Original Article

Three-dimensional speckle-tracking echocardiography-derived deformation analysis of the morphologic left ventricle in adults with corrected dextro-transposition of the great arteries—insights from the CSONGRAD Registry and MAGYAR-Path Study

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Background: Dextro-transposition of the great arteries (dTGA) stands out as a prevalent cyanotic congenital heart defect (CHD), characterized by an intricate reversal in the arrangement of the major arteries. In the past, several surgical procedures have been used to treat dTGA, including the atrial switch. Although the method is no longer used, survivors of the procedure still living among us. Recent advancements in cardiovascular imaging have led to the emergence of several novel echocardiographic techniques, notably three-dimensional (3D) and/or speckle-tracking echocardiography (STE). The present study aimed to employ 3DSTE to determine morphologic left ventricle (mLV) strain parameters in adults with dTGA who underwent Senning or Mustard procedure at infancy. Furthermore, it was also aimed to assess whether the type of correction procedure had any impact on mLV deformation parameters.

Methods: Eleven dTGA patients, with a mean age of 28.8±8.5 years (6 males, 6 Senning- and 5 Mustard-operated patients) were enrolled. They were compared to 34 healthy controls matched for age and gender (age: 35.7±12.8 years, 21 males). All subjects underwent complete two-dimensional (2D) Doppler echocardiography with 3DSTE data acquisition as per recent guidelines.

Results: Comparing all dTGA patients to the control group no mean segmental or global mLV strains showed significant differences, however out of the regional strains, midventricular mLV longitudinal strain was significantly better (higher) in dTGA compared to the healthy group (−16.8%±7.4% *vs.* −13.3%±2.5%, P<0.05). The Mustard-operated patients showed significantly worse (lower) global mLV circumferential strain compared to that of controls (−22.1%±12.4% *vs.* −28.9%±4.7%, P=0.05). Out of the regional strains the Mustard procedure group had a significantly worse (lower) apical mLV circumferential strain (−24.8%±11.9% *vs.* −35.6%±9.0%, P=0.05), better (higher) midventricular mLV longitudinal strain (−20.1%±9.2% *vs.* −13.3%±2.5%, P=0.04) and a worse (lower) apical mLV area strain (−36.3%±17.0% *vs.* −48.8%±9.7%, P=0.03).

Conclusions: Significant mLV strain abnormalities are present in dTGA late after atrial switch procedures. These differences are more pronounced in the Mustard-operated group.

Keywords: Transposition of great arteries; strain; three-dimensional (3D); speckle-tracking echocardiography (STE); left ventricle (LV)

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Introduction

Dextro-transposition of the great arteries (dTGA) stands out as a prevalent cyanotic congenital heart defect (CHD), characterized by an intricate reversal in the arrangement of the major arteries (1,2). Notably, the aorta emerges from the morphologic right ventricle (mRV), while the pulmonary artery originates from the morphologic left ventricle (mLV), setting the stage for segregated systemic and pulmonary circulations (1,2). In the past, surgical interventions, including atrial redirection (switch), were embraced, with survivors from those pioneering procedures still living today (3). However, the dominance of the Senning and Mustard procedures waned in the early 1990s with the advent of arterial switch operation (ASO), hailed as the pinnacle of anatomical and physiological finesse (4). The Senning procedure intricately manipulated the atrial septum to redirect blood flow through a crafted baffle, while the Mustard procedure employed a conduit fashioned from prosthetic tissue post-atrial septum excision. Despite their ingenuity, these techniques did not address ventricular-level pathologies (3,4).

The assessment of myocardial mechanics plays a crucial role in comprehending adaptations to various physiological and pathological conditions (5,6). Recent advancements in cardiovascular imaging have led to the emergence of several novel echocardiographic techniques, notably three-dimensional (3D) and/or speckle-tracking echocardiography (STE). Combining the benefits of both methodologies, three-dimensional speckle tracking echocardiography (3DSTE) enables simultaneous assessment of volumes and functional parameters such as strains from a single 3D dataset (7-10). The unique hemodynamic role of the mLV in corrected dTGA sets it apart from the typical physiological circulation. Nevertheless, there is limited information regarding the deformation mechanics of the mLV in dTGA (11). The present study aimed to employ 3DSTE to determine mLV strain parameters in adults with dTGA who underwent Senning or Mustard procedure at infancy. Furthermore, it was also aimed to assess whether the type of correction procedure had any impact on mLV deformation parameters. We present this article in accordance with the STROBE reporting checklist (available at https://cdt.amegroups.com/article/view/10.21037/cdt-24-266/rc).

Highlight box

Key findings

- Significant morphologic left ventricle (mLV) strain abnormalities are present in dextro-transposition of the great arteries late after atrial switch procedures. These differences are more pronounced in the Mustard-operated subgroup.

What is known and what is new?

- Previously it has been suggested that Senning-operated patients have better functional status and better long-term outcomes compared to Mustard-operated patients.
- In our article we show that Mustard-operated patients have significantly impaired mLV deformation pattern compared to controls, furthermore Senning-operated patients retain the normal mLV deformation pattern in our cohort. These changes might have a contributing factor in observed better long-term outcomes in the Senning-operated patients.

What is the implication, and what should change now?

- This article further enhances the need for the implementation of routine speckle-tracking echocardiography in clinical practice as these parameters detect subclinical changes and define later outcomes.

Methods

Patient population

Clinical data of dTGA patients were obtained from the CSONGRAD Registry [Registry of C(S)ONGenital caRdiAc Disease patients at the University of Szeged], established to compile clinical variables and parameters of CHD patients treated at the University of Szeged, Hungary. Among 195 infants with dTGA operated on without arterial switch between 1961–2013, 34 underwent the Senning procedure and 47 underwent the Mustard procedure. Initially, 18 dTGA patients who had undergone atrial switch were recruited for this study, but 7 were excluded due to inferior image quality. The remaining 11 dTGA patients, with a mean age of 28.8±8.5 years (6 males, 6 Senning- and 5 Mustard-operated patients), were followed by the Division of Cardiology at the University of Szeged (*Figures 1,2*). Routine two-dimensional (2D) Doppler echocardiographic and 3DSTE studies of dTGA patients were performed by the same observer (Á.K.) at the same time. All dTGA patients were asked to participate in the study on a voluntary basis, they were examined within the same week. Their data were compared to that of 34 healthy controls matched for age and gender (age: 35.7±12.8 years, 21 males), who had no known disorders or clinical conditions. This retrospective cohort study is part of the MAGYAR-Path Study (Motion Analysis of the heart

Figure 1 Inclusion and exclusion criteria for patients with corrected dTGA are presented. dTGA, dextro-transposition of the great arteries.

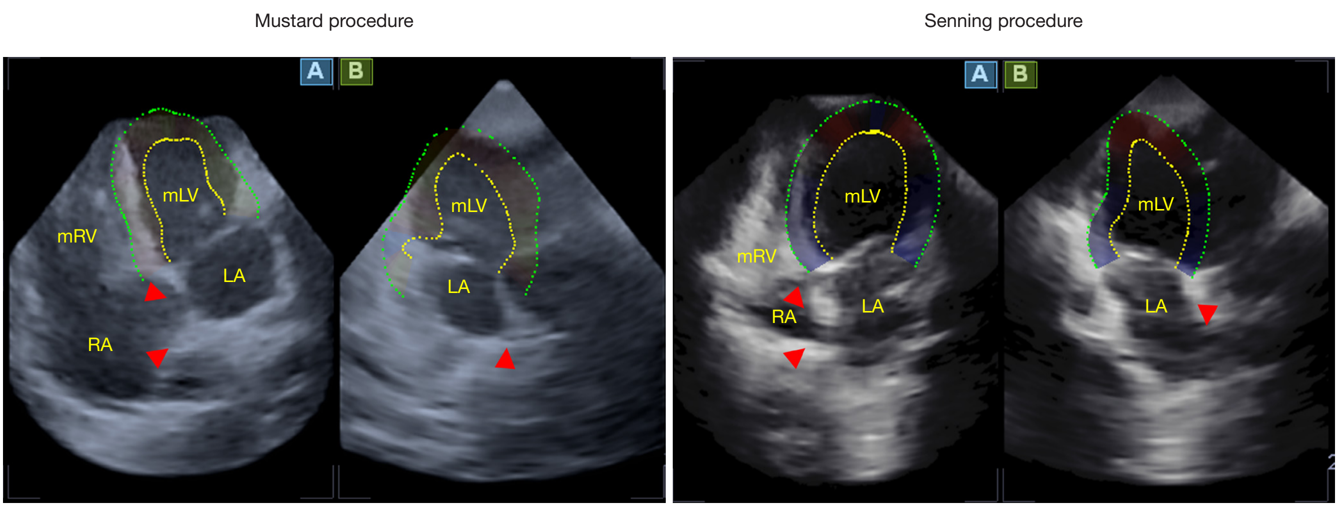

Figure 2 Echocardiographic images [(A) apical 4-chamber view; (B) apical 2-chamber view] showing the two types of atrial baffle corrections: Mustard and Senning procedures. Mustard procedure uses artifical baffle to shunt superior caval vein and inferior caval vein to the LA, whereas Senning procedure uses the patient's tissue to achieve this. Red triangles show baffle position on both images. mLV, morphologic left ventricle; LA, left atrium; mRV, morphologic right ventricle; RA, right atrium.

and Great vessels bY three-dimensionAl speckle-tRacking echocardiography in Pathological cases—"MAGYAR" means Hungarian in the Hungarian language), focusing on disease-specific abnormalities of 3DSTE-derived cardiac mechanics, including mLV strain measurements in dTGA. The study adhered to the Declaration of Helsinki (as revised in 2013) and was approved by the Institutional and Regional Human Biomedical Research Committee of the University of Szeged, Hungary (No. 71/2011). Informed consent was obtained from all participants.

2D Doppler echocardiography

Both corrected dTGA patients and healthy control subjects underwent a comprehensive routine 2D Doppler echocardiographic assessment utilizing the Toshiba Artida^{TM} system (Toshiba Medical Systems, Tokyo, Japan) coupled with a PST-30SBP (1–5 MHz) phased-array transducer. Chamber quantifications and valvular assessments were conducted following the latest guidelines (12).

3DSTE

To conduct the 3DSTE study, the same Toshiba Artida^{TM} cardiac ultrasound system was employed (Toshiba Medical Systems) equipped with a PST-25SX matrix-array transducer capable of 3D imaging. Initially, subjects were positioned in the left lateral decubitus position, and 3D echocardiographic data were acquired through the apical window. To optimize image quality, patients were instructed to hold their breath while six subvolumes were acquired and automatically merged to generate a complete volume 3D echocardiographic dataset. Subsequently, the acquired data were analyzed offline following data acquisition within a week using the vendor-provided 3D Wall Motion Tracking software version 2.7 (Ultra Extend, Toshiba Medical Systems, Tokyo, Japan). The process involved selecting optimal standard apical longitudinal views, as well as basal, midventricular, and apical cross-sectional planes. Additionally, the mitral annular septal and lateral insertion points and the endocardial surface of the mLV apex were defined. A virtual 3D model of the mLV was then constructed through sequential analysis (*Figure 1*). Using this mLV 3D model, measurements were taken for global unidirectional/unidimensional longitudinal (LS), circumferential (CS), radial (RS), and complex/multidirectional/multidimensional area (AS), as well as 3D (3DS) strains. Additionally, segmental and mean segmental mLV strains were evaluated using a 16-segment mLV model. From segmental mLV strains, mLV regional strains (apical, midventricular, and basal) were also computed (*Figure 3*).

Statistical analysis

Continuous variables were reported as mean ± standard deviation, while categorical variables were presented as numbers and percentages. Statistical significance was determined at P<0.05. Fischer's exact test was applied to all categorical variables. Normality of distribution for continuous variables was assessed using the Shapiro-Wilks test. Student's *t*-test was employed for normally distributed data, while the Mann-Whitney-Wilcoxon test was utilized for non-normally distributed data. For intraobserver and interobserver correlations, intraclass correlation coefficients (ICCs) were calculated. Statistical analyses were conducted using Medcalc software (Medcalc, Mariakerke, Belgium).

Results

Clinical and demographic data

There were no significant differences observed in mean age (35.7±12.8 *vs.* 28.8±8.5 years, P=0.10) or gender distribution (21 males, 62% *vs.* 6 males, 60%) between healthy *vs.* dTGA groups. None of the dTGA patients or matched healthy controls exhibited hypercholesterolemia or diabetes mellitus. Hypertension was present in 3 dTGA patients (27%), which was a statistically significant difference (P=0.01). Atrial and ventricular septal defects, as well as patent ductus arteriosus, were identified in 3, 3, and 4 dTGA patients, respectively. The average age at the time of the initial procedure in the dTGA patient population was 1.4±1.1 years. On average, 27.8±8.2 years had elapsed between the intervention and the 3DSTE examination in this group (*Table 1*).

2D Doppler echocardiography

Between all dTGA patients and controls thickness of the interventricular septum (IVS) (10.5±2.3 *vs.* 9.0±1.3 mm, P=0.002) and mLV posterior wall (10.3±1.4 *vs.* 9.1±1.2 mm, P=0.02) differed significantly from the routine 2D echocardiographic data. The Senning procedure group had a significantly thicker IVS compared to controls (10.3±1.0 *vs.* 9.0±1.3 mm, P=0.05). The Mustard procedure group had a

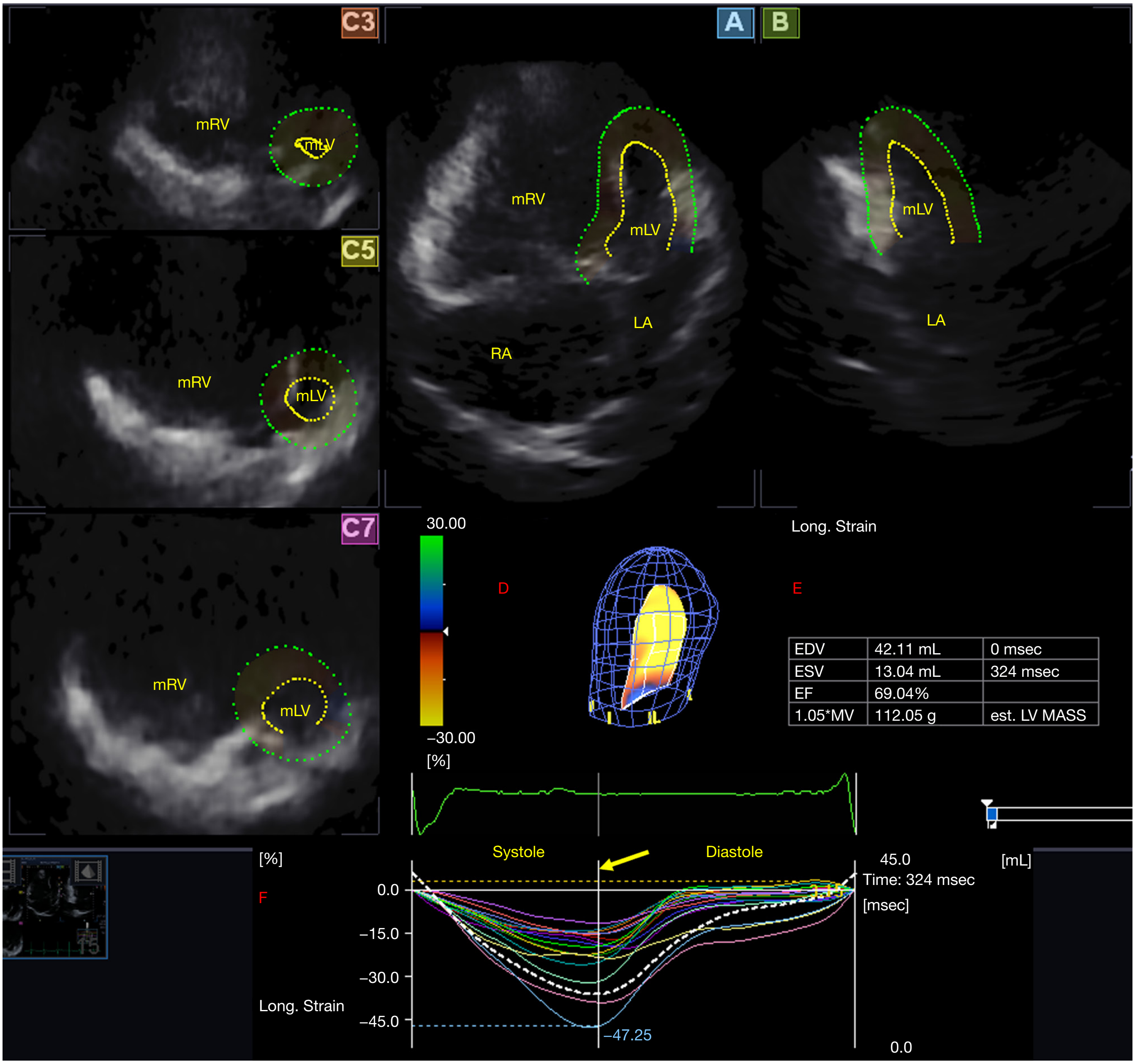

Figure 3 3D speckle-tracking echocardiographic assessment of the mLV longitudinal strain imaging from an mLV focused view in a patient with Senning-operated dextro-transposition of the great arteries. Apical four-chamber (A) and two-chamber views (B) and basal (C3), midventricular (C5) and apical (C7) short-axis views are demonstrated, which we were able to automatically extract from the acquired 3D echocardiographic database. (Red D) shows 3D model of the mLV, while (red E) shows mLV volumetric parameters and ejection fraction. (Red F) shows segmental mLV longitudinal strain curves. Yellow arrow represents peak systolic contraction (end-systole). mLV, morphologic left ventricle; LA, left atrium; mRV, morphologic right ventricle; RA, right atrium; EDV, end-diastolic volume; ESV, end-systolic volume; EF, ejection fraction; est. LV MASS, estimated morphologic left ventricular mass; 3D, three-dimensional.

Table 1 Baseline demographic and two-dimensional echocardiographic data in patients with dextro-transposition of the great arteries and controls

Parameters	Controls (n=34)	dTGA patients (n=11)	P value
Risk factors			
Age (years)	35.7±12.8	28.8±8.5	0.10
Male	21 [62]	6 [55]	0.73
Hypertension	0	3 [27]	0.01
Diabetes mellitus	0	0	>0.99
Hypercholesterolaemia	0	0	>0.99
Two-dimensional echocardiography			
LA diameter (mm)	37.9±3.9	33.8±6.0	0.16
mLV end-diastolic diameter (mm)	48.5±3.7	49.3±2.6	0.62
mLV end-diastolic volume (mL)	109.5±30.6	117.0±17.4	0.53
mLV end-systolic diameter (mm)	32.9±3.6	31.3±4.3	0.31
mLV end-systolic volume (mL)	39.5±8.9	40.9±11.3	0.73
Interventricular septum (mm)	9.0±1.3	10.5±2.3	0.002
mLV posterior wall (mm)	9.1±1.2	10.3±1.4	0.02
mLV ejection fraction (%)	64.8±3.3	64.1±5.4	0.70

Data are presented as mean ± standard deviation or n [%]. dTGA, dextro-transposition of the great arteries; LA, left atrial; mLV, morphologic left ventricle.

significantly smaller LA diameter (30.4±2.3 *vs.* 37.9±3.9 mm, P=0.05) and lower mLV ejection fraction (60.5%±4.0% *vs.* 64.8%±3.3%, P=0.04) compared to the healthy group. Between the Senning and Mustard procedure groups, Mustard-operated patients showed significantly smaller LA diameter compared to the Senning procedure group (30.4±2.3 *vs.* 39.3±6.5 mm, P=0.05) (*Table 1*).

3DSTE-derived mLV strain parameters

Comparing all dTGA patients to the control group no mean segmental or global mLV strains showed significant differences, however out of the regional strains, midventricular mLV-LS was significantly higher in dTGA compared to the healthy group (−16.8%±7.4% *vs.* −13.3%±2.5%, P=0.05). Global, mean segmental and regional mLV strains of the Senning-operated group showed no significant differences compared to the healthy controls. Similar mLV strains between the Senning and Mustard procedure groups showed no significant difference. The Mustard-operated patients showed significantly lower global mLV-CS compared to that of controls (−22.1%±12.4% *vs.* −28.9%±4.7%, P=0.05). Out of the regional strains the Mustard procedure group had a significantly lower apical mLV-CS (−24.8%±11.9% *vs.* −35.6%±9.0%, P=0.04), higher midventricular mLV-LS (−20.1%±9.2% *vs.* −13.3%±2.5%, P=0.04) and a lower apical mLV-AS (−36.3%±17.0% *vs.* −48.8%±9.7%, P=0.03) (*Tables 2,3*) compared to controls.

Reproducibility of 3DSTE-derived LV parameters

Intraobserver ICCs for 3DSTE-derived global mLV-RS, mLV-CS, mLV-LS, mLV-3DS and mLV-AS proved to be 0.86, 0.82, 0.81, 0.81, and 0.84, respectively. Interobserver ICCs for the same parameters proved to be 0.81, 0.76, 0.78, 0.77, and 0.81, respectively.

Discussion

dTGA is a rare CHD characterized by the abnormal positioning of the aorta and pulmonary artery. This results in a parallel arrangement, where the aorta arises from the mRV and the pulmonary artery from the mLV. During embryogenesis, the physiological rotation of the cardiac outflow tract rotation is disrupted, resulting in a pathologic ventriculoarterial connection (1,2).

3DSTE offers advantages over traditional 2D techniques for strain imaging due to its ability to provide volumetric data, enabling comprehensive assessment of myocardial deformation throughout the entire cardiac cycle. Unlike 2D echocardiographic methods, which are inherently limited by the single-plane nature of acquisition, 3DSTE allows for analysis from multiple viewpoints, enhancing accuracy and reproducibility in strain measurements. Additionally, 3DSTE mitigates errors associated with out-of-plane motion, providing more reliable and clinically relevant information for assessing cardiac mechanics (7-10).

To the best of the authors' knowledge, this is the first study in which mLV deformation abnormalities were investigated in Senning- and Mustard-operated dTGA patients using 3DSTE methodology. In case of arterial

Table 2 Comparison of three-dimensional speckle-tracking echocardiography-derived global and mean segmental strains of the morphologic left ventricle between controls and different in dextro-transposition of the great arteries patient groups

Data	Controls (n=34)	dTGA patients		
		All (n=11)	Senning-operated (n=6)	Mustard-operated (n=5)
Global (%)				
mLV-RS	23.7±4.9	22.2±17.4	22.3±20.2	22.1±21.0
mLV-CS	–28.9±4.7	–25.9±10.3	–29.1±8.0	–22.1±12.4*
mLV-LS	–15.6±2.5	–15.7±5.3	–15.0±4.9	–16.5±6.2
mLV-3DS	26.0±5.1	25.6±18.8	24.8±20.8	26.6±18.3
mLV-AS	–41.1±4.6	–38.5±12.2	–40.9±10.6	–35.5±14.5
Mean segmental (%)				
mLV-RS	26.3±4.5	26.3±17.0	26.2±20.2	26.4±14.7
mLV-CS	–30.1±4.5	–27.9±9.2	–30.3±7.9	–25.0±10.7
mLV-LS	–16.4±2.3	–16.8±5.2	–15.7±4.6	–18.2±6.1
mLV-3DS	28.3±4.5	29.4±18.2	28.3±21.0	30.7±16.5
mLV-AS	–42.2±4.3	–40.2±11.1	–41.8±10.3	–38.3±13.0

Data are presented as mean ± standard deviation. *, P=0.05 *vs.* controls. dTGA, dextro-transposition of the great arteries; mLV, morphologic left ventricle; RS, radial strain; CS, circumferential strain; LS, longitudinal strain; 3DS, three-dimensional strain; AS, area strain.

switch correction, the literature is more abundant. In a meta-analysis pooling the results of 21 studies regarding exercise capacity and mLV function in dTGA patients after ASO, LV function was retained in the 6 years of follow-up after operation (13). In another study, the authors compared 62 dTGA patients to healthy children using 2DSTE, and they found that ASO dTGA patients had a significantly lower global mLV-LS compared to controls (14). In a 3D echocardiographic study it was found that after ASO mLV retains its function, however there are signs for subclinical maladaptation (15). In a different ASO cohort global mLV-LS and mLV function was impaired and LA strains were also impaired compared to healthy subjects (16). At this point it is clear the STE has an important role for assessing dTGA and other CHD populations as the methodology offers the ability of detecting subclinical changes in mLV deformation pattern and these changes have a profound effect on outcomes (17). Our group has previously assessed the mLV rotational pattern in a similar dTGA population, and we have found that mLV 'rigid body rotation' was prevalent in this population, furthermore mLV twisting was preserved due to mLV basal rotation increase which offsets the impaired apical mLV rotation (18).

The primary finding of this study reveals that Senning-operated patients exhibited mLV strains comparable to those of the control group, while the Mustard-operated patient cohort displayed significantly impaired mLV-CS relative to controls. While the overall deformation pattern was preserved in the Senning procedure group, Mustard-operated patients exhibited a shift in regional strain patterns as compared to either controls or the other group. In the healthy group mLV-CS and (from the midventricle) mLV-LS progressively increase towards the apical region, however in the Mustard-operated group, midventricular mLV-CS and mLV-LS are higher compared to the apical ones, suggesting a shift in the mLV deformation pattern. This pattern is preserved in the Senning-operated patients. These findings suggest that the functional non-uniformity of mLV deformation is lost, or at least impaired in the Mustang-operated patients. These findings are particularly intriguing as the mLV of atrial-switched dTGA patients serves the pulmonary circulation. Consequently, the results suggest that the underlying anatomy and microstructure of a ventricle may outweigh the influence of its loading conditions. To further support the importance of functional non-uniformity and importance of a preserved mLV deformation pattern: in a different cohort Senning patients had a slightly better survival in long-term follow up

Table 3 Comparison of three-dimensional speckle-tracking echocardiography-derived regional strains of the morphologic left ventricle between controls and different in dTGA patient groups

Data	Controls (n=34)	dTGA patients		
		All (n=11)	Senning-operated (n=6)	Mustard-operated (n=5)
mLV-RS (%)				
Basal	28.3±7.7	30.5±19.3	31.2±24.9	29.6±12.6
Midventricular	29.2±5.7	26.9±20.4	27.6±25.2	26.1±15.8
Apical	19.0±8.0	19.1±14.8	16.6±8.1	22.1±21.0
mLV-CS (%)				
Basal	−24.9±3.7	−26.1±8.5	−27.6±7.0	−24.3±10.6
Midventricular	−31.6±5.3	−28.1±10.8	−30.0±9.8	−25.9±12.6
Apical	−35.6±9.0	−30.2±12.6	−34.8±12.2	−24.8±11.9*
mLV-LS (%)				
Basal	−18.6±4.2	−16.5±5.3	−15.2±4.5	−18.0±6.2
Midventricular	−13.3±2.5	−16.8±7.4*	−14.0±4.6	−20.1±9.2**
Apical	−17.8±5.1	−17.4±8.3	−18.9±8.7	−16.5±6.2
mLV-3DS (%)				
Basal	31.3±6.5	34.7±20.7	34.7±26.5	34.8±13.9
Midventricular	30.3±5.4	29.7±21.5	28.9±25.7	30.7±18.0
Apical	20.8±8.8	20.7±15.2	17.7±7.6	24.3±21.8
mLV-AS (%)				
Basal	−38.4±4.6	−38.7±11.0	−39.7±12.6	−37.4±10.1
Midventricular	−41.5±5.1	−40.6±13.0	−40.8±10.9	−40.4±16.6
Apical	−48.8±9.7	−41.9±15.6	−46.5±14.1	−36.3±17.0***

Data are presented as mean ± standard deviation. *, P=0.05 *vs.* controls; **, P=0.04 *vs.* controls; ***, P=0.03 *vs.* controls. dTGA, dextro-transposition of the great arteries; mLV, morphologic left ventricle; RS, radial strain; CS, circumferential strain; LS, longitudinal strain; 3DS, three-dimensional strain; AS, area strain.

(30 years) compared to the Mustard-operated patients, and Senning patients had better functional status as well (19).

Limitation section

Some important limiting factors affected the present study.

Both 2DSTE and 3DSTE suffer in a number of limitations including intervendor variability, the long learning curve and the potential influence of the chest wall conformation on reproducibility of myocardial strain parameters (20-22).

Moreover, 3DSTE is well known to have inferior spatial and temporal resolution as compared to 2DSTE (23,24).

dTGA is a relatively rare condition, especially patients who previously underwent atrial switch procedure.

There is a relatively large time gap between the surgery date and the enrollment in care for dTGA patients, so we did not consider the impact of factors (such as other, non-cardiac surgeries, other than cardiologically relevant drug use, etc.) occurring in the intervening period in our study.

mLV rotation and twist was not assessed in the present study; however, it has been reported previously (18).

Conclusions

Significant mLV strain abnormalities are present in dTGA late after atrial switch procedures. These differences are more pronounced in the Mustard-operated group.

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Footnote

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