Intramyocardial Analysis of Regional Systolic and Diastolic Function in Ischemic Heart Disease with Doppler Tissue Imaging: Role of the Different Myocardial Layers

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Background: **Preliminary experimental data have shown a nonuniform distribution of myocardial velocities (MVs) across the myocardial wall in normal conditions. However, after ischemic damage to the myocardium, a different pattern of reduction in the myocardial layers has been reported. The aim of this study is to analyze the spatial distribution of MVs and the resultant myocardial velocity gradients (MVGs) during the systolic and diastolic time periods. Doppler tissue imaging (DTI) in color M-mode was used to evaluate 3 different myocardial layers (endocardium, mesocardium, and epicardium) and their changes as a result of ischemia.**

Methods: **Thirty-two consecutive patients were studied with DTI color M-mode: 18 patients with a history of previous or ongoing myocardial infarction and 14 healthy subjects. Postprocessing of images was accomplished with proprietary software. MV and MVG values of all layers along both systolic and diastolic time were calculated. For temporal analysis, systole was subdivided in 3 equal periods. Early- and late-diastolic times were also identified.**

Results: **In ischemic patients, the mean MV and maximum MV throughout systole decreased significantly in the endocardium and mesocardium, whereas only slightly in the epicardium. The mean MVG was less in ischemic patients (0.66 ± 0.11 vs 0.23 ± 0.15, $P < .03$). Temporal analysis showed a decrease in the maximal MV and MVG in all layers over the 3 systolic periods. This decrease was the more consistent in mesocardium. In diastole, there was a decrease in maximal MV in all layers, being more pronounced in endocardium and mesocardium. Diastolic mean MVG was shown to be different between control and ischemic groups (–0.2 ± 0.05 vs –0.10 ± 0.04, $P < .06$). A significant decrease of the maximal MV in endocardium and mesocardium was reported in the temporal analysis during early diastole. No change was reported in the epicardium. The MVG value also showed a significant decrease (–2.69 ± 0.29 vs –1.59 ± 0.89, $P < .02$). In ischemic patients in late diastole, the maximum MV was increased in all layers of the myocardium, and this increase was observed mainly in the endocardium. An increase in the MVG (–0.78 ± 0.18 vs –1.47 ± 0.85, P = NS) was also reported during late diastole.**

Conclusion: **There is a nonuniform distribution of velocities in the different myocardial layers under normal conditions. This distribution of velocities undergoes a significant change in patients with ischemic myocardial damage. Intramyocardial wall motion analysis could have clinical applications in both the early detection of ischemia and myocardial viability.** (J Am Soc Echocardiogr 2002;15:99-108.)

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Doppler tissue imaging (DTI) is an echocardiographic tool developed in recent years to allow the analysis of regional function of the myocardium through the quantification of wall motion velocities.[1] Doppler tissue imaging has been widely employed in both clinical and experimental settings to assess myocardial function in several physiologic and pathologic conditions, that is, healthy subjects, patients with aging hearts, hypertensive cardiomy-

opathy, dilated cardiomyopathy, hypertrophic cardiomyopathy, and ischemic heart disease (IHD).[2-6] Investigation of IHD is of major importance given the high incidence and clinical impact on patient care. Doppler tissue imaging in IHD has been performed in several ways, using different methodologies and instrumentation. Pulsed wave Doppler and 2-dimensional color DTI have demonstrated differences in regional myocardial performance in several clinical and experimental conditions produced by ischemia.[7-14] Doppler tissue imaging color M-mode has been used because of its superior spatial and temporal resolution resulting from higher sampling rates and a lower signal-to-noise ratio. These particular properties of DTI color M-mode allow a more precise measurement of regional myocardial velocities.[15] Gallagher et al[16] demonstrated that the regional damage to the myocardium by ischemia is heterogeneous in both spatial and temporal dimensions. Damage to the myocardium was shown to vary throughout the distinct myocardial layers, from the endocardium to the epicardium during systole and diastole.[16]

A preliminary experimental study has shown the potential use of DTI color M-mode to analyze this intramyocardial spatial nonuniformity.[17] In addition, it provides experimental evidence as to the temporal evolution of the different myocardial layers during the diastole.[17] To our knowledge, this nonuniform behavior of the myocardial layers has not been evaluated in a clinical setting. The aim of our study is to evaluate, by using DTI color M-mode, regional spatial and temporal behavior of 3 different myocardial layers (endocardium, mesocardium, and epicardium) during both systole and diastole in patients with IHD.

MATERIAL AND METHODS

Patients referred to our laboratory with known IHD, defined by the presence of previous or ongoing myocardial infarction, were evaluated for their inclusion in this study. The classification of ongoing myocardial infarction was those patients hospitalized because of an acute myocardial infarction. The study was performed at least 48 hours after the onset of the acute event, and all had received reperfusion therapy. Only patients with Q-wave myocardial infarctions were considered.

All echocardiography examinations were carried out with an Acuson Sequoia System (Acuson Corp, Mountain View, Calif) using a 3.5-M Hz phased-array transducer with Doppler tissue imaging capabilities. A complete transthoracic echocardiogram was performed. Regional contractility of all myocardial segments was assessed as normal or dys-synergic. Special attention was focused on the assessment of the contractility in the posterior segment in parasternal long-axis view. A well-trained cardiologist carried out all the studies. Cardiac cycles of all echocardiographic views were digitally stored. A second expert cardiologist then performed a blind study to assess the wall motion in all the segments. When discrepancies were detected between observers, a third expert cardiologist in stress echocardiography examined the stored images to determine the presence or absence of abnormal wall motion. DTI color M-mode, in the parasternal long-axis view, was then carried out in patients with dyssynergy in the posterior myocardial segment. Only segments with an end-diastolic wall thickness 6 mm or greater were evaluated. Hence, they were neither akinetic nor thin segments, such as scarring tissue. Control patients had no known cardiomyopathic conditions.

DTI Color M-Mode Analysis

The parasternal long-axis view was imaged and correctly aligned to ensure a perpendicular incidence of the scan line in basal posterior segment. Gain was adjusted to obtain the best B-mode imaging. The focus was placed at the myocardial wall level and DTI was activated. The mixer was turned off. The DTI color scale velocity map was adjusted to a velocity of 0.23 cm/s to minimize aliasing. A cursor corresponding to the scan line of M-mode was visualized and positioned so that little or no subvalvular structures were present in the image. The angle of incidence between the cursor and the myocardial wall was maintained at 90 degrees (Figure 1, *A*), the region of interest was magnified, and M-mode was activated. The Doppler gain and time gone compensation were optimized to minimize noise and black spots. (Black spots are small image defects, which do not correspond to low velocities.) In preliminary experimental studies, we identified black spots as a source of error in the calculation of controlled phantom velocity.[18,19] This artifact was also identified in our population. This effect degrades noticeably the quality of quantitative data and curves drawn from these images. As previously described, a selective median filtering algorithm, which fills in black spots without altering the remaining valid pixels was used in this study.[18,19] Doppler mode was disabled during the imaging to allow correct visualization of the posterior basal segment and placement of the M-mode scan line to be continuously assessed in B-mode. During a breath hold, a good quality image consisting of 2 or more consecutive beats was acquired. Simultaneous digital records of color M-mode DTI and gray-scale M-mode were stored on a magneto-optical disk. The records were transferred to a workstation for post-processing of the images. This was accomplished with proprietary software developed to automatically analyze DTI color M-mode. This methodology has been previously validated and widely described.[18,19]

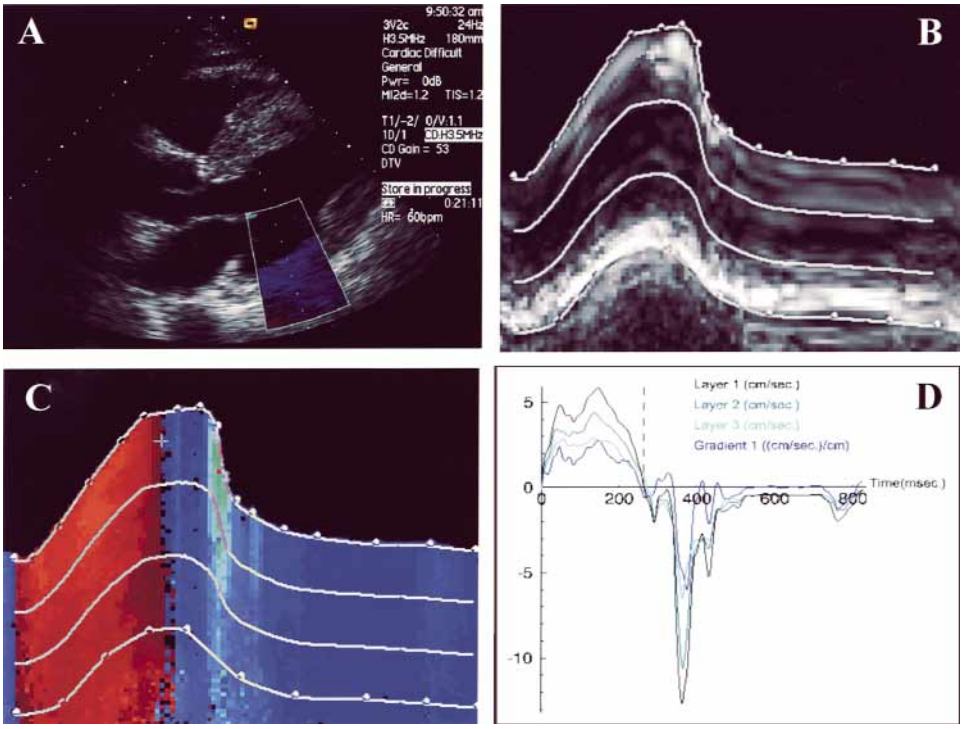

Figure 1 Intramyocardial analysis using Doppler tissue imaging color M-mode. **A**, Parasternal long-axis view showing region of interest traced over posterior segment. **B,** Color M-mode registry obtained is processed with proprietary software. Both endocardial and epicardial boundaries are semiautomatically traced using drawing tool on averaged gray-scale image. Three equal layers are automatically calculated and displayed. **C,** Segmentation performed on gray-scale image is exported to red, green, and blue image and has been previously filtered and averaged to eliminate and minimize influence of "black spots." **D,** Graphic registry obtained after automatic calculation of MV in 3 layers and MVG of region of interest. *Dotted line* marks point where red color turns to blue (end systole). Note positive values in systole and negative values in diastole. Early and late nadir of MV represent early relaxation (*e*) and atrial emptying (*a*).

Postprocessing of the images was carried out as follows: Color Doppler images consisted of a color overlay over the gray-scale image. The velocity information coded in the red, green, and blue components was provided externally through a color table. The image was enhanced using the selective median filtering algorithm. The first step was to calculate a median filtered version of the original image (adjustable kernel size, usually 5×5). The new image was then constructed with the filtered values replacing the original ones for those points whose value in the initial image is significantly lower than their homologous equivalent in the filtered one, thus filtering only the areas affected by the black spot artifact. The record obtained (2 or more cycles) was averaged using the R wave of the electrocardiogram and the signal stored simultaneously to the tissue Doppler map. Averaging improved the signal-to-noise ratio of the single cycle obtained. The time-averaging algorithm takes into account only points with velocity information above a defined threshold to avoid the effects of possible black spots. Intramyocardial analysis was carried out with the segmentation of myocardial wall in the single averaged image. Over gray-scale M-mode imaging, and with an assisted drawing tool, spline curves were adjusted to endocardial and epicardial boundaries (Figure 1, *B*). The wall is automatically divided in a number of predefined layers, all of equal thickness (the endocardium, mesocardium, and epicardium). The segmentation was performed in gray-scale imaging because it provided more information on endocardial and epicardial boundaries. Finally, the segmentation was exported to the color M-mode tissue Doppler image (Figure 1, *C*). The mean myocardial velocity (MV) across the myocardium in the different layers and along the cardiac cycle was calculated and graphically represented (Figure 1, *D*). The myocardial velocity gradient (MVG) was calculated as the unitary spatial rate of change of velocity across the myocardium.[20] A mark was placed at the end of the systole in the color M-mode image to show the exact location in time of this event in the graphic representation. Global analysis of the MV and MVG in systole and diastole was performed. For temporal behavioral analysis of the different systolic layers, the values of MV and MVG in protosystole, mesosystole,

Table 1 Global intramyocardial analysis of systolic time

	Control	Ischemic	*P*
Mean velocity			
Endocardium	3.18 ± 0.15	2.45 ± 0.37	.01
Mesocardium	3.10 ± 0.18	2.35 ± 0.33	.02
Epicardium	2.19 ± 0.12	2.05 ± 0.25	NS
Maximal velocity			
Endocardium	5.37 ± 0.26	4.33 ± 0.63	.03
Mesocardium	4.84 ± 0.30	3.95 ± 0.52	.08
Epicardium	3.59 ± 0.21	3.71 ± 0.44	NS
Mean MVG	0.66 ± 0.11	0.23 ± 0.15	.03
Maximal MVG	1.63 ± 0.17	1.37 ± 0.23	.28

MVG, Myocardial velocity gradient; *NS,* nonsignificant.

Table 2 Global intramyocardial analysis of diastolic time

	Control	Ischemic	*P*
Mean velocity			
Endocardium	–1.79 ± 0.13	–1.59 ± 0.13	NS
Mesocardium	–1.82 ± 0.16	–1.57 ± 0.13	NS
Epicardium	–1.42 ± 0.13	–1.39 ± 0.13	NS
Maximal velocity			
Endocardium	–10.07 ± 0.79	–7.04 ± 0.83	<.01
Mesocardium	–9.65 ± 0.66	–6.40 ± 0.78	<.01
Epicardium	–6.11 ± 0.5	–5.08 ± 0.56	.05
Mean MVG	–0.23 ± 0.05	–0.10 ± 0.04	.06
Mean MVG	–2.85 ± 0.37	–2.13 ± 0.58	.14

MVG, Myocardial velocity gradient; *NS,* nonsignificant.

and telesystole were also calculated by subdividing systole into 3 equal-length periods. In diastole, the MV and MVG were calculated in both early and late diastole.

Intraobserver and Interobserver Variability

Postprocessing of images, data management, and subsequent calculations were carried out by a DTI-trained cardiologist. To assess the intraobserver variability, a secondary analysis of a random sample of both healthy and ischemic patients was carried out 3 months after the first one. The interobserver variability was assessed by a second cardiologist (blinded to the previous results) carrying out an analysis of random samples of both healthy and ischemic patients.

Statistical Analysis

Continuous variables are expressed as mean ± SEM. For comparisons of the MV and MVG between groups, a nonparametric Mann-Whitney *U* test was performed. Interobserver and intraobserver variability were assessed using Pearson bivariant correlation. Statistical significance was established in a P value < .05.

RESULTS

Of 32 evaluated patients (18 patients with well-documented previous or ongoing myocardial infarction and 14 healthy subjects without known cardiomyopathy), 6 patients with IHD were excluded because of the absence of wall-motion abnormalities in the posterior basal segment. Thus, 12 patients with dyssynergia (aged 66.2 ± 3.2 years; range 42-78, 83% men) in the posterior basal segment formed the ischemic group and 14 healthy patients (aged 23.2 ± 2.3 years old; range 16-45, 79% men) formed the control group. All the ischemic patients had a Q-wave, transmural myocardial infarction. The posterobasal wall thickness was 6 mm or greater.

Global Systolic and Diastolic Analysis

The mean and maximal MV and MVG in all the layers in systole, both in healthy subjects and ischemic patients, are shown in Table 1. In healthy subjects, the MV was greater in endocardium and mesocardium than epicardium. This nonuniform distribution translated into and was reflected in the positive value of the MVG readings obtained. In ischemic patients, the mean MV, a marker of total motion along the systole, decreased in endocardium, mesocardium, and only slightly in epicardium. In the endocardial and mesocardial layers (but not in the epicardium), the maximal MV, an expression of peak systolic motion, was decreased in ischemic patients compared with the control group. The mean MVG was significantly decreased in ischemic patients (0.66 ± 0.11 vs 0.23 ± 0.15, $P < .03$), whereas the maximal MVG showed no significant change. Intramyocardial analysis in healthy subjects showed similar behavior in both the diastole and systole. A reduction in the maximal MV but not the mean MV was observed in ischemic patients. Although the maximal MV decreased in all layers, the difference was more pronounced in endocardium and mesocardium compared with the epicardium (Table 2). The diastolic mean MVG was different between control and ischemic groups but just failed to be statistically significant (–0.23 ± 0.05 vs –0.10 ± 0.04, $P < .06$).

Temporal Analysis of Systole

Table 3 shows the maximal MV and MVG in all layers throughout the 3 systolic periods. Healthy subjects showed the highest values of MV in endocardium and mesocardium throughout the entire systolic period, and the results showed that the maximal value was reached during mesosystole. The epicardium was the layer with the lowest MV but had the most regular distribution throughout the systolic

Table 3 Temporal intramyocardial analysis of systolic time

	Control	Ischemic	*P*
Maximal velocity			
Protosystole			
Endocardium	3.91 ± 0.32	3.24 ± 0.39	.08
Mesocardium	3.88 ± 0.33	3.21 ± 0.37	.02
Epicardium	2.87 ± 0.25	2.67 ± 0.36	NS
Mesosystole			
Endocardium	4.48 ± 0.30	3.33 ± 0.37	.02
Mesocardium	4.40 ± 0.31	3.35 ± 0.36	.02
Epicardium	3.03 ± 0.24	2.54 ± 0.32	NS
Telesystole			
Endocardium	3.06 ± 0.22	2.59 ± 0.31	.08
Mesocardium	3.14 ± 0.22	2.40 ± 0.29	.01
Epicardium	2.05 ± 0.16	1.95 ± 0.22	NS
Velocity gradient			
Protosystole	0.80 ± 0.23	0.45 ± 0.15	NS
Mesosystole	0.97 ± 0.24	0.60 ± 0.16	.15
Telesystole	0.50 ± 0.22	0.43 ± 0.13	NS

NS, Nonsignificant.

period. In contrast, in ischemic patients, maximal MV consistently decreased in mesocardium in the 3 periods (Figure 2, *A*, *B*, and *C*) compared with the endocardium. The most significant decrease in endocardium was seen during mesosystole. The change in the MVG was minor in the ischemic group in all systolic periods, and this decrease was slightly superior in mesosystole (0.97 ± 0.24 vs 0.60 ± 0.16, $P < .15$).

Temporal Analysis of Diastole

The intramyocardial analysis of diastole had different results, depending on the evaluated period (Table 4) and population. Thus, in early diastole corresponding to rapid ventricular filling, healthy subjects had higher values of both the MV and MVG. The nonuniformity described in the global analysis (Table 1) was also observed in this period. However, in ischemic patients there was a significant decrease of maximal MV both in endocardium and mesocardium (mainly in the latter) (Figure 3). There was no difference in the MV in the epicardium. The changes in the MVG reflected those observed for the maximal velocity, that is, significantly reduced in ischemic patients (–2.69 ± 0.29 vs –1.59 ± 0.89, $P < .02$). In healthy subjects during late diastole, a regular distribution of MV values among all the layers was observed. These values were less than those reported during early diastole. In ischemic patients the maximal MV and MVG demonstrated an opposite pattern to that of early diastole (Figure 4). That means maximal MV increased in all layers, especially in the endocardium. MVG, in addition, increased in ischemic patients in this period (–0.78 ± 0.18 vs –1.47 ± 0.85, $P < .8$).

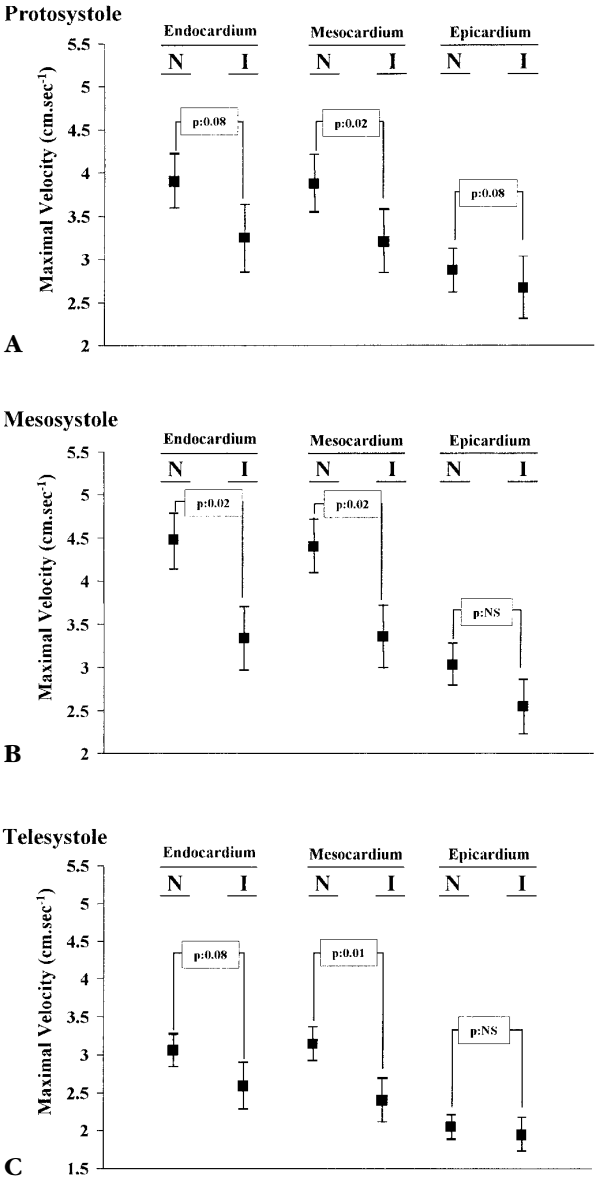

Figure 2 Temporal intramyocardial analysis of maximal myocardial velocities in healthy subjects and ischemic patients during systolic time. *N,* Normal healthy patients; *I,* ischemic patients.

These differences in late diastole did not reach statistical significance.

Intraobserver and Interobserver Variability

There was a good correlation between the measures obtained by the 2 different blind observers: systolic MV, r: 0.81 ($P < .001$), early diastolic MV, r: 0.89 ($P < .001$), and late diastolic MV, r: 0.94 ($P < .001$). The 2 measurements obtained by the same observer showed a good correlation in both systolic and dias-

Table 4 Temporal intramyocardial analysis of diastolic time

	Early diastole (e)			Late diastole (a)		
	Control	Ischemic	*P*	Control	Ischemic	*P*
Maximal velocity						
Endocardium	–9.85 ± 0.70	–6.78 ± 1.22	<.01	–2.50 ± 0.35	–4.18 ± 0.82	.08
Mesocardium	–9.92 ± 0.72	–6.29 ± 1.14	<.01	–2.58 ± 0.42	–3.86 ± 0.73	.17
Epicardium	–5.93 ± 0.47	–5.05 ± 0.76	NS	–1.80 ± 0.34	–2.97 ± 0.67	.08
Velocity gradient	–2.69 ± 0.29	–1.59 ± 0.89	.02	–0.78 ± 0.18	–1.47 ± 0.85	NS

NS, Nonsignificant.

tolic measures: systolic MV, *r*: 0.70 ($P < .001$), early diastolic MV, *r*: 0.91 ($P < .001$), and late diastolic MV, *r*: 0.95 ($P < .001$).

DISCUSSION

Previous studies have demonstrated that the regional damage to the myocardium by ischemia is heterogeneous in both spatial and temporal dimensions.[16] In preliminary cases carried out in our laboratory, we showed DTI color M-mode as a potential tool in the analysis of intramyocardial spatial nonuniformity. The results of this study confirm the possible use of DTI color M-mode as the gold standard method for the study of the different myocardial layers. Results in healthy subjects showed a heterogeneous distribution of intramyocardial velocities in both the spatial and temporal dimensions. This was observed throughout the entire intramyocardial analysis of regional systolic and diastolic function. In ischemic patients, significant changes in the maximum and mean MV values were reported.

Intramyocardial Systolic Function in Healthy Subjects

The distribution of MV across the myocardium showed a clear nonuniform response in healthy subjects. Similar to experimental studies, this was greater in the endocardium than the epicardium.[17] The nonuniform response was seen throughout the entire systolic and diastolic time periods. The asymmetrical distribution of velocities is easily demonstrated by the assessment of the velocity gradient. This takes into account only the velocity generated by the myocardium and excludes any influence of translational and rotational heart movement.

Anatomic studies of the human heart have shown different arrangements of the muscle fibers in the myocardial wall. The fibers in the mid wall are circumferential, with their best development toward the base and upper part of the septum. Subendocardial fibers, however, are longitudinally directed.[21] Previous works show that these differences in fiber architecture have physiological implications. Models of left ventricular (LV) wall mechanics have shown that the distribution of fiber strain during ejection is sensitive to the orientation of muscle fibers in the wall.[22] These results suggest that the mesocardium may have an important role in normal wall motion. It is likely that the array of mesocardial fibers would explain its important contribution to regional systolic myocardial function. In addition, the subdivision of the systole allowed for greater interrogation of the temporal distribution of MV. Mesosystole was found to be the period in which MV values were highest.

Early-diastolic relaxation is known to be an active phenomenon, with a high consumption of energy. The nonuniform distribution of velocities in this period (as seen in systole) would reflect a more active role for the endocardial and mesocardial layers in this phase. However, in late-diastolic relaxation, secondary to atrial emptying and of lower energy expenditure, a more regular distribution among the 3 layers was shown, suggesting a passive role of the myocardial fibers.

Intramyocardial Systolic and Diastolic Function in Ischemic Patients

In ischemic patients, the global analysis of systole showed an important decrease of MV in endocardial and mesocardial layers, with no modification in epicardial layer. Myocardial velocity gradient, when used as an indicator of global regional performance, was decreased. This was reflected to a greater extent in the reduction of the mean MVG. When temporal analysis of systole was performed, a nonuniform behavior of the different layers in ischemic patients was noted. The greatest decrease in MV values of the endocardial and mesocardial layers, in the 3 systolic times evaluated, was shown just before the maximal wall excursion.

Experimental studies have demonstrated a nonuniform response of the myocardial layers in relation

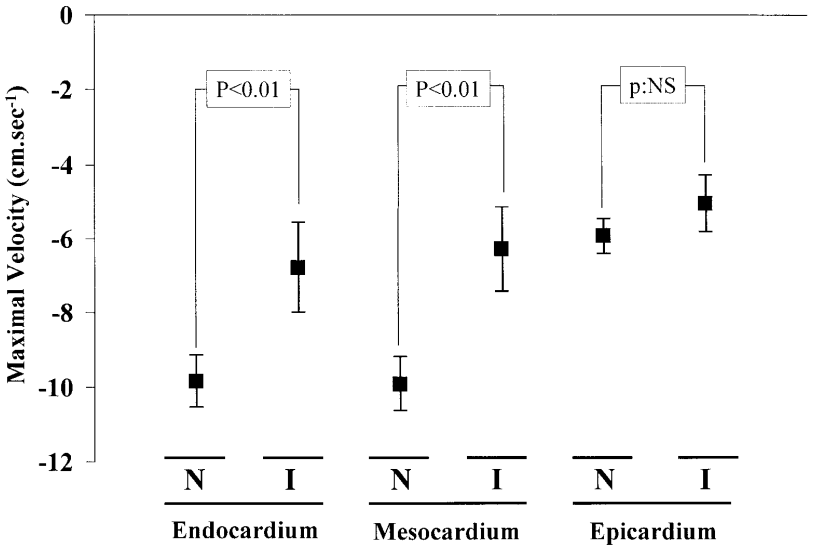

Figure 3 Temporal intramyocardial analysis of maximal myocardial velocities in healthy subjects and ischemic patients during diastolic time. Results of early-diastolic time analysis. *N,* Normal healthy patients*; I,* ischemic patients.

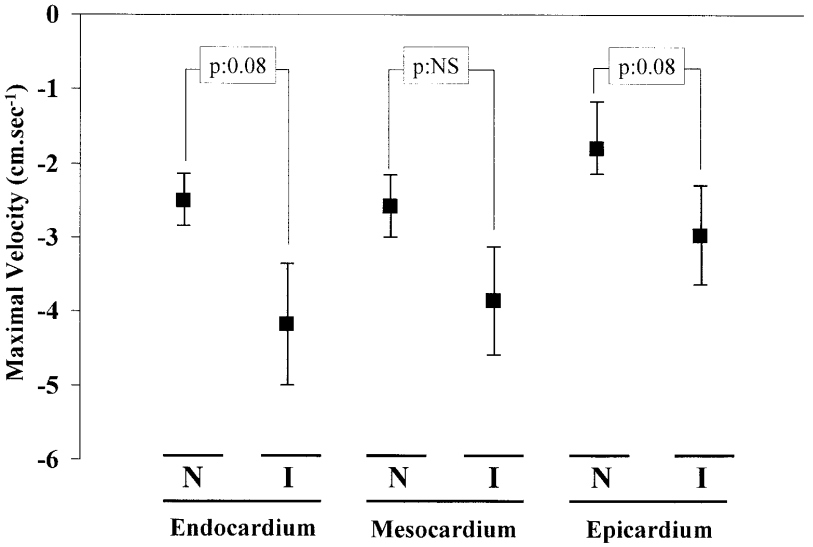

Figure 4 Temporal intramyocardial analysis of maximal myocardial velocities in healthy subjects and ischemic patients during diastolic time. Results of late diastolic time analysis. *N,* Normal healthy patients*; I,* ischemic patients.

to the behavior of myocardial flow and their shortening after ischemic damage. The endocardium segmental shortening assessed with ultrasonic crystals is strongly related to myocardial blood flow. The epicardial motion, however, is related to that of the endocardium and not the condition of coronary flow.[23] Ischemia is found to produce a nonuniform response among layers, which is reflected in the varying degrees of shortening in the different layers. Nontransmural ischemia generates a more significant decrease in myocardial blood flow as well as a global reduction in systolic wall thickening, ranging from 35% to 80%. The epicardial shortening, however, demonstrated no decrease, or a lesser degree in reduction of thickening (21%–37%), and only when a marked dysfunction is observed.[24] Necroscopic studies of patients with IHD have observed predominant damage to subendocardial fibers.[25] Simulta-

neous echocardiographic assessment of myocardial shortening, in both longitudinal and short axis in healthy patients, has also shown that this spatial nonuniformity contributes to the global thickening of the endocardial and epicardial layer. This is shown in important temporal differences in their behavior throughout both systole and diastole. After ischemic damage to the myocardium, there is a predominant decrease in shortening in the longitudinal axis, suggesting greater damage of fibers oriented in this direction. This shortening in the longitudinal axis gives rise to a change in the normal relation among layers, hence, having an impact on the normal shape of the left ventricle, resulting in a more spherical shape before ejection.[25]

The determination of MV with color M-mode DTI and its variation under pathologic conditions correlates well with the changes observed in wall thickness.[26] Compared with other DTI methods, color M-mode offers greater spatial and temporal resolution as well as a better signal-to-noise ratio. In patients with and without impaired regional LV function, the MV assessed by 2-dimensional DTI was lower than that obtained with M-mode DTI. This fact correlates positively with the presence of black zone and reflects poor signal-to-noise ratio with 2-dimensional color DTI.[15] Color M-mode has been applied in a clinical setting to assess if it represents a reliable indicator of regional LV systolic function after ischemic damage to the myocardium. Thus, in patients with asynergia caused by myocardial infarction, color M-mode DTI consistently detects the modification in the values of MVG through the analysis of MV, both in anterior septum and basal posterior segment.[8] The potential applications of color M-mode DTI in the intramyocardial analysis have been recently studied in an experimental setting. In this work, systolic MV values of the endocardial layer were higher in the epicardial MV, establishing an inner/outer MVG. When ischemia was produced, systolic MV decreased in both layers with disappearance of the gradient. This decrease of systolic MV correlated with the parallel reduction of segment shortening, assessed with sonomicrometry, and myocardial blood flow with radioactive microspheres. After reflow, systolic MV improves in a nonuniform way, more in the endocardium than the epicardium.[17]

The mesocardium is an important layer, especially in basal and middle segments.[21] Its fibers have a circumferential arrangement with a greater contribution to shortening resulting in ejection, opposite to the predominant role of longitudinal fibers of the endocardium in the modification of LV shape during the pre-ejection period.[25] In systole, the reduction of MV in the endocardium and epicardium presented a similar pattern to previous studies with DTI. There was a reduction in normal MVG findings in ischemic patients. The mesocardium had similar velocities to those in the endocardium and the reduction in these velocities was of a similar degree. Temporal analysis, however, showed that the reduction in mesocardial MV was more consistent throughout the systole and with the reduction in endocardial movement being lower in telesystole. This behavior suggests that the mesocardium would have a predominant role in both mesosystolic and telesystolic periods, when ejection occurs. As a result, the greatest ischemic damage may occur during these periods. Previous works have demonstrated that this nonuniform effect on the myocardium is seen before the appearance of alterations in other parameters of systolic dysfunction, such as fractional shortening.[25] The importance of mid-wall fibers has been evaluated in other conditions, such as LV hypertrophy. Subtle abnormalities, such as decreased shortening, are present and detected previous to the appearance of alterations in systolic ejection indexes.[27,28]

Intramyocardial Diastolic Function in Ischemic Patients

In diastole, global behavior was similar to that of the systole. The MV value was decreased to a higher degree in endocardial and mesocardial layers. This decrease was mainly reported in the maximal MV; the mean MV showed less decrease. However, as an expression of global myocardial performance, diastolic MVG showed a strong decrease in ischemic patients. In diastole, the behavior of layers was reported to be the opposite in early as opposed to late diastole. The MV was significantly decreased in early diastole in the endocardium and mesocardium. In late diastole, however, there was an increase in MV and it tended to occur in endocardium and epicardium and not in mesocardium.

Color M-mode DTI is of great help in the study of regional diastolic function. Previous studies have shown that early-diastolic MV decreased during ischemia, but late diastolic MV increased.[17] This behavior has also been observed in a previous experimental study that used pulsed Doppler tissue.[29] A similar pattern was observed in a clinical setting in patients with IHD.[7]

In diastole, our results are very similar to those reported for other authors in an experimental setting. The opposite behavior of early- and late-diastolic velocities would reflect the active role of myocardial fibers in the former and the passive role of them in the latter. This event reflects the loss of relaxation

properties of the myocardium caused by ischemic damage and the increasing role of atrial emptying to reach the end-diastolic volume necessary to maintain the cardiac output. Intramyocardial analysis showed great value for unmasking the contribution of the different layers in each diastolic period. The reduction of MV was very similar in endocardium and in mesocardium, though higher in the latter. This also suggests a predominantly active role of this layer in this event. The opposite occurred in late diastole. The increase in MV was predominantly in the endocardium and the epicardium and was probably because of a greater loss of compliance in mesocardium.

Limitations of the Study

The present study suggests that color M-mode DTI is a useful method for intramyocardial evaluation of the regional systolic and diastolic function. However, this technique has several technical limitations. First, because of the angle dependence of all Doppler-based methods, accurate determination of myocardial velocities needs an adequate alignment between the ultrasound beam and the main vector direction of the LV segmental wall motion. To minimize this effect, the analysis was performed in posterior segment in parasternal long-axis view. In patients with anterior myocardial infarction, contractility in mid-basal septum (supplied by the first septal coronary artery) is usually preserved and there is less damage from ischemia. When we tried to study the mid-distal segment, misalignment made it difficult to carry out accurate intramyocardial analysis. Myocardial wall motion does not take place in a single direction. Further studies to investigate the role of the different layers in the excursions of the LV myocardium are warranted in longitudinal and circumferential axis.

Noise is another limitation of this study. The filter and average algorithms used help to reduce this problem but not to abolish it. Thus, the velocities and gradients calculated could be an underestimation of their true value. End systole was designed to be placed in the turn of color-coded velocity from red to blue (inward to outward). A more exact definition of end systole, that is, second sound in a simultaneous phonocardiogram registry, was not carried out. Finally, some criticism could be voiced about the selection of a control group. Controls were volunteers of a wide age range; however, most were aged 30 years or younger. This special group was selected because of their healthy intramyocardial regional function and their lack of risk factors, such as hypertension or diabetes mellitus, which may cause damage to the myocardium. According to previous studies, the differences between the ages of the 2 groups could to some degree influence and explain the differences in the velocity analysis of the late diastolic period, but not those found in the systolic period and early diastole.[30]

Conclusions

Our study is the first clinical application of intramyocardial analysis for the assessment of regional myocardial function, using DTI, in learning the role of the different myocardial layers. Our method offers advantages over other previously studied experimental methods. It has the capability of performing a more detailed intramyocardial analysis by subdividing the segment in the 3 principal layers, corresponding to the real anatomic structure of the myocardium.

Intramyocardial analysis of regional myocardial function with DTI color M-mode showed nonuniformity between the different layers in systole and diastole in healthy subjects. This nonuniformity also had been observed in the behavior of myocardial velocities in each layer after ischemic damage. This was also shown in the temporal pattern during systole and diastole, represented by changes in the values of the corresponding gradient. In a clinical setting, intramyocardial analysis of myocardial layers provides a greater understanding of the physiology of regional myocardial function and its pathologic modification. This may also have important practical implications in the evaluation of ischemia. Intramyocardial analysis of MV could help in the early detection of impairment of the regional function in provocative tests, that is, dobutamine stress echocardiography. Likewise, its correction in dys-synergic segments could constitute a sign of viability. Further studies are warranted to clarify the potential role of intramyocardial analysis of regional myocardial function in early detection of ischemia or viability.

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