

Selecting the Best Site for Pacing Leads After Cardiac Surgery by Evaluating the Asynchrony of Myocardial Deformation Observed With Different Pacing Sites

José Luis Moya-Mur,^a Enrique Oliva-De Anquin,^b Tomasa Centella-Hernández,^b Soledad Ruiz-Leira,^a Alicia Megías-Sáez,^a Juan Pablo Tomás-Zarlenga,^a Antonio Hernández-Madrid,^a Eva García-Galloway,^a and Concepción Moro^a

^aServicio de Cardiología, Hospital Ramón y Cajal, Madrid, Spain

^bServicio de Cirugía Cardiovascular, Hospital Ramón y Cajal, Madrid, Spain

Introduction and objectives. After cardiac surgery, temporary pacing leads are routinely implanted in the right ventricle (RV). The objective was to investigate the effect of different ventricular pacing locations on cardiac synchrony (by evaluating myocardial deformation, or strain) and efficiency in patients undergoing cardiac surgery.

Methods. Interventricular asynchrony (i.e. the difference in the time of onset of deformation between right and left ventricles; T_ε-R/L) and intraventricular asynchrony (i.e. the standard deviation and maximum difference in the time of onset of deformation in six segments of the left ventricle [LV]; T_ε-SD and T_ε-MD, respectively) were assessed in 19 patients. Doppler echocardiography was used to evaluate these parameters and cardiac output after pacing in the RV and in three different LV segments.

Results. Pacing in the RV resulted in the greatest increases in asynchrony parameters from baseline: T_ε-R/L 59.8 ms (standard deviation [SD] 40.5 ms) vs. 28.23 ms (SD 56.9 ms), *P* = .002; T_ε-SD 53.2 ms (SD 34.4 ms) vs. 36.6 ms (SD 34.9 ms), *P* = .007; and T_ε-MD 135.3 ms (SD 82.9 ms) vs. 90.5 ms (SD 87.4 ms), *P* = .007. Pacing in the LV resulted in less asynchrony: for anterior LV pacing, T_ε-R/L was 17.2 ms (SD 53.8 ms), T_ε-SD was 35.8 ms (SD 17.9 ms), and T_ε-MD was 91.3 ms (SD 45.2). The change from baseline was not significant. Cardiac output was lower after RV pacing than after anterior LV pacing: 4.36 (SD 1) vs. 4.70 (SD 1); *P* = .001.

Conclusions. Pacing in the LV produced less asynchrony than RV pacing. In addition, anterior LV pacing resulted in a higher cardiac output than RV pacing. These findings suggest that the location normally used for temporary leads after cardiac surgery should be changed.

Key words: *Electrical pacing. Cardiac surgery. Asynchrony. Myocardial deformation.*

Selección del mejor lugar de estimulación tras cirugía cardíaca evaluando la asincronía con *strain* tras diferentes estimulaciones

Introducción y objetivos. Implantar electrodos transitorios en ventrículo derecho (VD) tras cirugía cardíaca es habitual. El objetivo es estudiar en pacientes intervenidos el efecto de la estimulación en diferentes localizaciones ventriculares en la sincronía, analizando la deformación miocárdica (*strain*), y en la eficacia cardíaca.

Métodos. En 19 pacientes se midió la asincronía inter-ventricular (diferencia en el tiempo al comienzo del *strain* entre VD y ventrículo izquierdo [VI]: T_ε DI) y la intraventricular (desviación estándar [T_ε DE] y máxima diferencia en el tiempo de comienzo del *strain* en las seis caras del VI [T_ε MD]). Estas estimaciones y el gasto cardíaco (GC) mediante Doppler se determinaron tras la estimulación en VD en tres diferentes segmentos del VI.

Resultados. La estimulación en VD fue la que más aumentó los parámetros de asincronía respecto al estudio basal: T_ε DI, 59,8 ± 40,5 frente a 28,23 ± 56,9 ms (*p* = 0,002); T_ε DE, 53,2 ± 34,4 frente a 36,6 ± 34,9 ms (*p* = 0,007); T_ε MD, 135,3 ± 82,9 frente a 90,5 ± 87,4 ms (*p* = 0,007). La estimulación en VI produjo menos asincronía (estimulación en segmento anterior del VI: T_ε DI, 17,2 ± 53,8 ms; T_ε DE, 35,8 ± 17,9 ms; T_ε MD, 91,3 ± 45,2 ms (sin significación estadística respecto a basal). El GC tras la estimulación en VD fue menor que tras estimulación en la cara anterior del VI: 4,36 ± 1 frente a 4,7 ± 1 (*p* = 0,001).

Conclusiones. La estimulación en VI produce menos asincronía que en VD. Asimismo, la estimulación en la cara anterior del VI consigue mayor GC que la estimulación en VD. Estos datos indican que se debería modificar la localización de los electrodos transitorios tras cirugía cardíaca.

Palabras clave: *Estimulación eléctrica. Cirugía cardíaca. Asincronía. Deformación miocárdica.*

Correspondence: Dr. J.L. Moya Mur.
Hospital Ramón y Cajal.
Ctra. Colmenar, Km 9,300, 28034 Madrid. Spain.
E-mail: jmoya.hrc@salud.madrid.org

Received April 22, 2009.

Accepted for publication March 12, 2010.

ABBREVIATIONS

ε : strain, myocardial deformation
 T_{ε} MD: maximum difference in the time of onset of strain in the 6 segments of the left ventricle
 T_{ε} R/L: difference in time to onset of strain between the right and left ventricle
 T_{ε} SD: SD in time from onset of strain in the 6 segments of the left ventricle

INTRODUCTION

Implantation of temporary epicardial electrodes in cardiac surgery is common practice. Generally, the ventricular electrodes are placed in the right ventricle (RV). It has not been confirmed that this is the best site for pacing. RV pacing can resolve the arrhythmic complications, but it does not induce physiological activation of the left ventricle (LV), and initiates electrical activation and asynchronous ventricular contraction.

Different studies have shown the potential negative effect of RV pacing, particularly when performed over long time periods, as reflected by an increase in the number of hospitalizations and a decrease in the functional class of patients, essentially in those with ventricular failure.¹⁻⁵

Tissue Doppler (TD) imaging techniques can allow an analysis of mechanical asynchrony.^{6,7} The myocardial strain analysis used in this study has the advantage of differentiating between active myocardial contraction and passive myocardial movement, and it has been used to demonstrate mechanical asynchrony.⁷⁻⁹

Placement of electrodes in the LV using the coronary sinus as access can be very difficult, as it depends on the venous anatomy. However, in cardiac surgery, electrodes can be placed in any epicardial position and the effect of pacing at each of these sites can be observed.

Therefore, we have performed this study in patients submitted to cardiac surgery, in whom temporary electrodes were implanted in the RV and in different epicardial positions in the LV. The objectives of the study were, on one hand, to analyze the effects of acute pacing in the RV and at different sites in the LV on synchrony, and on the other, to determine whether there was a site where greatest heart efficiency could be obtained after pacing.

METHODS

Study Population

Consecutive adult patients were selected from a waiting list for elective cardiac surgery. These patients were in sinus rhythm and gave their written informed consent to participate in the study, which was approved by the ethics committee of our hospital. Exclusion criteria were atrial fibrillation, complete left bundle-branch block, implanted pacemaker, and failure to meet the inclusion criteria. Nineteen patients were included (4 women [21%]) with mean (SD) age of 68 (10.62) years. The mean (SD) ejection fraction (EF), estimated from echocardiography using the Simpson method¹⁰ was 57.6% (14.6%). Only 4 patients had an ejection fraction <50% (actual values, 25%, 30%, 45%, and 45%); 16 patients had ischemic heart disease and 6 had had a prior infarction (4 anteroapical and 2 inferobasal). All patients were in sinus rhythm and no patients had a QRS interval duration greater than 120 ms. (The QRS interval corresponds to the part of the electrocardiogram that represents ventricular polarization.) Sixteen patients underwent revascularization and 3 underwent aortic valve replacement. No serious postoperative complications were reported.

Surgical Technique

Temporary epicardial electrodes were implanted at 3 locations in the LV (anterior, inferior, and lateral), as well as in the inferior segment of the RV close to the apex (Figures 1 and 2). Temporary atrial electrodes and 2 skin electrodes were also implanted as indifferent electrodes.

External generators were used (5388 dual-chamber Medtronic, Medtronic Inc., Minneapolis, Minnesota, USA). The atrial electrodes were connected to the atrial channel of generator no. 1 in bipolar mode. Pacing of different ventricular regions was done in monopolar mode using 1 of the skin electrodes as the positive electrode. The pacing frequency was 10 bpm greater than the heart rate of the patient and the atrioventricular interval was 130 ms. These parameters remained fixed regardless of the region paced. Ventricular capture during pacing was confirmed by QRS morphological analysis of the surface electrocardiogram (ECG). The electrodes were withdrawn after finishing the study.

Echocardiographic Study

The echocardiographic study was performed between the third and fifth day after surgery. A Vivid 7 device (General Electrics Medical systems, Horton, Norway) was used with a 3.4 MHz probe.

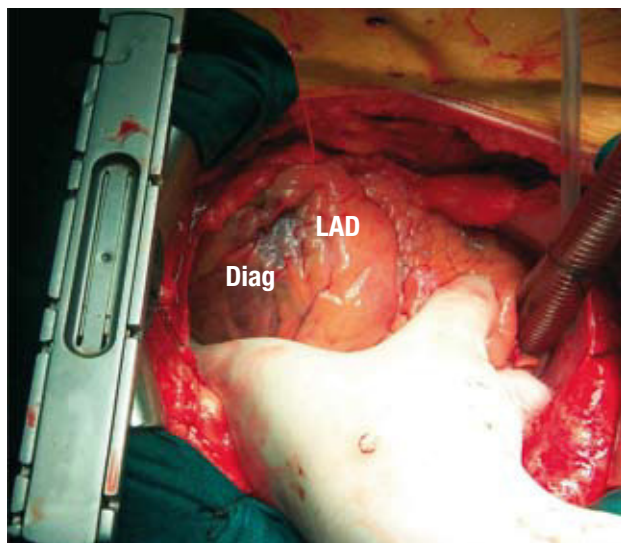


Figure 1. Temporary electrode in the anterior segment of the left electrode, between the left anterior descending artery (LAD) and the diagonal artery (Diag).

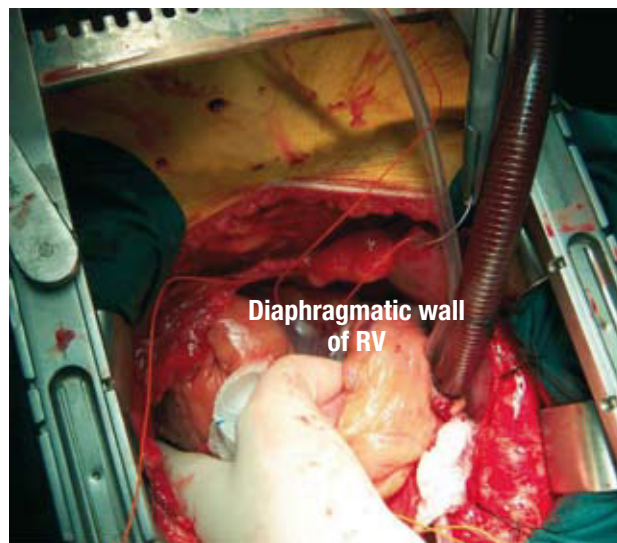


Figure 2. Temporary electrode placed in the diaphragmatic wall of the right ventricle (RV).

Five consecutive echocardiographic studies were undertaken; without pacing, with RV pacing, with pacing at the anterior wall, with lateral pacing, and with pacing in the lower LV.

Images were obtained using parasternal projections in the long and short axes and apical planes in 2, 3, and 4 chambers. The LV outlet flow velocity was recorded in the 5-chamber apical plane using pulsed Doppler technique. Five consecutive beats were obtained in each plane during the baseline study and during each pacing.

Asynchrony was analyzed using 2-dimensional images obtained with TD techniques. The studies were performed in the 2-, 3-, and 4-chamber apical planes. To achieve a higher frame rate, the narrowest sector that permitted satisfactory analysis of the ventricular walls, excluding the atrial walls was used. The frame rate was always >100 fps. Five consecutive beats were obtained in each plane. The images were recorded with the patients holding their breaths, with optimal ECG signal, and excluding extrasystoles.

Analysis of the Echocardiographic Studies

The data were collected using an external work station (Echopac, General Electrics, Horton, Norway). Different measurements in mode M, 2 dimensions, and the determination of EF were carried out in accordance with the recommendations of the American Society of Echocardiography using the Simpson method.¹⁰ Cardiac output (CO) was determined by Doppler echocardiography.¹¹ To obtain the strain curves (ϵ), a region of interest 10×30 mm was defined in the basal

and medial regions of each of the 6 segments of the LV (anterior, anterolateral, inferolateral, inferior, inferoseptal, and anterosseptal), and in the lateral wall of the RV. For each segment, the time was measured from onset of the QRS complex to the where the line that follows the descending fundamental part of the systole curve exceeded zero velocity. The time at which the line crossed the line of zero velocity was used to measure the onset of strain (Figure 3), in similar fashion to that published previously for cardiac magnetic resonance imaging (MRI) studies.¹² The average time from 5 cardiac cycles were used. To obtain synchrony indexes, we used the mean time of each of the ventricular segments (mean of baseline and medial segments).

Asynchrony Parameters

To estimate the interventricular mechanical asynchrony, the difference in time to onset of strain between the RV and LV was used ($T\epsilon$ R/L), that is, the mean time from the onset of strain in the 6 segments of the LV.

To estimate intraventricular asynchrony, the following measures were used: SD of the time of start of strain of the 6 segments of the LV ($T\epsilon$ SD), and maximum difference between the time from start of myocardial strain of 2 different segments of the LV ($T\epsilon$ MD).

Statistical Analysis

Quantitative data were expressed as means (SD). The correlation between the different quantitative

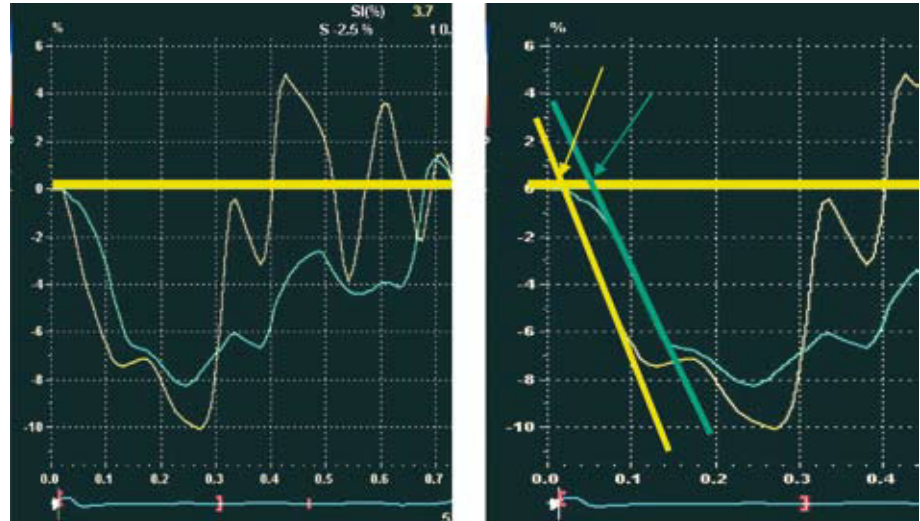


Figure 3. For each segment, the strain-time curves were measured from the onset of the QRS complex where the line that follows the descending fundamental part of the systole curve exceeded zero velocity (arrows). In yellow, the septal segment curve, and in green, the lateral segment.

parameters was analyzed using the Spearman test. The Friedman and Wilcoxon tests were used for analysis of differences between paired groups, using the Bonferroni correction. The intraclass correlation coefficient (ICC) and 95% confidence intervals (CI) were used to evaluate the intraobserver and interobserver agreement in the analysis of $T\epsilon$ SD, $T\epsilon$ MD, and calculation of the integral of flow velocity at the LV outlet tract. To estimate the variability in the calculation of CO, this variable was analyzed, given that it is the only one that is modified when CO is calculated with the different types of pacing. Statistical significance was set at $P < .05$. SPSS (version 11.0) software was used for the statistical analysis (SPSS Inc., Chicago, Illinois, USA).

RESULTS

The mean (SD) asynchrony parameters were $T\epsilon$ LV, 28.3 (56.9) ms; $T\epsilon$ SD, 36.6 (34.9) ms; and $T\epsilon$ MD, 90.5 (87.4) ms. There was a good correlation between the last 2 parameters ($r=0.971$; $P < .0001$).

Likewise, $T\epsilon$ SD and $T\epsilon$ MD showed a good correlation with EF ($r=0.62$ and $r=0.6$, respectively; $P < .001$) and with a history of prior infarction. Patients with prior infarction and low EF had worse asynchrony parameters. Patients with prior infarction ($n=6$) showed greater asynchrony, but without reaching statistical significance: $T\epsilon$ R/L, 13.9 (45.9) versus 28.19 (24.8) ms; $T\epsilon$ SD, 23.7 (11.3) versus 41.9 (25.2) ms ($P=.06$); $T\epsilon$ MD, 60 (25.9) versus 100 (67.2) ms ($P=.1$).

All asynchrony parameters increased with respect to baseline values when the RV was paced: $T\epsilon$ R/L, 59.8 (40.5) versus 28.23 (56.9) ms ($P=.002$); $T\epsilon$ SD, 53.2 (34.4) versus 36.6 (34.9) ms ($P=.007$); $T\epsilon$ MD, 135.3 (82.9) versus 90.5 (87.4) ms ($P=.007$)

(Table; Figures 4 and 5). This pacing was the one that produced most asynchrony (Table). Pacing in the anterior and lateral segments of the LV lead to less asynchrony than pacing in the RV. Likewise, pacing in the anterior region of the LV produced less difference with respect to the baseline study in the asynchrony parameters analyzed (Table).

The mean (SD) CO obtained in the different studies was as follows: baseline, 4.4 (1.2); RV pacing; 4.3 (1), pacing in the anterior segment of the LV, 4.7 (1); pacing in the lateral segment of the LV, 4.5 (1.2); pacing in the inferior segment, 4.4 (0.9) (Friedman test, $P=.0018$). The CO after pacing at the anterior segment of the LV was significantly greater than that obtained after RV pacing (Wilcoxon test, $P=.001$).

TABLE 1. Values of the Asynchrony Parameters at Baseline and After Each Pacing

Pacing	$T\epsilon$ R/L	$T\epsilon$ SD	$T\epsilon$ MD
Baseline	28.2 (56.9)	36.6 (35)	90.5 (87.4)
Right ventricle	59.8 (40.5) ^a	53.2 (34.5) ^a	135.3 (83) ^a
Anterior	17.2 (53.6) ^b	35.8 (17.9)	91.3 (45.2) ^b
Lateral	14.7 (76.4)	42.4 (29.3)	97.9 (53.8)
Inferior	27.6 (51.8)	47.5 (26.7) ^c	126.3 (71.7) ^a
<i>P</i> (Friedman test)	.023	.002	<.001

$T\epsilon$ SD indicates SD in time from onset of strain in the 6 segments of the left ventricle; $T\epsilon$ R/L, difference in time from onset of strain between the right and left ventricle; $T\epsilon$ MD, maximum difference in the time of onset of strain in the 6 segments of the left ventricle.

^aWilcoxon test, $P < .01$.

^bWilcoxon test, significant versus right ventricle, $P < .01$. Significance of the difference in values of $T\epsilon$ R/L, $T\epsilon$ SD, and $T\epsilon$ MD obtained after pacing at the LV sites and RV pacing.

^cSignificance versus baseline, $P < .05$. Significance of the difference in values of $T\epsilon$ R/L, $T\epsilon$ SD, and $T\epsilon$ MD obtained after pacing at the LV sites and baseline. RV pacing is that one that yields most significant differences in the asynchrony parameters vs baseline.

Values presented as means (SD) of asynchrony parameters obtained without pacing and after each type of pacing.

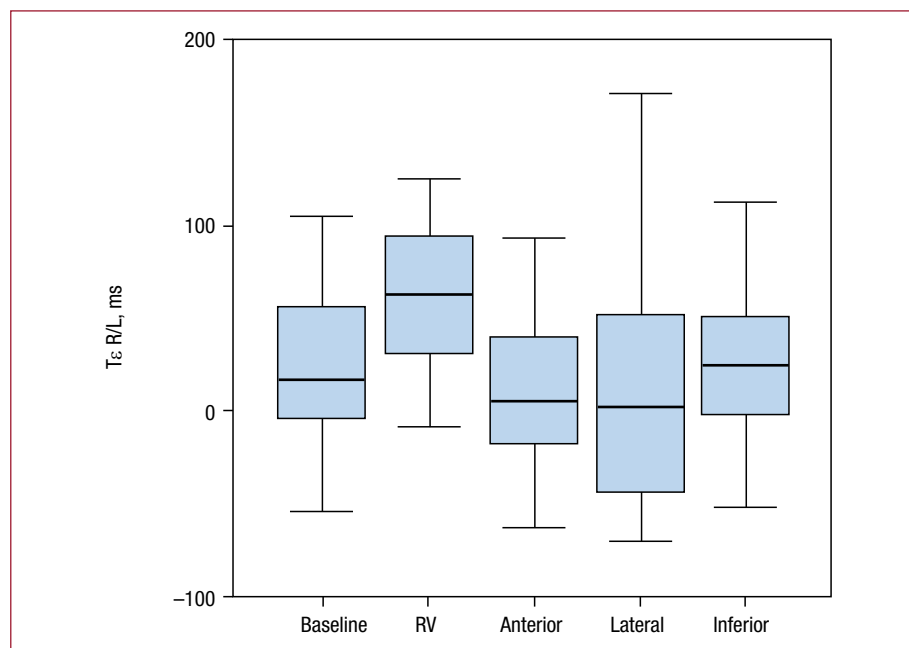


Figure 4. Bar diagram representing the difference in time between the onset of strain in the right and left ventricle ($T_{\epsilon} R/L$) at baseline and after each type of pacing. RV indicates right ventricle.

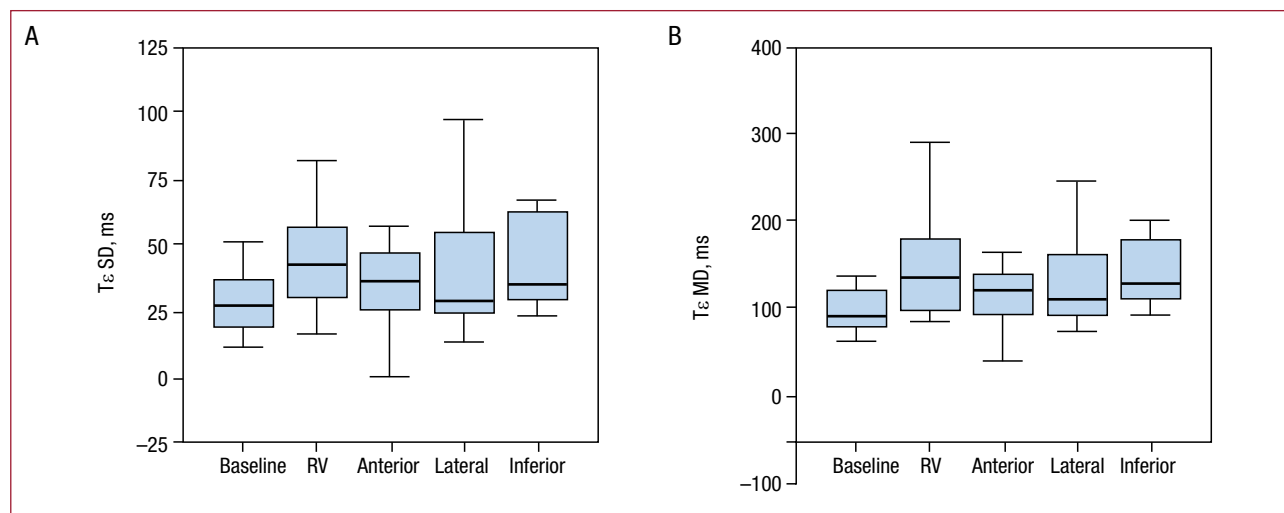


Figure 5. Bar diagram. A: SD in time from onset of strain in the 6 segments of the left ventricle ($T_{\epsilon} SD$). B: maximum difference in the time of onset of strain in the 6 segments of the left ventricle ($T_{\epsilon} MD$), at baseline and after pacing at different sites. RV indicates right ventricle.

The remaining types of pacing at other sites in the LV did not show statistical differences in the CO with respect to pacing in the RV (Figure 6).

The interobserver and intraobserver ICCs were 0.74 (0.48-0.88) and 0.89 (0.77-0.95) for $T_{\epsilon} SD$ and 0.73 (0.46-0.87) and 0.87 (0.73-0.94) for $T_{\epsilon} MD$, respectively. The interobserver and intraobserver ICCs for estimating the integral of the LV outlet tract velocity were 0.997 (0.992-0.999) and 0.998 (0.996-0.999), respectively.

DISCUSSION

This is the first study to analyze in detail the acute effect on mechanical asynchrony and efficacy of cardiac contractile function after pacing at different sites during the period immediately after heart surgery. Our study shows that, of the different pacing sites analyzed, the RV is the site that produces most interventricular and intraventricular asynchrony, whereas the sites that give a result most similar to

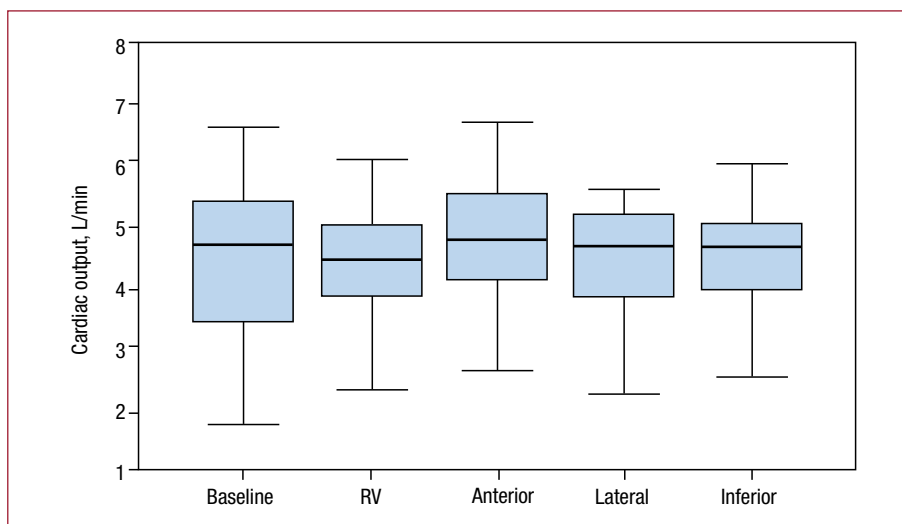


Figure 6. Bar diagram representing cardiac output at baseline and after pacing at the different sites. RV indicates right ventricle.

baseline are the anterior and lateral segment of the LV. On the other hand, although the CO obtained with pacing at these sites of the LV is not different to that obtained in baseline conditions, pacing at the anterior segment of the LV yields significantly greater COs than those obtained when the pacing site is the RV.

Method Validity

The utility of studying mechanical synchrony is subject to debate, essentially after publication of the PROSPECT study,¹³ in which the mechanical asynchrony indexes did not appear to be reliable indicators of response after resynchronization therapy. However, asynchrony was not determined using strain-based methods, and so the results cannot be extrapolated to studies performed using these methods. Recent studies using the strain technique have shown greater utility at predicting the effect of resynchronization therapy.¹⁴⁻¹⁶ A recent study compared the velocity-based methods and strain-based methods obtained with TD techniques to determine which parameter is the best predictor of response after resynchronization therapy.¹⁷ No parameter obtained with TD velocities indicated improvement after resynchronization therapy, whereas the SD of the strain was a good predictor of volume reduction after resynchronization.

We have analyzed asynchrony parameters based on strain in a similar fashion in a previous study,¹⁷ but here we used a broad sector, with simultaneous recording of opposing segments. We could thus avoid measurement errors caused by variation in cardiac frequency. However, the frame rate obtained is lower, and the segment alignment is not always ideal. These problems are not so great in our patients

because there was a good signal-to-noise ratio and alignment was easier given they did not have dilated hearts. We also measured the strain time in a different way. Sometimes, it is difficult to select the time peak, either because there might be multiple peaks or because the peaks might be variable. To avoid this problem, for our study, we chose the point where the straight line that shows the main deformation of the segment exceeds zero strain. We thus reflect the main behavior of the strain curve and homogenize the measurement of extrapolating the curve at the same time, the zero value of strain. This approach avoids the difficulty of measurement associated with more than one strain peak or with poor definition of that peak (Figure 3). This method has been previously validated in cardiac MRI studies,¹² and the variability study obtained good results in the ICCs for the different measures used.

Effect of Pacing on Cardiac Function in Patients With Impaired and Conserved Ventricular Function

The asynchrony caused by RV pacing gives rise to different deleterious effects, particularly in patients with low EF: decreased EF, increased episodes of heart failure, and increased mortality.¹⁸⁻²⁰ In addition, in patients with ventricular dysfunction and conduction disorders, biventricular or LV pacing is more beneficial.²¹⁻²⁸

Our study population was not characterized by impaired ventricular function. A recent study in patients with abnormal sinus rhythm who received a dual-chamber device and who had normal atrioventricular node conduction and EF has shown that RV pacing leads to a decrease in EF in the long-term.²⁹ In addition, Puggioni et al,³⁰ on comparing

LV pacing with RV pacing in patients with atrial fibrillation and atrioventricular node ablation, found that LV pacing led to a favorable acute hemodynamic effect, with an increase in EF and a decrease in the degree of mitral valve failure. The effect was similar in patients with normal EF and impaired EF.

Similarly, our study shows that RV pacing is associated with worsening of the interventricular and intraventricular asynchrony parameters and that LV pacing causes less interventricular and intraventricular asynchrony than RV pacing. The pacing sites associated with least asynchrony were the anterior and lateral walls of the LV. This pacing was not accompanied by an increase in cardiac output, although greater output was observed with RV pacing.

Studies After Cardiac Surgery

Few studies are available that analyze the effect of different types of pacing in the postoperative period after cardiac surgery, and the studies that are available have reported contradictory results. Healy et al³¹ showed the DDD mode pacing (pacemaker with dual sensing, dual pacing, and dual response) increased coronary flow, CO, and flow from the coronary duct with respect to VVI mode pacing (left ventricular volume). Dual-chamber pacing did not have an additive effect. Likewise, Schmith et al³² did not find any improvement in the general or segmental left ventricular function parameters in patients with cardiac failure and conduction disorders when performing dual-chamber pacing after surgery. Bakhtiary et al,³³ in contrast, observed an increase in CO with dual-chamber pacing in approximately 59% of patients with ventricular function impairment and broad QRS. Flynn et al³⁴ studied patients with ventricular dysfunction. Using a thermodilution catheter, they analyzed the effect of pacing in the RV and anterior and posterior segment of the LV and showed that pacing at the inferolateral wall of the LV increased the cardiac index and mean arterial pressure compared to RV pacing. They concluded that pacing in the inferolateral segment of the LV provides a beneficial effect in surgical patients.

The aforementioned studies were performed in patients with LV dysfunction and generally with conduction disorders. However, the present study was conducted in patients with normal QRS who were not selected for impaired EF. In these patients, we found that the changes in CO achieved by changing pacing site are small. Nevertheless, we were able to observe a trend toward decreasing CO on RV pacing in contrast to pacing in the anterior segment of the LV.

Study Limitations

The patients studied were not selected for ventricular dysfunction or bundle-branch block. Therefore, the results cannot be extrapolated to other studies that recruited patients with left ventricular dysfunction or bundle-branch block. Given that the number of patients studied was small, the results should be confirmed in subsequent studies.

Different studies such as the PROSPECT trial¹³ have not confirmed the validity of the usual methods for assessing mechanical asynchrony and, in general, these methods are not very reproducible. In contrast, our method, on using the same patient as a baseline control, minimizes errors of interpretation. Moreover, these changes are easier to analyze than comparisons between 2 groups of patients. Analysis of radial and circumferential strain would have provided more information for the study and would have increased its validity. Unfortunately, the study was done using TD techniques, and so radial and circumferential analyses were impossible.

In this study, we did not analyze EF or ventricular volumes as parameters of ventricular function. To carry out these measurements reliably and reproducibly, good image quality is necessary, although this is not always easy to obtain after cardiac surgery. We therefore preferred to analyze changes in CO, which only depends on changes in the Doppler signal in the LV outlet tract and is less influenced by image quality.

CONCLUSIONS

RV pacing led to significant interventricular and intraventricular asynchrony in patients in the immediate postoperative period after cardiac surgery. In these patients, the pacing sites that led to least asynchrony were the lateral and anterior wall of the LV.

Although there were no significant differences in CO of the patients without pacing compared to those with pacing, we did see a significant difference between CO obtained with RV pacing compared to that obtained with pacing of the LV anterior wall.

In view of our results, we believe that the usual pacing site should be changed, given how easy it is to place electrodes on any part of the epicardium after surgery. If the patient does not have ventricular dysfunction, the electrodes should be placed in the atrium and the anterior or lateral segment of the LV for DDD mode pacing.

ACKNOWLEDGMENTS

We thank the members of the Department of Biostatistics, and Alfonso Muriel and Victor Abaira in particular.

REFERENCES

1. Wilkoff BL, Cook JR, Epstein AE, Greene HL, Hallstrom AP, Hsia H, et al; Dual Chamber and VVI Implantable Defibrillator Trial Investigators. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator. *JAMA*. 2002;288:3115-23.
2. Sweeney MO, Hellkamp AS, Ellenbogen KA, Greenspon AJ, Freedman RA, Lee KL, et al; Mode Selection Trial Investigators. Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction. *Circulation*. 2003;107:2932-7.
3. Steinberg JS, Fischer A, Wang P, Schuger C, Daubert J, McNitt S, et al. MADIT II Investigators. The clinical implications of cumulative right ventricular pacing in the multicenter automatic defibrillator trial II. *J Cardiovasc Electrophysiol*. 2005;16:359-65.
4. Adomian GE, Beazell J. Myofibrillar disarray produced in normal hearts by chronic electrical pacing. *Am Heart J*. 1986;112:79-83.
5. Tse HF, Lau CP. Long-term effect of right ventricular pacing on myocardial perfusion and function. *J Am Coll Cardiol*. 1997;29:744-9.
6. Søgaard P, Hassager C. Tissue Doppler imaging as a guide to resynchronization therapy in patients with congestive heart failure. *Curr Opin Cardiol*. 2004;19:447-51.
7. Gorcsan J 3rd, Abraham T, Agler DA, Bax JJ, Derumeaux G, Grimm RA, et al; American Society of Echocardiography Dyssynchrony Writing Group. Echocardiography for cardiac resynchronization therapy: recommendations for performance and reporting. *J Am Soc Echocardiogr*. 2008; 21:191-213.
8. Prinzen FW, Augustijn CH, Arts T, Allessie MA, Reneman RS. Redistribution of myocardial fiber strain and blood flow by asynchronous activation. *Am J Physiol*. 1990;259: H300-8.
9. Breithardt OA, Stellbrink C, Herbots L, Claus P, Sinha AM, Bijnens B, et al. Cardiac resynchronization therapy can reverse abnormal myocardial strain distribution in patients with heart failure and left bundle branch block. *J Am Coll Cardiol*. 2003;42:486-94.
10. Lang RM, Biering M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, et al. Recommendations for chamber quantification. *Eur J Echocardiogr*. 2006;7:79-108.
11. Ascah KJ, Stewart WJ, Levine RA, Weyman AE. Dopplerechocardiographic assessment of cardiac output. *Radiol Clin North Am*. 1985;23:659-70.
12. Zwanenburg JJ, Götte MJ, Kuijper JP, Heethaar RM, van Rossum AC, Marcus JT. Timing of cardiac contraction in humans mapped by high-temporal-resolution MRI tagging: early onset and late peak of shortening in lateral wall. *Am J Physiol Heart Circ Physiol*. 2004;286:H1872-80.
13. Chung ES, Leon AR, Tavazzi L, Sun JP, Nihoyannopoulos P, Merlino J, et al. Results of the Predictors of Response to CRT (PROSPECT) trial. *Circulation*. 2008;117:2608-16.
14. Gorcsan J 3rd, Tanabe M, Bleeker GB, Suffoletto MS, Thomas NC, Saba S, et al. Combined longitudinal and radial dyssynchrony predicts ventricular response after resynchronization therapy. *J Am Coll Cardiol*. 2007;50:1476-83.
15. Suffoletto MS, Dohi K, Cannesson M, Saba S, Gorcsan J 3rd. Novel speckle-tracking radial strain from routine black-and-white echocardiographic images to quantify dyssynchrony and predict response to cardiac resynchronization therapy. *Circulation*. 2006;113:960-8.
16. Dohi K, Suffoletto MS, Schwartzman D, Ganz L, Pinsky MR, Gorcsan J 3rd. Utility of echocardiographic radial strain imaging to quantify left ventricular dyssynchrony and predict acute response to cardiac resynchronization therapy. *Am J Cardiol*. 2005;96:112-6.
17. Miyazaki C, Powell BD, Bruce CJ, Espinosa RE, Redfield MM, Miller FA, et al. Comparison of echocardiographic dyssynchrony assessment by tissue velocity and strain imaging in subjects with or without systolic dysfunction and with or without left bundle-branch block. *Circulation*. 2008;117:2617-25.
18. Nielsen JC, Kristensen L, Andersen HR, Mortensen PT, Pedersen OL, Pedersen AK. A randomized comparison of atrial and dual-chamber pacing in 177 consecutive patients with sick sinus syndrome: echocardiographic and clinical outcome. *J Am Coll Cardiol*. 2003;42:614-23.
19. Sweeney MO, Hellkamp AS, Ellenbogen KA, Greenspon AJ, Freedman RA, Lee KL, et al. Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction. *Circulation*. 2003;107:2932-7.
20. Wilkoff BL, Cook JR, Epstein AE, Greene HL, Hallstrom AP, Hsia H, et al. Dual-chamber pacing or ventricular backup pacing in patients with an implantable defibrillator: the Dual Chamber and VVI Implantable Defibrillator (DAVID) Trial. *JAMA*. 2002;288:3115-23.
21. Abraham WT, Fisher WG, Smith AL, Delurgio DB, Leon AR, Loh E, et al. Cardiac resynchronization in chronic heart failure. *N Engl J Med*. 2002;346:1845-53.
22. Bristow MR, Saxon LA, Boehmer J, Krueger S, Kass DA, de Marco T, et al. Cardiac-resynchronization therapy with or without an implantable defibrillator in advanced chronic heart failure. *N Engl J Med*. 2004;350:2140-50.
23. Cleland JG, Daubert JC, Erdmann E, Freemantle N, Gras D, Kappenberger L, et al. The effect of cardiac resynchronization on morbidity and mortality in heart failure. *N Engl J Med*. 2005;352:1539-49.
24. Swedberg K, Cleland J, Swedberg K, Cleland J, Dargie H, Drexler H, et al. Guidelines for the diagnosis and treatment of chronic heart failure. *Eur Heart J*. 2005;26:1115-40.
25. Heart Failure Society of America. Executive summary: HFSA 2006 comprehensive heart failure practice guideline. *J Card Fail*. 2006;12:10-38.
26. Stevenson WG, Sweeney MO. Single site left ventricular pacing for cardiac resynchronization. *Circulation*. 2004;109:1694-6.
27. Blanc JJ, Etienne Y, Gilard M, Mansourati J, Munier S, Bosch J, et al. Evaluation of different ventricular pacing sites in patients with severe heart failure: results of an acute hemodynamic study. *Circulation*. 1997;96:3273-7.
28. Blanc JJ, Bertault-Valls V, Fatemi M, Gilard M, Pennec PY, Etienne Y. Midterm benefits of left univentricular pacing in patients with congestive heart failure. *Circulation*. 2003;109:1741-4.
29. Liu WH, Chen MC, Chen YL, Guo BF, Pan KL, Yang CH, et al. Right ventricular apical pacing acutely impairs left ventricular function and induces mechanical dyssynchrony in patients with sick sinus syndrome: a real-time three-dimensional echocardiographic study. *J Am Soc Echocardiogr*. 2008;21:224-9.
30. Puggioni E, Brignole M, Gammage M, Soldati E, Bongiorno MG, Simantirakis EN, et al. Acute comparative effect of right and left ventricular pacing in patients with permanent atrial fibrillation. *J Am Coll Cardiol*. 2004;43:234-8.

31. Healy DG, Hargrove M, Doddakulla K, Hinchion J, O'Donnell A, Aherne T. Impact of pacing modality and biventricular pacing on cardiac output and coronary conduit flow in the post-cardiotomy patient. *Interact Cardiovasc Thorac Surg*. 2008;7:805-8.
32. Schmidt C, Frielingsdorf J, Debrunner M, Tavakoli R, Genoni M, Straumann E, et al. Acute biventricular pacing after cardiac surgery has no influence on regional and global left ventricular systolic function. *Europace*. 2007;9:432-6.
33. Bakhtiary F, Dogan S, Dzemali O, Ackermann H, Kleine P, Schächinger V, et al. Impact of different pacing modes on left ventricular contractility following cardiopulmonary bypass. *Pacing Clin Electrophysiol*. 2007;30:1083-90.
34. Flynn MJ, McComb JM, Dark JH. Temporary left ventricular pacing improves haemodynamic performance in patients requiring epicardial pacing post cardiac surgery. *Eur J Cardiothorac Surg*. 2005;28:250-3.