Differentiation of the Left and Right Side Interventricular Septum Function in Healthy Subjects by Vector Velocity Imaging

ORIGINAL INVESTIGATION

ABSTRACT

Background: The present study aimed to assess and compare regional strain of the right and left sides of interventricular septum in healthy subjects using velocity vector imaging analysis due to the importance of interventricular septum and limited basic information about the exact function of the interventricular septum.

Methods: The present study was conducted on 40 healthy subjects. Echocardiography was performed in the apical 4-chamber view in the left lateral decubitus position. Image analysis was done offline with velocity vector imaging; the longitudinal strain and strain rate were calculated during 3 cardiac cycles. Strain-time and strain rate-time curves in basal, middle, and apical segments of the left and right sides of interventricular septum were recorded; peak values and time to peak strain were determined.

Results: There was no significant difference between the longitudinal strain in the right and left basal ($-17.7 \pm 5.10\%$ vs. $-18.2 \pm 5.14\%$, $P = .550$), middle ($-17.1 \pm 4.53\%$ vs. $-17.9 \pm 4.29\%$, $P = .197$) segments, strain rate of basal (-1.1 ± 0.36 1/s vs. -1.0 ± 0.36 1/s, $P = .350$), and middle (-1.0 ± 0.30 1/s vs. -1.1 ± 0.32 1/s, $P = 0.551$) segments. However, there was a significant difference between the longitudinal strain ($-22.2 \pm 5.55\%$ vs. $-16.6 \pm 4.45\%$, $P < .001$) and strain rate (-1.5 ± 0.46 1/s vs. -1.1 ± 0.33 1/s, $P < .001$) of the apical segment. Time to peak strain was significantly different only in the middle segment of interventricular septum (right side: 351.0 ± 11.5 ms vs. left side: 344.4 ± 13.1 ms, $P = .004$).

Conclusions: The findings of this study suggest that the right and left function of the septum was comparable in the basal and middle segments of healthy subjects; this function was significantly different in the apical segments.

Keywords: Healthy volunteers, heart, ventricular septum, cardiac imaging technique, mechanical phenomena

INTRODUCTION

Both the right and left ventricles (LV) are involved in the formation of interventricular septum (IVS). Although this wall is considered as a single functional wall in clinical studies, previous studies have shown that it is divided into 2 right and left sides (RS and LS) and are structurally and functionally bilayer.[1,2] Besides, both sides of the septum are different from each other in secondary branches of the arterial coronary supplying and venous drainage.[3,4] The development of imaging techniques makes it possible to obtain more accurate information about IVS function.[4-7]

Strain is considered a mechanical parameter and refers to the amount of tissue deformation (contractile characteristics), which is usually expressed as a percentage. There are 3 normal strain types, including longitudinal, radial, and circumferential strains. Strain rate is defined as strain per time unit and is a measure of deformation rate.[8,9] In 2 different studies on normal subjects using the tissue Doppler imaging (TDI) method, Boettler et al[6] and also Park et al[7] evaluated strain, strain rate, and tissue velocity in the middle segment of the RS of the ventricular septum compared to the LS.

One of the limitations of TDI is angle dependency, which leads to the underestimation of results.[6,7] Speckle tracking echocardiography (STE) is a new method and is angle independent; it is also independent of cardiac translation. This method

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analyzes tissue movements by integrating frame-to-frame changes.[10,11] Vector velocity imaging (VVI) is a relatively new method that utilizes an ultrasonic speckle tracking algorithm with advanced geometric edge detection analysis. This technique, unlike TDI, directly measures velocity and tissue strain without angle dependency and makes it possible to perform a global and regional evaluation of the tissue function.[11-14]

Considering that only the middle segment of IVS was examined in most studies,[6,7] and also due to the lack of basic information about the exact function of IVS segments, as well as the possibility of having access to advanced techniques with fewer imaging restrictions, the present study was designed and aimed to investigate and determine the regional function of IVS in healthy subjects in terms of longitudinal strain, strain rate, and time to peak strain parameters in basal, middle, and apical segments RS compared with LS using VVI.

METHODS

This prospective study was conducted on 40 healthy male and female volunteers aged 20-60 years old.

The inclusion criteria were no history of heart disease and coronary artery disease, including myocardial infarction, medication, surgery, atrial or ventricular arrhythmia, heart failure, hypertrophy, block nerve conduction, pulmonary hypertension, valvular diseases, and diabetes. Also, the results of electrocardiography (ECG) and echocardiography and exercise stress tests (if performed) were normal (2 cases). A 12-lead ECG was obtained in all subjects and a normal ECG was an inclusion criterion. No subject had cardiovascular risk factors including arterial hypertension, diabetes mellitus, obesity, dyslipidemia (total cholesterol and/or triglyceride higher than normal range), and smoke habit. Necessary information was collected from the subjects in the form of a checklist, including age, sex, family history of heart disease, cause of referral for echocardiography, history of drug prescription, weight, height, BMI, blood pressure, and basic echocardiographic parameters such as septum thickness, left ventricular end-systolic volume and left ventricular end-diastolic volume indexed to body surface area, and left ventricular ejection fraction. This study was approved by the Ethics Committees of Guilan University of Medical Sciences (IR.GUMS.REC.1394.357). All subjects signed informed written consent before participation in the study. The research

process was explained to the participants to understand the details of the procedures and the ethical considerations before performing echocardiography.

Echocardiographic Study and Off-Line Analysis
The echocardiography was performed by an experienced echocardiographist using echocardiography system AG Siemens (model PRIME ACUSON SC2000; D-80333 Muenchen, Germany) equipped with a multi-frequency-phased array ultrasonic transducer, with the possibility of generating ultrasonic waves in the frequency range of 1.5-4 MHz. The echocardiography system enables imaging using 2-dimensional (2D) B-mode, M-mode methods, harmonic, Doppler, and Doppler tissue imaging.

The ECG was recorded by connecting ECG leads. The results of the ECG were used to determine cardiac phases and to calculate the cardiac strain. The 2D echocardiography of the subjects was performed in the apical 4-chamber view. An appropriate sector angle was adjusted in the range of 30°-45° to ensure the highest possible sampling frequency (60-90 fps). In order to reduce the effect of breathing, as well as technical problems such as drift artifact, all imaging process was performed at the end of the exhalation respiratory cycle. Two-dimensional images were stored on the memory system during 3 cardiac cycles.

Offline analysis of images was performed using VVI. At the end of the diastole phase, as the reference point, the endocardial edge was specified on the right and left of IVS by determining the scope of 18 points from the mitral annulus valve to the apex, as the left endocardial edge; from the apex to tricuspid annulus valve, it was determined as the right endocardial edge. Then, automatic tracing was performed in the above anatomical points during 3 cardiac cycles; the tissue velocity was displayed as a vector projected on the 2D images, where the vector showed the direction and velocity of the myocardial movement (Figure 1).

The velocity vector data were translated into strain and strain rate by the software (Syngo, VB10E, Ver.4) automatically. Strain-time and strain rate-time curves were obtained during 3 cardiac cycles and in basal, middle, and apical segments of the RS and LS. The mean peak values were calculated in terms of longitudinal strain and strain rate and time to peak strain values. The negative longitudinal value represents shortening, whereas the positive longitudinal value denotes lengthening. The analysis was performed twice on 15 images to calculate the intra-observer and interobserver variabilities.

Statistical Analysis
Statistical analysis was performed using Statistical Package for the Social Sciences (Ver.16). Continuous data distribution was performed using the Kolmogorov—Smirnov test and the results were reported as mean ± standard deviation separately for RS and LS in the intended segments. The mean of RS and LS in the intended segments was compared using paired samples t-test, and comparison between basal, middle, and apical segments was performed using the Friedman test at a CI of 95% ($P < .05$). Intra- and inter-observer variability was reported as a coefficient of variation. This measure

HIGHLIGHTS

- We assessed the regional strain of the right and left sides of the interventricular septum in healthy subjects using a new proposed velocity vector imaging analysis.
- Right and left side functions (longitudinal strain and strain rate) were similar in the basal and middle segments; however, their function was significantly different in the apical segment.
- Right and left sides' time to peak strain of the middle segment was significantly different.
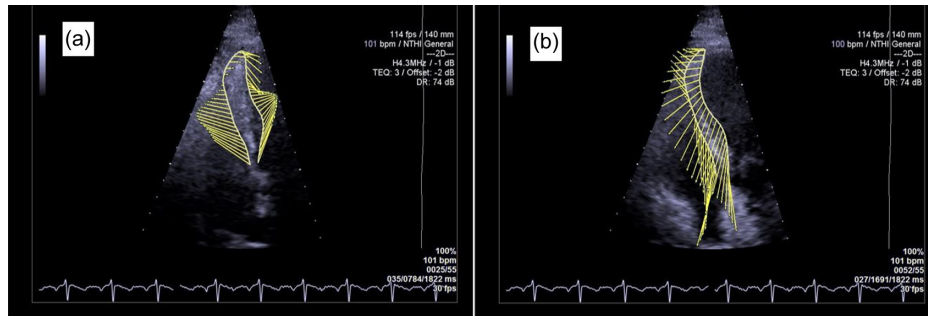
Figure 1. Interventricular septum velocity vectors in a healthy subject from the apical 4-chamber view at the end of systole (A) and diastole (B).

of reproducibility was based on 2 repeated measures from each individual and quoted as a percentage according to the formula:

$$CV\left(\%\right)=\left(\frac{SD\;diff}{\mu}\right)\times 100$$

RESULTS

The demographic information of the subjects is shown in Table 1. Based on the results, female and male participants were accounted for 25 (62.5%) and 15 (37.5%) of the subjects, respectively, and the mean age was 40.0 ± 11.4 years.

Longitudinal Strain and Strain Rate

The results of the 2 subjects were excluded because of unsuitable quality of data. Figure 2 shows longitudinal strain and strain rate curves during 3 cardiac cycles, respectively for the basal, middle, and apical segments of RS and LS in a healthy subject. Strain and systolic strain rate polarity were negative on both sides of the septum in all segments, and the diastolic strain rate was positive. Negative strain values indicate shortening/contraction in IVS; more negative value is associated with better systolic function.

The results of comparing the mean values in basal, middle, and apical segments of RS and LS showed no significant difference between the basal and middle segments

Table 1. The Demographic Information of the Subjects (n = 38)

Variables	Mean	SD
Age (year)	40.0	11.4
Weight (kg)	72.7	11.9
Height (cm)	167.1	9.9
BMI	26.0	3.9
Systolic BP (mm Hg)	112.5	11.7
Diastolic BP (mm Hg)	79.0	6.7
Heart rate (beats/min)	79.2	9.8
Septum thickness (mm)	7.5	0.8
LVESV (mL/m^2)	21	3
LVEDV (mL/m^2)	48	6
LVEF (%)	58	4

BMI, body mass index; BP, blood pressure; LVESV, left ventricular end-systolic volume; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; SD, standard deviation.
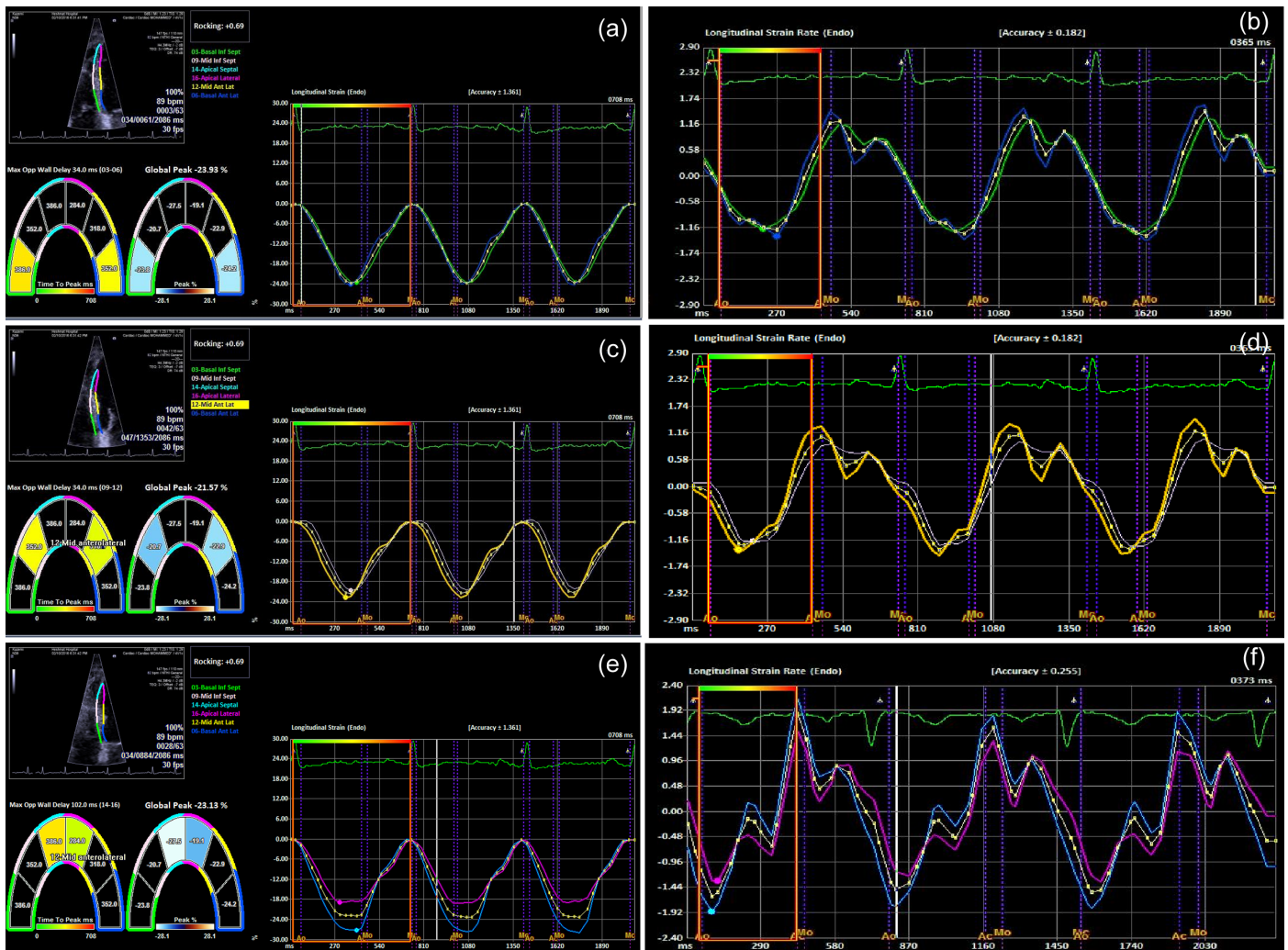
in terms of peak longitudinal strain and strain rate values (Table 2). However, there was a significant difference between RS compared to LS in terms of peak longitudinal strain and strain rate in the apical and total segments. The longitudinal strain and strain rate in the right apical and total segments were larger than the LS (Table 2).

In addition, the results of the mean longitudinal time to peak strain of the studied segments in RS and LS showed that this time was not statistically different in the basal and apical segments of RS and LS; however, it was significantly greater in the middle segment of RS than LS (Table 3).

The results of comparing the mean rank of the basal, middle, and apical segments of RS and LS of IVS in terms of longitudinal strain and strain rate and time to peak strain parameters are presented in Table 4. There was no significant difference between studied segments in terms of longitudinal strain and strain rate on the left side, while a significant difference was observed on the right side. The study of time to peak strain showed that there was a significant difference in the left side segments in mean rank comparison, while no significant difference was observed in the right side. Our results showed that intra- and inter-observer variabilities were lower than 10%.

DISCUSSION

Muscle structure, physiology, and blood supply of IVS have been the focus of researchers' attention for years.[3,4,15] Because of advances in technology particularly imaging methods in recent years, we can now investigate the physiology in more detail, including the resulting function. Today, with 2D echocardiography techniques, a white line is clearly visible, which separates RS and LS from each other.[6,7] In the present study, longitudinal strain and strain rate of the septum were examined, as well as longitudinal systolic time to peak strain. Since the strain is relatively independent of tethering, investigating the effect of this parameter on features such as velocity and displacement was preferred.[16] It is noteworthy that measurement of the left ventricular walls strain, including IVS, was evaluated as a single-functional wall in previous studies; the functional differences in the RS and LS of the septum were not discussed. To the best of our knowledge, the RS and LS contractile function of IVS in basal, middle, and apical segments of healthy subjects was determined for the first time in the present study.

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Figure 2. The longitudinal strain (left corner) and strain rate (right corner) of IVS in a healthy subject during 3 cardiac cycles. Basal segment (A and B; green and blue curves that show IVS right and left sides, respectively). Middle segment (C and D; pink and yellow curves that show IVS right and left sides, respectively) and apical segment (E and F; azure and violet curves that show right and left sides IVS, respectively). IVS, interventricular septum.

In most of the previous studies, TDI was used to quantify mid-segment IVS regional function.[6,7] Unfortunately, TDI is an angle-dependent method, which may compromise the validity of results[17]; it accounts for a major limitation for evaluating the myocardial regional function.[18] In this study, we used the VVI method for the assessment of right and left IVS strain and strain rate parameters. Velocity vector imaging is an advanced STE method based on the myocardial feature of frame-by-frame tracking of the ultrasound speckles within the images; it assesses the myocardial strain in 2D.[19] The use of VVI for the assessment of regional myocardial function has been validated in previous studies.[20,21] Pirat et al[22] validated VVI against the sonomicrometry method in an experimental set.

In the present study, there was no statistically significant difference between RS compared to LS in terms of average longitudinal time to peak strain in basal and apical segments,

Table 2. Longitudinal Peak Systolic Strain and Strain Rate of Right and Left Interventricular Septum Segments

IVS Segments	Longitudinal Strain (%)			Longitudinal Strain Rate (1/second)		
	RS (Mean ± SD)	LS (Mean ± SD)	P	RS (Mean ± SD)	LS (Mean ± SD)	P
Basal	−17.7 ± 5.10	−18.2 ± 5.14	.550	−1.1 ± 0.36	−1.0 ± 0.36	.350
Middle	−17.1 ± 4.53	−17.9 ± 4.29	.197	−1.0 ± 0.30	−1.1 ± 0.32	.551
Apical	−22.2 ± 5.55	−16.6 ± 4.45	<.001	−1.5 ± 0.46	−1.1 ± 0.33	<.001
Total	−19.0 ± 5.53	−17.6 ± 4.66	.007	−1.2 ± 0.43	−1.0 ± 0.34	<.001

IVS, interventricular septum; RS, right side of IVS; LS, left side of IVS; SD, standard deviation.

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Table 3. Longitudinal Systolic Time to Peak in the Segments of Right and Left Interventricular Septum

	Time to Peak (Milliseconds)		
IVS Segments	RS (Milliseconds) (Mean ± SD)	LS (Milliseconds) (Mean ± SD)	P
Basal	351.7 ± 13.1	352.8 ± 13.4	.679
Middle	351.0 ± 11.5	344.4 ± 13.1	.004
Apical	346.3 ± 13.4	345.4 ± 11.4	.660
Total	348.1 ± 12.7	347.4 ± 12.9	.622

IVS, interventricular septum; RS, right side of IVS; LS, left side of IVS; SD, standard deviation.

but its value was significantly greater in the right middle segment than the LS. The longitudinal strain and strain rate in the basal and middle segments of RS and LS were not significantly different, but they were different in the total and apical segments of RS and LS; so that the longitudinal strain and strain rate of the total and apical segments of RS were larger than LS. According to our study methodology, the main reason for the difference in the apical part of the LS and RS strain cannot be explained. However, several hypotheses have been proposed regarding the difference of the RS and LS of the whole septum based on previous studies. First of all, there might be different amounts of gap junctions and their subtypes at both sides of the IVS. Second, morphological features in fiber arrangement at both sides of ventricular septum are different from each other (left side: oblique with 30 ° to 80°, right side: short axis with −20° to 20°). Finally, because of different functions of calcium-independent potassium currents of ventricles and lower repolarization time of LV, depolarization's messages transfer faster longitudinally, and rapid contractions occur in the LS.[23,24]

Overall, the findings of the present study were consistent with control normal findings obtained by Park et al[7], and also Boettler et al[6]; they examined only the middle segment of the IVS.[6,7] Park et al[7] in part of their study on 20 normal subjects using TDI[6] found that there was no significant difference among normal subjects in terms of longitudinal strain and strain rate in the middle segment of RS and LS ($P = .28$ and .27, respectively). Boettler et al[6] also conducted a study on the RS and LS of the mid-septum of 30 normal subjects using TDI; they found that the longitudinal strain and strain rate did not differ in RS and LS of the middle septum (−25 ± 12% vs. −28 ± 12%; $P =$ NS and −2.0 ± 0.06 1/s vs. −2.2 ± 0.07 1/s;

$P =$ NS, respectively). In both the above studies, only the middle septum was evaluated, while in the present study, the septum was divided into basal, middle, and apical segments, and each segment was separately evaluated.

Park et al[21] conducted another study on patients with pulmonary arterial hypertension (PAH). In their study, longitudinal strain and strain rate, as well as time to peak strain of the right septum and the right ventricular free wall, were obtained in basal, middle, and apical segments using the VVI method. One of the limitations of the above study was the lack of control group. In their study, on average, the longitudinal strain in all basal, middle, and apical segments of RS of the septum was about 24% lower (−14.5% in Park's study vs. −19.0% in the present study), and time to peak strain was about 9% higher (382 ms vs. 348 ms) than the average results of the present study.

A study conducted by Hardegree et al[20] on PAH patients was one of the few studies where the longitudinal strain was analyzed and reported in 3 segments of the RS and also LS of IVS using VVI method. Total longitudinal strain of RS was about 37% (−12% in Hardegree study vs. −19.0% in the present study) and the total longitudinal strain of LS was 18% less than the results of the present study (−14% vs. −17.6%). The results of these comparisons can be attributed to better systolic function in healthy subjects of the present study.

Despite the results of the present work and previous studies, the separation and function of both sides of the septum are still not entirely clear. There are several important hypotheses, which might explain the dual functions of IVS that are as follows:

(1). The heart consists of a single muscle rope that is twisted on itself with 2 turns in a helical model.[25] Interventricular septum separates 2 ventricles of the heart. Torrent−Guasp showed that IVS was composed of 2 layers of descending and ascending muscle fibers converged toward the apex and made up of a single myocardial band. Anderson et al[26] rejected this concept because of disruption of ventricular mass in at least 5 areas and the existence of 3-dimensional mesh between myocytes. Furthermore, others showed IVS had 3 layers: recurrent, ascending, and descending segments.[1] In addition, the geometric model of IVS muscle fibers also includes 2 longitudinal subendocardial and subepicardial muscles along with their different fiber directions.[27,28] The presence of the hyperechoic region of IVS in B-mode and M-mode echocardiography images[6,7] may be due to abrupt changes in muscular fibers' direction.

2. Large septal arteries originating from anterior and posterior interventricular arteries give off secondary branches to supply the RS and LS of the septum. As a result, the septum can be divided into RS and LS, by the boundary existing between these secondary branches.[3] The presence of these arteries between the RS and LS of the septum can cause echogenic signals in the echocardiography images. Furthermore, the differentiation of the right—from left—side of IVS in diastole is better than systole in the resulting

Table 4. Comparison of Longitudinal Strain, Strain Rate, and Time to Peak

IVS	Segments	Strain (Mean Rank)	Strain Rate (Mean Rank)	Time to Peak Strain (Mean Rank)
Left IVS	Basal	1.9	2.1	2.3
	Middle	2.0	1.9	1.7
	Apical	2.1	1.9	1.9
	P	.582	.534	.019
Right IVS	Basal	2.2	2.3	2.1
	Middle	2.4	2.3	2.0
	Apical	1.4	1.4	1.9
	P	<.001	<.001	.572

IVS, interventricular septum.

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images; it is due to the presence of blood flow in the coronary arteries during cardiac diastole.[6] Abrupt changes in muscular fibers directions in the septum are supplied by different branches of coronary arteries; they show that the septum is functionally and morphologically bilayer structure; thus reduced blood flow to one side relative to the other, there would be the possibility of observing different septal function.

In this study, we investigated the septal contraction in healthy subjects as basic research, which can be important in the diagnosis and also in treatment fields. Establishing the normal patterns of IVS properties will be a prerequisite to discern the evolution of myopathic heart disease. Several studies have shown that right ventricle (RV) and LV do not act independently, and the role of IVS in this interaction is still not fully determined. There is considerable interest in determining how alterations in IVS properties might affect LV and RV performance. The studies of Damiano et al[29] and Sanz-de la Garza et al[30] indicated that the IVS compartment of LV was important for RV-developed pressure, volume outflow, and RV global strain. Other studies showed that the RS and LS of the IVS responded differently to various hemodynamic, loading, and pathological conditions; for example, LV hypertrophy primarily affected the LS of the IVS.[6] The RV component of the IVS may have important functional information on RV diseases, such as RV ischemia, infarction, arrhythmogenic dysplasia, pulmonary valve disease, and ventricular septal defect.[6,31]

Limitations of Study

The actual anatomic border dividing the septum into RS and LS, as well as arterial septal supply, was not specified in this clinical study. In addition, the present study only evaluated the longitudinal strain and strain rate of IVS; radial, circumferential, and shear strains were not examined. The quality of imaging is very important while using the VVI technique; considering the apical segment has a lower quality in the studied view (because of technical limitations such as reverberations and near-field artifacts), part of the results might have been impacted. By comparison with TDI, the ability to track anatomic details was affected by the relatively low temporal resolution.[32] Due to ethical issues, participants did not undergo invasive or semi-invasive tests such as coronary angiography to diagnose or evaluate coronary artery disease.

CONCLUSIONS

The present study showed that the left and right septal function is similar in the basal and middle segments of healthy subjects; however, its function was significantly different in the apical segment. The longitudinal strain and strain rate in RS were higher than LS. There was no difference between right and left basal and apical segments in terms of time to peak strain, but the time to peak strain of the right middle segment was significantly higher than the left side. Further studies are needed to achieve a better understanding of myocardial function and its blood supply in normal and pathological states.

REFERENCES

1. Hristov N, Liakopoulos OJ, Buckberg GD, Trummer G. Septal structure and function relationships parallel the left ventricular free wall ascending and descending segments of the helical heart. *Eur J Cardiothorac Surg*. 2006;29(suppl 1):S115-S125. [CrossRef]
2. Corno AF, Kocica MJ, Chappory LA, Moore SA, Sutherland H, Alphonso N. Inter-ventricular septum: new observations on the structure and function coupling. *Basic Appl Myol*. 2009;19(1):41-48.
3. Farrer-Brown G, Rowles PM. Vascular supply of interventricular septum of human heart. *Br Heart J*. 1969;31(6):727-734. [CrossRef]
4. Kaul S. The interventricular septum in health and disease. *Am Heart J*. 1986;112(3):568-581. [CrossRef]
5. Fernandez-Teran MA, Hurle JM. Myocardial fiber architecture of the human heart ventricles. *Anat Rec*. 1982;204(2):137-147. [CrossRef]
6. Boettler P, Claus P, Herbots L, et al. New aspects of the ventricular septum and its function: an echocardiographic study. *Heart*. 2005;91(10):1343-1348. [CrossRef]
7. Park SM, Hong SJ, Lim DS, Shim WJ. Differentiation of the left from right side ventricular septum in acute anterior myocardial infarction by tissue Doppler imaging. *Echocardiography*. 2011;28(1):38-43. [CrossRef]
8. Dandel M, Lehmkuhl H, Knosalla C, Suramelashvili N, Hetzer R. Strain and strain rate imaging by echocardiography-basic concepts and clinical applicability. *Curr Cardiol Rev*. 2009;5(2):133-148. [CrossRef]
9. Maréchaux S. Speckle-tracking strain echocardiography: any place in routine daily practice in 2014? *Arch Cardiovasc Dis*. 2013;106(12):629-634. [CrossRef]
10. Ancona R, Comenale Pinto S, Caso P, et al. Left atrium by echocardiography in clinical practice: from conventional methods to new echocardiographic techniques. *ScientificWorldJournal*. 2014;2014:451042. [CrossRef]
11. Peng QH, Zhou QC, Zeng S, et al. Evaluation of regional left ventricular longitudinal function in 151 normal fetuses using velocity vector imaging. *Prenat Diagn*. 2009;29(12):1149-1155. [CrossRef]

12. Kim KH, Park JC, Yoon HJ, et al. Usefulness of aortic strain analysis by velocity vector imaging as a new echocardiographic measure of arterial stiffness. *J Am Soc Echocardiogr*. 2009;22(12):1382-1388. [CrossRef]

13. Younoszai AK, Saudek DE, Emery SP, Thomas JD. Evaluation of myocardial mechanics in the fetus by velocity vector imaging. *J Am Soc Echocardiogr*. 2008;21(5):470-474. [CrossRef]

14. Pu DR, Zhou QC, Zhang M, Peng QH, Zeng S, Xu GQ. Assessment of regional right ventricular longitudinal functions in fetus using velocity vector imaging technology. *Prenat Diagn*. 2010;30(11):1057-1063. [CrossRef]

15. Saleh S, Liakopoulos OJ, Buckberg GD. The septal motor of biventricular function. *Eur J Cardiothorac Surg*. 2006;29(1):S126-S138. [CrossRef]

16. Verhaert D, Mullens W, Borowski AG, et al. Right ventricular response to intensive medical therapy in advanced decompensated heart failure. *Circ Heart Fail*. 2010;3(3):340-346. [CrossRef]

17. Kowalski M, Kukulski T, Jamal F, et al. Can natural strain and strain rate quantify regional myocardial deformation? A study in healthy subjects. *Ultrasound Med Biol*. 2001;27(8):1087-1097. [CrossRef]

18. Kim DH, Kim HK, Kim MK, et al. Velocity vector imaging in the measurement of left ventricular twist mechanics: head-to-head one way comparison between speckle tracking echocardiography and velocity vector imaging. *J Am Soc Echocardiogr*. 2009;22(12):1344-1352. [CrossRef]

19. Liu X, Li Z. Assessment of cardiac twist in dilated cardiomyopathy using velocity vector imaging. *Echocardiography*. 2010;27(4):400-405. [CrossRef]

20. Hardegree EL, Sachdev A, Fenstad ER, et al. Impaired left ventricular mechanics in pulmonary arterial hypertension: identification of a cohort at high risk. *Circ Heart Fail*. 2013;6(4):748-755. [CrossRef]

21. Park JH, Park MM, Farha S, et al. Impaired global right ventricular longitudinal strain predicts long-term adverse outcomes in patients with pulmonary arterial hypertension. *J Cardiovasc Ultrasound*. 2015;23(2):91-99. [CrossRef]

22. Pirat B, Khoury DS, Hartley CJ, et al. A novel feature-tracking echocardiographic method for the quantitation of regional myocardial function: validation in an animal model of ischemia-reperfusion. *J Am Coll Cardiol*. 2008;51(6):651-659. [CrossRef]

23. Rohr S. Role of gap junctions in the propagation of the cardiac action potential. *Cardiovasc Res*. 2004;62(2):309-322. [CrossRef]

24. Holland MR, Gibson AA, Bauer AQ, et al. Echocardiographic tissue characterization demonstrates differences in the left and right sides of the ventricular septum. *Ultrasound Med Biol*. 2010;36(10):1653-1661. [CrossRef]

25. Torrent-Guasp F, Buckberg GD, Clemente C, Cox JL, Coghlan HC, Gharib M, eds. The structure and function of the helical heart and its buttress wrapping. I. The normal macroscopic structure of the heart. *Semin Thorac Cardiovasc Surg*. 2001;13(4):301-319. [CrossRef]

26. Anderson RH, Sanchez-Quintana D, Redmann K, Lunkenheimer PP, eds. How are the myocytes aggregated so as to make up the ventricular mass? *Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu*. 2007;10(1):76-86. [CrossRef]

27. Streeter DD, Spotnitz HM, Patel DP, Ross J, Sonnenblick EH. Fiber orientation in the canine left ventricle during diastole and systole. *Circ Res*. 1969;24(3):339-347. [CrossRef]

28. McLean M, Ross MA, Prothero J. Three-dimensional reconstruction of the myofiber pattern in the fetal and neonatal mouse heart. *Anat Rec*. 1989;224(3):392-406. [CrossRef]

29. Damiano Jr RJ, La Follette Jr P, Cox JL, Lowe JE, Santamore WP. Significant left ventricular contribution to right ventricular systolic function. *Am J Physiol*. 1991;261(5 Pt 2):H1514-H1524. [CrossRef]

30. Sanz-de la Garza M, Giraldeau G, Marin J, et al. Should the septum be included in the assessment of right ventricular longitudinal strain? An ultrasound two-dimensional speckle-tracking stress study. *Int J Cardiovasc Imaging*. 2019;35(10):1853-1860. [CrossRef]

31. Jamal F, Bergerot C, Argaud L, Loufouat J, Ovize M. Longitudinal strain quantitates regional right ventricular contractile function. *Am J Physiol Heart Circ Physiol*. 2003;285(6):H2842-H2847. [CrossRef]

32. Badran HM, Faheem N, Soliman M, Hamdy M, Yacoub M. Comparison of vector velocity imaging and three-dimensional speckle tracking echocardiography for assessment of left ventricular longitudinal strain in hypertrophic cardiomyopathy. *Glob Cardiol Sci Pract*. 2019;2019(1):6. [CrossRef]