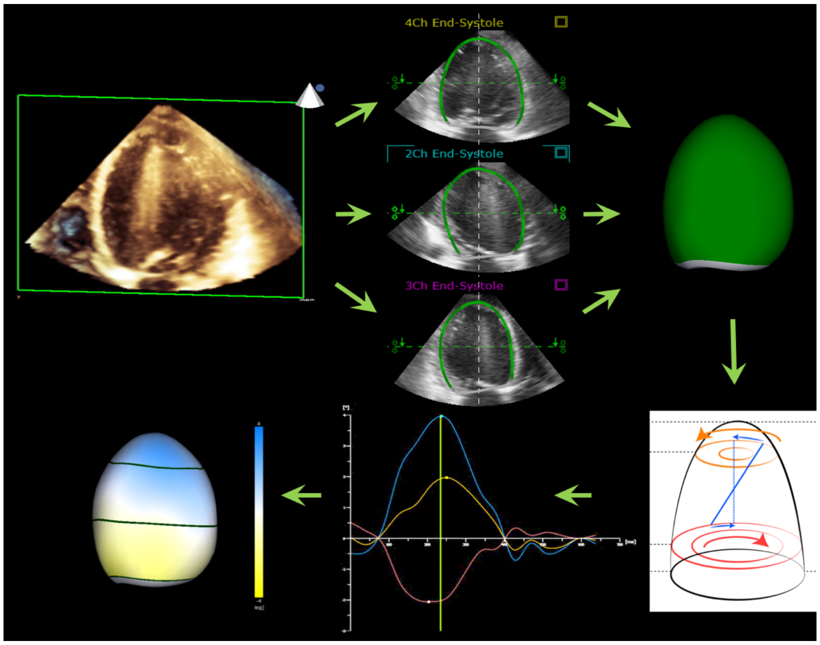

Figure 1. Automated technique for left-heart 3D chamber quantification. Following initial fully-automated detection of LV and LA endocardial surfaces (left), the software allows the user to perform manual corrections of the endocardial boundaries when needed (center), resulting in final 3D casts of the cardiac chambers. Optional corrections are performed in non-foreshortened 2D planes showing focused long-axis views of both chambers, both automatically extracted from the 3D dataset.

Quantitative analysis was performed using 4D LV-Function software (Research Arena, TomTec) to create a dynamic LV cast and measure volumetric and rotational indices. The first steps of analysis involved manual definition of the LV long axis at end-diastole followed by automatic extraction of anatomically correct, non-foreshortened 2-, 3- and 4-chamber views at both end-diastole and end-systole (Figure 1, top center). Then a 3D model of the LV cavity was automatically generated (Figure 1, top right) and tracked throughout the cardiac cycle using speckle tracking technology. Fine-tuning was performed interactively to optimize boundary position as necessary. LV volumes were then numerically computed over time from the dynamic surface model and used to determine end-systolic and end-diastolic volumes and EF.

Also, rotational mechanics indices were measured, including apical and basal rotation angles (Figure 1, bottom right), which were displayed as time curves (Figure 1, bottom center). By convention, apical rotation angle was defined as positive, while basal rotation angle was defined as negative. From apical and basal rotation angles, LV twist angle was calculated as the sum of their absolute values. Finally, LV torsion was calculated as the twist angle divided by the longitudinal distance between the basal and apical measurement sites. For visual assessment, rotation angles were color-coded on the dynamic 3D model (Figure 1, bottom left).

In protocol 1, differences between pre- and post-LVAD implantation were tested for significance using paired two-tailed t-tests. In protocol 2, LV twist measurements between different LVAD speeds were compared using paired t-tests.

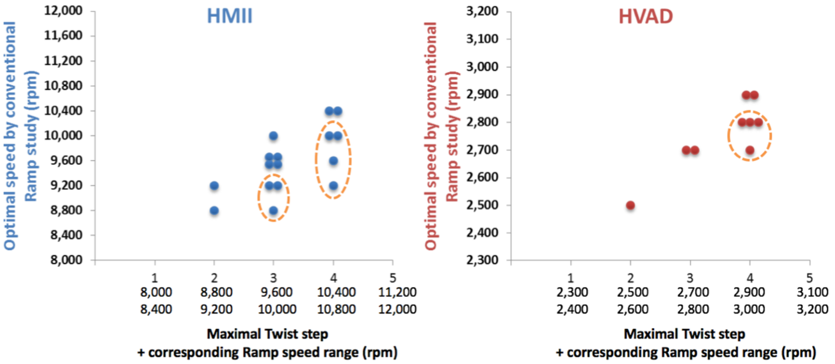

Figure 2. Relationship between optimal speeds determined during the conventional ramp studies and the speeds at which the maximal twist was detected by 3DE analysis in individual patients for both pump types: Heart Mate II (HMII, left) and HeartWare (HVAD, right). In both groups, peak LV twist was noted in the range of the optimal speed determined by the conventional ramp test in the majority of patients. However, in several patients, the two techniques disagreed in their assessment of the optimal conditions (represented by data points circled by a dashed orange line).

3. Results

Table 1 depicts rotational mechanics indices, pre- and post-implantation for the 30 patients in protocol 1. Pre-implantation values were considerably smaller in magnitude than the corresponding normal values. Following implantation, peak apical rotation, twist angle and torsion decreased significantly, reflecting the constrictive effects of the LVAD on the native rotational LV function, while peak basal rotation remained unchanged.

Table 1. Pre- and post-implantation rotational mechanics indices. Data are shown for the entire study group, as well as for two subgroups according to the type of LVAD.

		Total (N=30)		
		Pre	Post	p-value
Peak rotation (˚)	Apical	2.8 ± 1.9	0.94 ± 0.95	**0.000**
	Basal	-1.9 ± 1.3	-1.7 ± 1.5	0.633
	Twist	4.2 ± 2.7	2.3 ± 1.9	**0.001**
Tosion (˚/cm)		0.37 ± 0.23	0.23 ± 0.19	**0.007**

In protocol 2, on average, the LV twist remained stable during the first three imaging steps of the ramp protocol, reaching its maximum at step 4. However, on average, twist peaked at the same phase (Step 4: HMII = 10,400-10,800 RPM, HVAD = 2900-3000 RPM). Figure 2 shows the relationship between the optimal speeds determined during the conventional ramp studies and the speeds at which the maximal twist was detected by 3DE analysis in individual patients for both pump types. Of note, in 7/16 (44%) patients in the HMII group and in 4/9 (44%) in the HVAD group, the conventional hemodynamic/2DE methodology and 3DE assessment of maximal residual function did not indicate the same optimal conditions.

4. Conclusions

In this study, LV rotational mechanics were evaluated using 3DE before and after LVAD implantation and during hemodynamic/echocardiographic ramp studies. The main findings were: (1) peak apical rotation, twist angle and torsion decreased significantly after LVAD implantation, reflecting the constrictive effects of the pump on native rotational LV function, while peak basal rotation remained unchanged; (2) during ramp tests, LV twist was stable without significant changes until reaching the higher pump speeds, at which LV twist increased with both devices; and (3) in a significant number of patients, the conventional hemodynamic/2DE methodology and 3DE assessment of maximal residual function did not indicate the same optimal conditions.

Despite the fact that the overall effects of successful cardiovascular hemodynamic support by LVADs are well documented by an improvement in cardiac output, these devices are not designed to improve ventricular function, but rather to assist the failing ventricle. Little is known on how LVAD implantation affects the native function of the ventricle. Today, LVADs are increasingly used not only as a destination therapy or bridge to transplantation, but also as a temporary measure leading to recovery. Accordingly, it is important to ensure that their potential adverse effects on the residual native function of the heart are minimized, to augment the potential for recover in this subgroup of patients.

A well-known, important part of LVAD therapy is speed optimization, which aims to achieve best possible hemodynamics. However, since the pump and the ventricle function in tandem, it makes sense to optimize their interaction for maximal efficiency, without causing further deterioration of the native ventricular function. Accordingly, it is important to accurately assess ventricular function in patients with continuous-flow LVADs, in whom traditional indices, such as EF, are limited in their ability to either assess LV function, guide pump speed optimization or evaluate the effects of medical therapy.

Recent advances in echocardiographic speckle tracking offer new ways to quantitatively assess myocardial deformation, which reflects mechanical properties and functional capacity better than the traditional indices. Specifically, LV rotational mechanics are an important aspect of cardiac performance, which can be readily assessed using this new tool by measuring apical and basal rotation, twist and torsion as described previously [9-10]. Our study was designed to test the potential clinical value of this approach to assess the deleterious effects of LVADs on rotational mechanics, and to test whether the speed chosen to optimize hemodynamics by a conventional ramp protocol coincides with the speed at which maximal preservation of residual native function occurs.

One might expect that after LVAD implantation and optimization of pump function, resulting in improved hemodynamics, LV function would also improve. However, we found a significant decrease in peak apical rotation, twist and torsion, reflecting a further deterioration in LV mechanics. One of the possible explanations for this finding is the presence of a rigid foreign body, namely the LVAD, physically constricting the apical rotational motion. This further reduction in apical rotation caused by LVAD implantation, reflecting the constrictive effects of the inflow cannula, led us to investigate these indices as a potential guide to maximize residual native function during ramp tests. Importantly, our data from protocol 2 indicate that indeed 3D STE analysis of rotational LV mechanics may be a sensitive tool well suited for this purpose. Our finding that in some patients with both pump types, optimal speed chosen during the ramp test did not coincide with that favoring native residual function, raises the question whether conventional speed optimization is sufficient, or could be improved by incorporating the assessment of native function.

An important limitation of this approach is that 3DE imaging is challenging in patients with LVADs because of the artifacts that frequently result in low quality images. Therefore, our results cannot be extrapolated to consecutive patients.

In summary, 3D STE analysis of myocardial deformation may potentially be useful for the assessment of LVAD-related changes in cardiac mechanics in patients with end-stage heart failure. This approach was sensitive enough to detect changes in LV rotation, twist and torsion caused by LVAD implantation, which indicate that this approach may constitute a novel tool for minimizing adverse effects of LVAD on native myocardial function during LVAD speed optimization. These indices may also prove useful in the evaluation of the effects of medical therapy in these patients, in whom the value of conventional functional indices, such as LV EF is limited. Future studies are needed to determine whether this approach could help predict outcomes in patients receiving mechanical support.

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