Septal Deformation Patterns Delineate Mechanical Dyssynchrony and Regional Differences in Contractility: Analysis of Patient Data Using a Computer Model

Leenders et al: Septal Deformation in Dyssynchronous Heart Failure

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Abstract

Background—Response to cardiac resynchronization therapy (CRT) depends both on dyssynchrony and (regional) contractility. We hypothesized that septal deformation can be used to infer integrated information on dyssynchrony and regional contractility and thereby predict CRT response.

Methods and Results—In 132 CRT-candidates with left bundle branch block (LBBB)-like ECG morphology (left ventricular (LV) ejection fraction 19±6%; QRS-width 170±23ms), longitudinal septal strain was assessed by speckle tracking echocardiography. To investigate the effects of dyssynchronous activation and differences in septal and LV free wall (LVFW) contractility on septal deformation pattern, we utilized the CircAdapt computer model of the human heart and circulation. In the patients, three characteristic septal deformation patterns were identified: LBBB-1=double-peaked systolic shortening (n=28); LBBB-2=early systolic shortening followed by prominent systolic stretching (n=34); and LBBB-3=pseudonormal shortening with less pronounced late systolic stretch (n=70). LBBB-3 revealed more scar (2 [2-5] segments) compared to LBBB-1 and LBBB-2 (both 0 [0-1], p<0.05). In the model, imposing a time difference of activation between septum and LVFW resulted in pattern LBBB-1. This transformed into pattern LBBB-2 by additionally simulating septal hypocontractility and into pattern LBBB-3 by imposing additional LVFW or global LV hypocontractility. Improvement of LV ejection fraction and reduction of LV volumes after CRT were most pronounced in LBBB-1 and worst in LBBB-3 patients.

Conclusions—A double-peaked systolic septal deformation pattern is characteristic for LBBB and results from intraventricular dyssynchrony. Abnormal contractility modifies this pattern. A computer model can be helpful in understanding septal deformation and predicting CRT response.

Key Words: bundle-branch block, cardiac resynchronization therapy, dyssynchrony, echocardiography, myocardial contraction
Left bundle branch block (LBBB) causes a disparity of electrical activation of the heart that results in a prominent electrical and mechanical activation delay (=dyssynchrony) between the right and the left ventricle (LV) and between the septum and the LV free wall (LVFW).\textsuperscript{1-3} Such activation delays give way to reciprocal contractile interactions that present as back and forth shortening and stretching of the myocardium (=mechanical discoordination) thereby instigating inefficient myocardial contraction and relaxation, and ultimately leading to heart failure and myocardial remodeling.\textsuperscript{3}

Because the interventricular septum is centered amidst the discoordinated right ventricular (RV) and LV walls and is additionally subject to altered loading by the abnormal right-to-left transseptal pressure gradient, it is particularly susceptible to motion and deformation abnormalities caused by LBBB.\textsuperscript{4, 5} Abnormalities of septal motion and deformation have therefore repeatedly been used to identify the mechanical consequences of LBBB.\textsuperscript{6-8} In line with the latter, parameters of mechanical dyssynchrony often rely on abnormal (early) septal motion or deformation for the identification of mechanical dyssynchrony and the prediction of response to cardiac resynchronization therapy (CRT).\textsuperscript{9}

Besides disparity in timing of mechanical activation and the abnormal transseptal pressure gradient, which are both primarily influenced by the dispersed electrical activation, regional heterogeneity in myocardial tissue properties (e.g., contractility and scarring) may additionally influence myocardial deformation.\textsuperscript{6, 10-13} Local tissue properties of the septum and LVFW may thereby either mask or mimic septal deformation abnormalities caused by mechanical dyssynchrony.
We hypothesized that the septal deformation pattern can be used to infer integrated information on dyssynchrony and regional contractility and thereby predict CRT response. In order to assess this hypothesis, we evaluated a patient population with LBBB and systolic heart failure by echocardiographic deformation imaging and additionally utilized the multiscale CircAdapt model of the human heart and circulation\textsuperscript{14},\textsuperscript{15} to further elucidate the influence of each factor individually on septal deformation.

Methods

Study population and protocol

The study population constituted a consecutive cohort of patients (enrolled in the University Medical Centre Utrecht between August 2005 and April 2009) undergoing CRT because of severe medication refractory heart failure (New York Heart Association class (NYHA) III-IV, LV ejection fraction (LVEF) <35\%) and evidence of conduction disturbances (QRS\textgreater{}120ms) with an LBBB-like morphology on the surface electrocardiogram. Eight patients with poor echocardiographic window, and one patient undergoing coronary artery and mitral valve surgery within 6 months prior to CRT were excluded from the analysis. Echocardiographic and clinical characteristics were prospectively assessed in all patients before and 6 months after CRT. The execution of the study complied to the principles outlined in the Declaration of Helsinki on research in human subjects and to the procedures of the local Medical Ethics Committee.
**Echocardiographic protocol**

Our echocardiographic protocol has been described in detail elsewhere. In brief, all data were obtained on a Vivid 7 ultrasound machine (General Electric, Milwaukee, USA) using a broad band M3S transducer for Doppler and 2D imaging. A minimum of 3 loops were acquired at breath hold and analyzed offline (Echopac version 6.0.1, General Electric). LVEF, LV end-systolic (LVESVi) and end-diastolic (LVEDVi) volumes indexed for body surface area were measured by biplane Simpson’s method. Mitral regurgitation effective regurgitant orifice (MRero) was quantified by the proximal isovelocity surface area method. Interventricular septal (IVSd) and LV posterior (LVPWd) wall thickness were measured on M-Mode in the parasternal long axis view.

LV end-diastolic sphericity was calculated by the ratio of the minor axis to the major axis length of the LV, as derived from the apical four-chamber view.

The LV was divided into 16 segments according to the recommendations of the American Society of Echocardiography. Segments which displayed akinesis or dyskinesis in combination with a disproportionate local wall thinning and hyperreflectivity in comparison to adjacent contractile segments were scored as “scarred”.

For offline deformation imaging, additional single wall images of the septum and lateral wall were prospectively acquired from the standard apical views at 51-109 frames per second. Timing of mitral and aortic valve opening and closure, as derived from Doppler flow patterns over the left sided valves, served as cardiac event timing markers.
Deformation analysis

Speckle tracking software was used to derive septal and lateral LVFW deformation from the single wall recordings. Deformation was measured from base to apex covering the entire wall thickness (Figure 1). Global longitudinal deformation (i.e., calculated over the entire length of the wall) was temporally aligned using onset of the QRS-complex as zero reference. Septal deformation patterns were classified based on the sequence of septal shortening and stretching during LV systole (i.e., between mitral and aortic valve closure). Peak systolic strain was defined where systolic shortening converted into stretching and the absolute strain value was maximally negative. More than one systolic peak was adjudicated only if the amplitudes of the peaks were within 150% relative range of each other, in all other cases the dominant peak was considered the only systolic peak (Figure 1).

Device implantation

Right atrial, RV and LV leads were placed conventionally and connected to a CRT device as described previously. Atrioventricular and ventriculo-ventricular intervals were optimized either by maximizing the invasively determined maximum rate of LV pressure rise (n=92) or by intracardiac electrogram based device algorithms (n=40).

CircAdapt Model

The effects of dyssynchronous activation and regional LV contractility differences on septal deformation were investigated utilizing the multiscale CircAdapt model of the cardiovascular system. The model contains modules representing myocardial walls,
cardiac valves, large blood vessels, and peripheral resistances. It can simulate realistic
beat-to-beat cardiovascular mechanics and hemodynamics under a wide variety of
(patho-)physiological circumstances.\textsuperscript{15, 18, 19, 20} To incorporate mechanical ventricular
interaction, three thick-walled segments representing the LVFW, the interventricular
septum, and the RV free wall are mechanically coupled.\textsuperscript{15} From the geometry of each
wall, representative local myofiber strain is calculated. From myofiber strain, myofiber
stress is determined using a three-element muscle model describing active and passive
cardiac myofiber mechanics.\textsuperscript{15} The latter model incorporates known sarcomere
properties, such as velocity of sarcomere shortening as function of passive stretch, and
strength and duration of activation as function of sarcomere length.\textsuperscript{21-23} Global left and
right ventricular pump mechanics are related to representative myofiber mechanics in the
three ventricular walls, using the principle of conservation of energy. Since the
pericardium can significantly modulate ventricular interaction,\textsuperscript{24-27} the effect of the
pericardium on ventricular mechanics was included in the model (see online supplement).

\textit{Simulation of normal cardiovascular mechanics and hemodynamics}

First, the CircAdapt model was used to obtain the NORMAL simulation, representing the
cardiovascular system under baseline resting conditions. Onset of mechanical activation
of the three ventricular walls was synchronous, with underlying identical
electromechanical delays in all walls. Myocardial contractility was normal. Size and mass
of cardiac walls and large blood vessels were tuned to obtain normal cardiac output (5.1
l/min), mean arterial blood pressure (92 mmHg) and heart rate (70 bpm) at tissue specific
physiological levels of mechanical load.\textsuperscript{14, 15} Changes in local deformation in subsequent
Simulations represent the effect of abnormal electrical activation, reduction of contractility and acute adjustments required to maintain normal levels of cardiac output and blood pressure.

**Simulation of ventricular mechanical dyssynchrony and hypocontractility**

To assess the effect of dyssynchronous mechanical activation on septal deformation, onset of septal and LVFW mechanical activation were delayed with respect to that of the RV free wall by 25 and 50 ms for the septum and 25, 50, 75, and 100 ms for the LVFW. In each simulation, septal deformation was quantified as the percent change in sarcomere length with respect to reference sarcomere length at onset of RV free wall mechanical activation (i.e., the first ventricular activation) which was similar in all simulations (about 130 ms after right atrial activation) and was assumed to correspond best to the zero-strain reference in the patients.

To assess the effect of local differences in contractile myofiber function on septal deformation, we reduced myofiber contractility by decreasing isometric active myofiber stress by 30 and 60% in the septum and in the LVFW. These assessments were performed in the simulation with 25 and 75 ms delayed onset of (mean) septal and LVFW activation, respectively. These values were chosen in order to cover the mean timing differences in RV, septum and LVFW, as observed in human LBBB patients.\(^1,^2\)

Additionally, to assess the isolated effect of regional contractility changes on septal deformation, hypocontractility simulations were also applied to the NORMAL simulation (online supplement).
Statistical analysis

Statistical analysis was performed using the SPSS statistical software package (SPSS Inc., Chicago, Illinois). Values are presented as mean and standard deviation (SD) or median and interquartile range for continuous variables as appropriate, and as numbers and percentages for categorical variables. Assumptions on homogeneity of variances and normally distributed residuals were checked by Levene’s test and Q-Q plots, respectively. Comparison of continuous data between subgroups was performed by one-way analysis of variance (ANOVA). Categorical data were compared by Chi-square or Fischer’s Exact test. Bonferroni post-hoc correction for multiple comparisons was applied when applicable. A p-value <0.05 was considered statistically significant for all analyses.

Results

Study population

The final study population constituted 132 patients: 93 male (70%), age 65±10 years, LVEF 19±6%, and 19 NYHA IV (14%). The cause of heart failure was ischemic in 69 patients (52%). In total 27 patients (20%) were previously known with atrial fibrillation. All patients were on stable, maximally tolerated heart failure medication with ACE inhibitors or angiotensin receptor blockers in 117 (89%), β-blockers in 103 (78%) and diuretics in 126 (95%).

In the total population, three characteristic patterns of septal deformation could be discerned (Figure 2): LBBB-1=double-peaked systolic shortening, in 28 patients (21%); LBBB-2=early pre-ejection shortening peak followed by prominent systolic stretching, in
34 (26%); and LBBB-3=pseudonormal shortening with a late-systolic shortening peak followed by less pronounced end-systolic stretch, in 70 (53%).

Baseline characteristics of the deformation pattern subgroups

Table 1 shows the baseline characteristics of the population. In general, patients with LBBB-1 had electrical dyssynchrony (evidenced by the broad QRS-width) but relatively mild adverse remodeling, as expressed by the moderate dilatation (LVEDVi and LVESVi), relatively preserved wall thickness (IVSd and LVPWd) and only mild mitral regurgitation (MRero). LBBB-2 patients had similar electrical dyssynchrony, but were characterized by more pronounced structural adaptation and more globular LV dilatation (as expressed by LV volumes and sphericity), decreased LVEF, and decreased septal-to-posterior wall thickness ratio compared to the other two groups. LBBB-3 patients more often had ischemic heart failure etiology with a larger number of scarred segments throughout the LV, particularly in the LVFW, when compared to the other two groups, and had on average less electrical dyssynchrony.

Model simulations

Effect of ventricular dyssynchrony on septal deformation

The septal deformation pattern in the NORMAL simulation showed continuous septal shortening during LV ejection. With progressive delay of LVFW activation (Figure 3A: upper row), an increasing part of septal shortening occurred before onset of LV ejection, in conjunction with an increase of septal rebound stretch during ejection. Conversely, progressively delaying septal activation (Figure 3A: left column) increased septal stretch
before LV ejection. This pre-stretch in turn increased systolic septal shortening by a local Starling-effect. The pattern of septal deformation appeared to be sensitive to changes of LV intraventricular (i.e., septal to LVFW) delay rather than interventricular mechanical delay (i.e., RV free wall to LVFW). For example, an intraventricular activation delay of 50 ms was consistently associated with a double-peaked septal deformation pattern. Similar to septal deformation pattern, LVESV and LVEF strongly depended on intraventricular dyssynchrony (Figure 3B). With increasing septal to LVFW delay of activation, the LV dilated and its systolic pump function decreased. With 100 ms intraventricular delay, LVEF decreased by 9%-points with LVESV increasing by 45%.

Effect of regional contractility changes on septal deformation pattern

Figure 4A shows the effect of regional LV myocardial contractility changes on the septal deformation pattern in case of 25 and 75 ms delay of septal and LV free wall activation, respectively. By decreasing septal contractility up to 60%, the septal deformation pattern gradually transformed into an early-peak pattern (Figure 4A: left column). On the other hand, a 60% decrease of LV free wall contractility lead to a late-peak pattern, irrespective of the presence of decreased septal contractility (Figure 4A: upper row and right column). Furthermore, the amount of septal systolic shortening decreased with decrease of septal contractility, but increased with decrease of LV free wall contractility. Changes in systolic septal deformation were markedly less pronounced in the absence of dyssynchrony (online supplement). With decreasing septal or LV free wall contractility, LVEF decreased and LVESV progressively increased, both parameters being more sensitive to LVFW than to septal hypocontractility (Figure 4B).
Measured vs simulated septal deformation patterns

The three characteristic septal deformation patterns as measured in the patients could also be identified in the simulations (Figure 5). The double-peaked LBBB-1 pattern was obtained by simulating typical LBBB dyssynchrony of ventricular activation. The early-peaked LBBB-2 pattern was obtained by additionally imposing septal hypocontractility. The late-peaked LBBB-3 pattern was obtained by simulation of dyssynchronous ventricular activation with decreased LVFW contractility whether or not in combination with decreased septal contractility.

Response to CRT

After 6 months CRT, a significant reduction of LV volumes (LVESVi 107±37 to 90±45 ml/m², p<0.001) and mitral regurgitation (MRero 9.2±7.4 to 6.0±6.1 mm², p<0.001) in combination with an improved LVEF (to 26±10%, p<0.001) was observed in the patients. There was a significant difference in response between the three subgroups (Table 2). Reverse remodeling and improvement of LVEF were most pronounced in patients with LBBB-1. Patients with LBBB-2 also showed significant, but less, remodeling and improvement of systolic function. Patients with LBBB-3 did not show a significant echocardiographic response to CRT, that was also significantly less compared to the other two groups.
Discussion

In this study, we demonstrated within a typical CRT patient population the presence of three characteristic septal deformation patterns that showed a different response to CRT. Using the CircAdapt model, we were able to demonstrate that these patterns can be explained by various combinations of intraventricular dyssynchrony and regional contractility. Therefore, septal deformation provides integrated information on two key determinants of CRT response: dyssynchrony, and reduced regional LV myocardial contractility.

Impact of dyssynchrony on septal deformation

The findings in both the model and the patients indicate that the double-peaked LBBB-1 pattern is the uncomplicated septal deformation pattern in the presence of LBBB. The premature interruption of early systolic shortening with systolic rebound stretch that determines the first part of this pattern is a characteristic feature of regional electrical pre-excitation and has been described in ventricular pacing, accessory atrioventricular pathways, and LBBB. In the case of LBBB, the early vigorous septal shortening has been ascribed to low local afterload during early activation. The model indicates that also the remaining part of the complicated septal deformation pattern in LBBB can be attributed to dyssynchronous activation, without additional alterations in myocardial tissue properties or loading conditions. The subsequent local rebound stretch in the septum most probably results from an imbalance in tensional forces between the early activated septum and the later activated LVFW whereas the second shortening peak, observed in LBBB-1, indicates re-equilibration of these forces later in systole.
The simulations also indicate that LV intraventricular rather than interventricular dyssynchrony is the main determinant of septal deformation. This finding may seem in contrast with previous echocardiographic M-mode studies attributing the observed motion abnormalities mainly to abnormal interventricular coupling and the resulting transseptal pressure gradient.4,33 Interventricular interaction and intraventricular dyssynchrony do however closely intertwine and intraventricular dyssynchrony almost inevitably leads to an abnormal transseptal pressure gradient.4,5,9 Our findings do not preclude an effect of interventricular coupling on septal deformation. They rather indicate that the interactions are initiated by LV intraventricular dyssynchrony and that the timing of activation of the RV free wall is of minor importance.

Modification of septal deformation by regional contractility changes

The model study furthermore indicates that, on top of dyssynchrony, regional contractility influences septal deformation. Pattern LBBB-2 and LBBB-3 were derived from the LBBB-1 pattern by reduction of septal and LVFW contractility, respectively. It thus appears that reduction of septal contractility precludes the equilibration of contractile forces during late systole while the relatively unopposed early shortening remains unaffected. On the other hand, reduction of LVFW contractility reduces the stretching forces imposed on the septum, thus allowing the septal contraction to be extended further into systole. The fact that contractility changes alone could not induce an early systolic shortening peak further confirms the specificity of this pattern as a marker of electrical dyssynchrony (online supplement).
The computer simulation does not distinguish between various causes of hypocontractility. In patients the cause could be either scar of an old infarct, hibernation or localized disease-specific processes. In the patients we found an increased amount of (LVFW) scar in conjunction with the LBBB-3 pattern, fitting with the reduced LVFW contractility required to obtain this pattern in the model (Table 1). In LBBB-2 patients however, we did not find an increased amount of septal scar, whereas the LBBB-2 simulation required the reduction of septal contractility. Alternatively, hibernation, echocardiographically undetectable midseptal scarring, or advanced LBBB-specific remodeling processes might explain the relatively reduced septal contractility, the latter being partly supported by the more pronounced remodeling in those patients (Table 1).

Relation of septal deformation with CRT response

In previous studies it has been demonstrated that the extent of dyssynchrony-induced deformation abnormalities (expressed as systolic rebound stretch in the entire LV or in the septum alone) relates to the functional impact of dyssynchrony and the benefit of resynchronization. This observation is in agreement with the demonstration in this study that septal deformation is directly linked to dyssynchronous activation within the LV, a recognized electro-mechanical substrate for CRT. In our simulations, application of dyssynchrony induced changes in global LV function and dimensions comparable to those observed in canine LBBB hearts. It is worth noting that in the model cardiac output and mean arterial blood pressure were kept constant. In vivo, pump function is reduced immediately after inducing dyssynchrony, but (partly) recovers after some time,
due to autonomic and renal compensation mechanisms. Therefore, the extent of increase in LVESV, and decrease in LVEF in the model, are more in line with changes after longer lasting LBBB than acutely after LBBB.

Previous studies have indicated that LV scarring reduces CRT response, especially when located in the posterolateral region.\textsuperscript{12,13} This has been attributed mainly to pacing delivery failure and lack of recruitable myocardium. Additionally, the results in the current study indicate that extensive LV hypocontractility might mitigate the translation of electrical dyssynchrony into mechanical discoordination. Accordingly, the presence of LVFW hypocontractility resulted in less discoordinate septal deformation with little systolic rebound stretch (i.e. LBBB-3), and likewise, with a smaller benefit of CRT. The moderate response in the LBBB-2 patients on the other hand, can be explained by the reduced amount of septal contractility that can be recruited upon CRT, either because of scarring or because of extensive and partly irreversible remodeling.\textsuperscript{37}

Potential clinical implications

The finding that uncomplicated LBBB results in double peaked septal deformation demonstrates that assessment of dyssynchrony by time-to-peak measurements is not straightforward.\textsuperscript{6,38} Our data further demonstrate that, at the same intraventricular dyssynchrony the peak shortening time depends on contractility of the septum and LVFW. These factors may explain why several studies showed a poor relation between time-to-peak measurements and CRT response. Conversely, our data suggest that the septal deformation pattern provides integrated information on intraventricular dssynchrony and regional LV scarring, two important determinants of CRT response.
Assessment of septal deformation, potentially assisted by a patient computer model, might therefore provide an alternative to multimodality assessment (i.e. echocardiography and magnetic resonance imaging or myocardial scintigraphy) before CRT.

**Limitations**

In our model, each of the three ventricular walls was lumped into a spherical wall segment containing a single contractile fiber describing representative passive and active sarcomere properties of the entire wall. This simplified setup allows inhomogeneity of material properties between ventricular walls, but does not allow local inhomogeneities within a wall. Despite the inherent limitations, this provides a clearer mechanistic view, because of less alternating parameters. The qualitative and sometimes quantitative agreement between the model simulations and the clinical measurements of septal deformation indicate that the simplifications made in the simulations do not obscure first-order effects of ventricular mechanical dyssynchrony and hypocontractility on the septal deformation pattern.

We used the echocardiographic aspect of the myocardium to diagnose the presence of scar. Although this is an accepted approach, the use of late gadolinium enhanced magnetic resonance imaging might have revealed additional areas of (more subtle) scarring.

Because the current study is the first study investigating the interrelation between dyssynchrony, contractility, and septal deformation, its design was mainly exploratory without predefined specific cut-offs for a clinically relevant magnitude of the differences.
Also only patient data from a single institution were analyzed. The results therefore need to be confirmed in a prospective multicenter study. In addition, future studies should establish whether the current findings can be generalized to patients with less severe heart failure.

**Conclusion**

The pattern of septal deformation is highly sensitive to ventricular dyssynchrony and regional differences in myocardial contractility and thereby predicts CRT response. Model simulations can extract otherwise concealed diagnostic information from the septal deformation patterns as measured in the patients.
Disclosures

This research was performed within the framework of CTMM, the Center for Translational Molecular Medicine (www.ctmm.nl), project COHFAR (grant 01C-203), and supported by the Dutch Heart Foundation. F.W. Prinzen has also received research grants from EBR Systems and MSD.

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Table 1. Baseline characteristics of septal deformation pattern subgroups
*median and interquartile range. Syst. BP=systolic blood pressure, LVESVi=LV end systolic volume index, LVEDVi=LV end diastolic volume index, LVEF=LV ejection fraction, LV sphericity=LV maximal short axis diameter divided by the maximal long axis diameter, IVSd=interventricular septum diastolic thickness, LVPWd=LV posterior wall diastolic thickness, S/P thickness ratio=IVSd/LVPWd, MRero=mitral regurgitation effective regurgitant orifice, IEGM=intracardiac electrogram algorithm
Table 2. Echocardiographic response of septal deformation pattern subgroups

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Figure 1. Measurement of septal deformation and adjudication of peaks

Longitudinal septal deformation is derived from single wall images (panel A, upper left corner). The dotted white line in panel A represents global deformation (negative slopes indicate shortening) of the interventricular septum and is used for septal deformation pattern classification. Aortic valve opening (AVO) and closure (AVC) define the ejection period. Onset of the QRS-complex (yellow circles and vertical lines) is used as zero strain reference. Adjudicated peaks are identified within the systolic period (i.e. between mitral valve closure (MVC) and AVC), and are indicated by red dots in panel B and C. Panel B shows a pattern where the amplitude of the first peak is within 150% of the second peak, and two systolic peaks are adjudicated. Panel C shows an example where the amplitude of the second peak is >150% that of the first peak, leading to the definition of a “late peak”.

Figure 2. Typical septal deformation patterns

Typical examples of septal deformation patterns in three LBBB-patients; LBBB-1: double-peaked systolic shortening, LBBB-2: early pre-ejection shortening peak followed by prominent systolic stretch, and LBBB-3: pseudonormal shortening with a late-systolic shortening peak and less pronounced end-systolic stretch. Green vertical lines indicate aortic valve opening (AVO) and closure (AVC).
Figure 3. Effect of ventricular dyssynchrony on the septal deformation pattern and on global left ventricular pump function and dimension.

A: Simulated septal myofiber strain (black lines) during a cardiac cycle with normal synchronous ventricular activation (NORMAL) and with dyssynchronous activation, i.e., delayed onset of LVFW (left to right) and septal (top to bottom) activation with respect to RV free wall activation. The LV ejection period is highlighted in grey. Changes of intraventricular and interventricular mechanical delay are illustrated by red dashed and solid black boxes, respectively. LVFW strain is indicated by grey lines. B: Maps showing the relative change of LV end-systolic volume (ESV) and the absolute change of LV ejection fraction (EF) due to dyssynchronous ventricular activation.

Figure 4. Effect of decreased myocardial contractility on the septal deformation pattern and on global left ventricular pump function and dimension.

A: Simulated septal myofiber strain (black lines) in a heart with typical LBBB dyssynchrony (25 and 75 ms delay of septal and LVFW activation, respectively) in combination with normal and regionally reduced LV myocardial contractility. The LV ejection period is highlighted in grey. Note that septal (from top to bottom) and LVFW (from left to right) hypocontractility affect the septal deformation pattern. LVFW strain is indicated by grey lines. B: Maps showing the relative change of LV end-systolic volume (ESV) and the absolute change of LV ejection fraction (EF) due to reduction of myocardial contractility.
Figure 5. Comparison of measured and simulated septal deformation patterns.

For a normal healthy subject (NORMAL) and three typical patients each representing one of the LBBB-subgroups (LBBB-1, LBBB-2, and LBBB-3), septal deformation patterns in the upper panels are compared to the model simulations in the lower panels (septal and LVFW strain indicated by solid and dashed lines, respectively). Vertical dashed lines indicate aortic valve opening and closure. Starting from the normal simulation (lower left corner), similar characteristic septal deformation patterns are obtained as measured in the study population by simple model simulations, i.e., classical LBBB (25 and 75 ms delay of septal and LVFW activation, respectively) with normal myocardial contractility (LBBB-1), LBBB with additional septal hypocontractility (LBBB-2), and LBBB with additional septal and LVFW hypocontractility (LBBB-3).
Septal Deformation Patterns Delineate Mechanical Dyssynchrony and Regional Differences in Contractility: Analysis of Patient Data Using a Computer Model
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SUPPLEMENTAL MATERIAL

Supplemental methods

Pericardium

In several studies, it has been shown that the pericardium significantly modulates ventricular interaction.\textsuperscript{1-4} Since ventricular interaction has been suggested to play an important role during left ventricular (LV) pacing,\textsuperscript{5,6} we included the pericardium in the CircAdapt model. The passive mechanical behavior of the pericardium was modeled by a pericardial pressure acting on the epicardium of the LV and RV free walls as well as of the atria (Figure S1). Consequently, transmural pressure across the LV free wall equals LV cavity pressure minus pericardial pressure whereas transmural pressure across the RV free wall equals RV cavity pressure minus pericardial pressure. Similarly, transmural pressure across the atrial walls equals atrial cavity pressure minus pericardial pressure. Moreover, the external pressure surrounding the pericardium is assumed to be zero.

Instantaneous pericardial pressure $p_{peri}$ depends on pericardial volume $V_{peri}$ by

$$p_{peri}(t) = p_{ref} \cdot \left( \frac{V_{peri}(t)}{V_{ref}} \right)^{10}$$

where the constants $p_{ref}$ and $V_{ref}$ represent reference pericardial pressure and volume, respectively. In experimental animals\textsuperscript{7} as well as in patients,\textsuperscript{8} the pericardium has been shown to be capable of adapting over time to changes in cardiac size. In our NORMAL model simulation, the pericardium is assumed to be adapted to a moderate level of exercise (3x resting cardiac output and 2x resting heart rate), i.e., $V_{ref}$ is adapted so that mean pericardial pressure amounts to the preset value $p_{ref}$ of 4 mmHg. In all other
simulations, the pericardium was not further adapted, i.e., passive pericardial material properties were identical in all simulations.

**Supplemental results**

*Effect of regional LV contractility changes on septal deformation pattern in the absence of ventricular dyssynchrony*

Figure S2A shows the isolated effect of regional LV myocardial contractility changes on the septal deformation pattern in a heart with normal (synchronous) activation of the ventricular walls. As in the dyssynchronous simulations, the amount of septal systolic shortening decreased with decrease of septal contractility, whereas it increased with decrease of LV free wall contractility. The majority of the dyssynchronous simulations however, were characterized by an early systolic peak. This peak only disappeared in case of severely decreased LV free wall contractility, transforming the septal deformation pattern into a pattern with a late systolic peak (Figure 4A). Conversely, isolated regional decrease of contractility in the absence of dyssynchrony did not result in an early systolic shortening peak. Decrease of septal contractility rather resulted in pronounced septal stretch before ejection and an extremely late postsystolic septal shortening peak. Decrease of LV free wall contractility on the other hand, resulted in a similar late-systolic peak as observed in dyssynchronous hearts with reduced LV free wall contractility (Figure S2A), but with less pronounced systolic rebound stretch after the peak. Figure S2B shows the changes of LV systolic pump function as a result of septal and LV free wall hypocontractility in the normal heart. Similar to the dyssynchronous simulations, decreases of septal or LV free wall contractility lead to a deterioration of global LV pump
function as evidenced by the increase of LV end-systolic volume and the decrease of LV ejection fraction.

Supplemental figures and figure legends

Figure S1: Schematic representation of the CircAdapt model

The CircAdapt model is designed as a network of modules representing myocardial walls, valves, large blood vessels, and peripheral resistances. The ventricular cavities are surrounded by three thick-walled segments representing the left ventricular (LV) free wall.
wall, the right ventricular (RV) free wall, and the septum. The pericardium is modeled as a passive sheet surrounding the ventricles and atria. The pulmonary (Pulm) and systemic (Syst) circulations enable hemodynamic interaction between the left and right side of the heart. Abbreviations: AoV = aortic valve; LA = left atrium; MiV = mitral valve; PuV = pulmonary valve; RA = right atrium; and TrV = tricuspid valve.
Figure S2: Effect of decreased myocardial contractility on the septal deformation pattern and on global left ventricular pump function and dimension in the absence of ventricular dyssynchrony.
A: Simulated septal myofiber strain (black lines) in a heart with normal synchronous ventricular activation in combination with normal and regionally reduced LV myocardial contractility. The LV ejection period is highlighted in grey. LVFW strain is indicated by grey lines. Note that, according to the model, an early systolic peak does not occur as a result of isolated contractility differences in the absence of dyssynchrony. B: Maps showing the relative change of LV end-systolic volume (ESV) and the absolute change of LV ejection fraction (EF) due to reduction of myocardial contractility.
Supplemental References


