Septal myocardial protection during cardiac surgery for prevention of right ventricular dysfunction

Kardiyak cerrahi sırasında sağ ventriküler disfonksiyonun önlemesinde septal miyokardiyal koruma

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ABSTRACT

Postoperative right ventricular (RV) failure is difficult to treat and develops from functional impairment of the underlying free wall and septum. This report describes the vital importance of the ventricular septum in RV structure /function relationships, demonstrates how the helical ventricular myocardial band model defines spatial geometry of the free wall and septum to provide architectural reasons for RV dynamic action, and focuses upon pathophysiologic reasons for adverse perioperative events resulting in right ventricular failure. Myocyte fiber orientation is the key to ventricular performance in health and disease. The transverse geometry of the free wall allows constriction (bellows type motion), whereas oblique septal fiber orientation and midline septal position is essential for ventricular twisting, the vital mechanism for RV ejection against increased pulmonary vascular resistance. The septum is considered "the lion or motor of RV performance". This central muscle mass occupies ~40% of myocardial ventricular weight, and injury from impaired myocardial protection is a preventable event.

Septal function should be the index of adequacy of myocardial protection and we will show echocardiographic evidence that the integrated cardioplegic method prevents its injury. Dysfunction of a normally functioning septum following surgical cardiac procedures calls for reevaluation of myocardial protection methods. *(Anadolu Kardiyol Derg 2008; 8: Suppl 2; 108-16)*

Key words: Septum, right ventricle, helical ventricular myocardial band, myocardial protection

ÖZET

Ameliyat sonu oluşan sağ ventrikül yetmezliğini tedavi etmek oldukça güçtür, genellikle serbest duvarın ve septumun fonksiyonel bozulmasından kaynaklanır. Bu derleme sağ ventrikülün yapı/fonksiyon ilişkisinde ventrikül septumunun yaşamsal önemini belirtir, sağ ventrikülün dinamik hareketi için yapısal nedenleri sağlamakta sağ ventrikül ve septumun uzaysal geometrisini tanımlayan sarmal ventrikül miyokardının bant modelini belirtir ve sağ ventrikül yetmezliği ile sonuçlanan elverişsiz perioperatif olayların patofizyolojik nedenlerine yoğunlaşır.Miyosit fibril oryantasyonu sağlam ve hastada ventrikül perfomansı için en önemli noktadır. Serbest duvarın transfer geometrisi konstriksiyonu sağlarken ("bellow type" hareket) oblik septal fibril oryantasyonu ve ortadaki septal pozisyon ventrikülün kıvrımsal hareketi için esas temeli oluşturur, pulmoner vasküler rezistansı artmasına karşı, sağ ventrikül ejeksiyonu yaşamsal bir mekanizmayı teşkil eder. Septum "sağ ventrikül performansının aslanı ya da motorudur," şeklinde düşünülür. Bu santral kas kitlesi ventrikül miyokard ağırlığının %40'ını oluşturur ve miyokardiyal korumanın zarar görmesi önlenebilir bir olaydır.

Septum fonksiyonu miyokardiyal koruma yeterliliğinin indeksi olarak kabul edilmelidir ve entegre kardiyoplejik yöntemlerin hasarı önlediği tarafımızdan ekokardiyografik yöntemlerle gösterilecektir. Kalp cerrahisi girişimlerinden sonra normal fonksiyonlu'da oluşan disfonksiyon, miyokard koruma yöntemlerinin yeniden değerlendirilmesini gündeme getirmektedir. *(Anadolu Kardiyol Derg 2008; 8: Özel Sayı 2; 108-16)*

Anahtar kelimeler: Septum, ventriküler miyokardiyal bant, miyokardiyal koruma

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Introduction

Efficient right ventricular performance is determined by proper functional activity of the free wall and intraventricular septum, which is the most important structural component. Dysfunction of the ventricular septum has been observed following open heart cardiac procedures for many years (1-5), has become an "expected outcome" of cardiopulmonary bypass, and is termed "post-bypass septum " or "paroxysmal septal motion (PSM)" in the echocardiography literature. Moreover, paroxysmal septal motion also follows coronary revascularization without use of the extracorporeal bypass (1-6), so that open heart procedures are not a prerequisite for functional septum impairment after cardiac surgery. Gradation of this adverse outcome by an echocardiography score quantifies a functional abnormality that progresses from mild hypokinesia, to severe hypokinesia, akinesia and then dyskinesia or septum paradox. (7) Septal dysfunction exists without ischemia, since Thallium scans are normal in the most advanced abnormality of a paradoxical septum (5), and 20% of patients display persistent dysfunction for more that one year (1).

A recent report of 3292 patients (6) focused only upon paradoxical septal motion and found that this was more frequent after valve procedures (aortic 48%, mitral 58% tricuspid 60%) interval), but also followed coronary grafting (CABG) with (34%) or without bypass (OPCAB, 19%). No data about lesser grades of septum malfunction was presented in this review.

Our manuscript questions whether septal injury should be accepted as an expected complication of cardiac surgery, identifies why patients with cardiac valve lesions are more vulnerable to perioperative septal damage, addresses the underlying structure/function mechanisms that are responsible for this abnormality, conveys a novel data analysis to demonstrate that septal dysfunction is an avoidable complication of cardiac surgery, and suggests that routine evaluation of septal function before and after cardiac procedures should be a routine component of measuring the efficiency of myocardial protection.

Understanding paroxysmal septal motion after heart surgery requires a clear appreciation of the spatial geometry of the right ventricle, how it contributes to myocardial function, and how the septum influences adjacent tricuspid valve and global right ventricular function. Different myocardial protection strategies should be assessed by functional rather than chemical markers. Examination of septal function is crucial after cardiac surgery, since the septum constitutes about 40% of the myocardial mass (8, 9).

Background

Myocardial function depends upon structure. The ventricular septum is a midline structure that separates the left and right ventricular chambers, and is the central component of this form / function relationship. The role of the septum in overall ventricular function was initially described in 1865 (9) , when the anatomist Hegar stated that "cardiac anatomy and function will be uncertain until the structure and function of the crossed angles of fibers in the septum are defined." Our report looks at the role of the septum in determining right ventricular function.

Structure / function relationships of the RV and septum

The cardiac architecture is comprised of circumferential and helical fiber arrangements, but until now, the roles of these components have not been related to function (10). These two fundamental components are described in the helical ventricular myocardial band model of Torrent Guasp (11), composed of two interconnected loops. The basal loop is transverse and wraps around the right and left ventricles. The band contains a central myocardial fold that changes fiber direction to an oblique direction and then creates a helix that involves an apical loop comprised of descending and a scending segments that form the left ventricular anterolateral free wall, apical vortex and septum (Fig. 1) (12). The RV free wall predominantly contains the transverse basal loop that surrounds the septum which is comprised of oblique fibers derived from the apical loop. The most important aspect of this model is that the septum does not have a predominant right or left ventricular side, but rather consists of a central structure between left- and right-sided cavities that is comprised of the same fiber elements that form the free left ventricular wall.

Figure 1. Fiber orientation relationship of the septum, composed of oblique fibers that arise from the descending and ascending segments of the apical loop, surrounded by the transverse muscle orientation of the basal loop that composes the free RV wall. Note the conical arrangement of the septum muscle and the basal loop wrap, forming the RV cavity.

RV -right ventricular

Septum and free wall

The ventricular septum separates the left and right ventricular chambers, is the central component of this form / function relationship and constitutes about 40% of the entire ventricular myocardial mass (Fig. 2) (8). In 1991 Dell'Italia observed that the ventricular septum is a central structure for both ventricles, since it binds them together with spiral muscle bundles that encircle them in a complex interlacing fashion to form a highly interdependent functional unit that exists despite their markedly different muscle mass and chamber geometry (13).

The RV free wall and septum are the two architectural components of the right ventricle, and the underlying premise is that fiber orientation determines functional efficiency. In a Petri dish only 15% muscle fiber shortening follows sarcomere

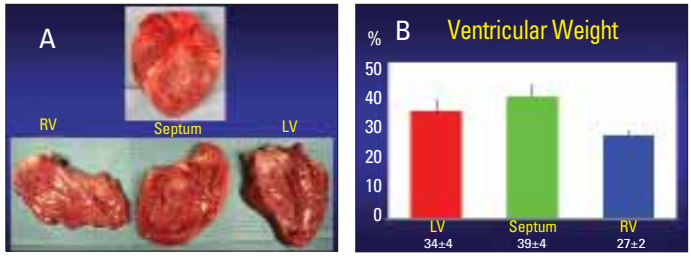

Figure 2. A. Intact heart in the upper tracing. The lower tracings show the muscular mass component after the right ventricle (RV) septum, and left ventricle that was separated from the intact heart following separation incisions made along the left anterior and right posterior descending vessels that pass along the septum.

B. Figure shows the percent total heart weight occupied by the RV, septum and LV muscle mass, displaying that the septum has the highest % muscle mass

LV-left ventricular, RV-right ventricle

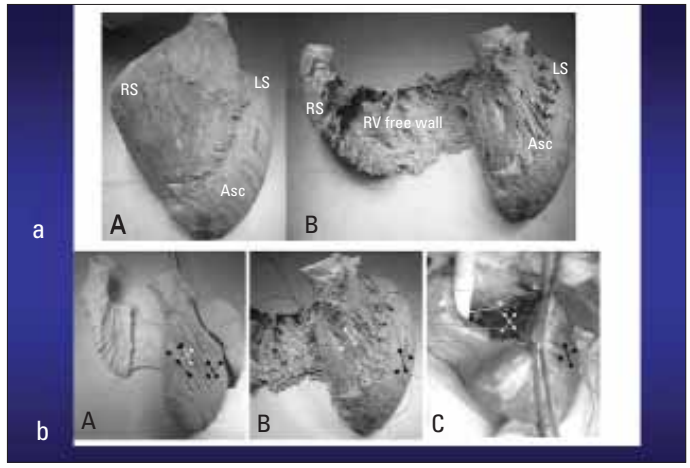

Figure 3. Anatomic preparations showing the orientation of the ventricular myocardial band of the (a) intact heart and (b) after exposing the septum by unfolding of the RV free wall. Note the similar configuration of the septum and LV free wall composed of the ascending segment of the apical loop. (C) showing sonomicrometer crystal positioning in the descending and ascending segments of the LV free wall. Crystal orientation was either in direction of LV free wall showing maximal segmental shortening of descending and ascending segment, or placed perpendicular to maximal segmental shortening position (as shown in Figure 4)

LS - left segment of basal loop, LV - left ventricular, RS - right segment of basal loop, RV - right ventricular

stimulation, but the intact heart has interconnected fibers with a varying angular orientation that result in the normal systolic ejection fraction of about 60%. In 1953 Rushmer (14) reported that global myocardial ejection fraction is approximately 30% if muscle fibers are oriented in a transverse or circumferential direction. Ingels (15) and Sallin (16) showed that ejection fraction increases to 60% if there is oblique myocardial fiber orientation. The documented evidence for the oblique crossing fiber configuration of the septum came from several sources including a) the collagen weave network of reciprocal septal spirals demonstrated by Lunkenheimer's air inflation studies (17) b) Greenbaum and Anderson's cross-sections showing crossing septal fibers (18), and c) the anatomic dissections of the unwrapped heart by Torrent Guasp (11). It has been shown that predominantly transverse myocardial fiber orientation exists in the RV free wall, with some oblique fibers in the right ventricular outflow tract (RVOT), (Fig. 3) while the septal component contains a right angle cross-striation of oblique fibers that are directed toward and away from the conical apical tip. This oblique fiber orientation within the septum provides a twisting motion that affects both the right and left ventricles and significantly augments RV function in concert with the transverse contractility of the free wall.

High resolution echocardiography has recently allowed visualization of the separate oblique layers of fiber orientation in the septum, showing different directional strain patterns generated by these layers of the ascending and descending segments that contract sequentially and confirmed by sonomicrometer crystals (Fig. 4) (19). These layers are evident by magnetic tensor imaging (Fig. 5), and not usually apparent with low resolution echocardiograms but their separation is evident by the hyperechogenic mid- septal line that is easily observed (Fig. 6) (20). Their oblique separation on either side of this line is demonstrated by high-resolution echocardiography (Fig. 7). The septum is hidden from external view because it is externally surrounded by the attachment of the RV free wall on its anterior and inferior surface, but reflects a continuation of the layers that form the left ventricular (LV) free wall, (Fig. 4) (19, 21, 22). Although the septal anatomy contains two predominant muscle layers, it functions as a single unit. Therefore, there is no functional left- and right-sided septum.

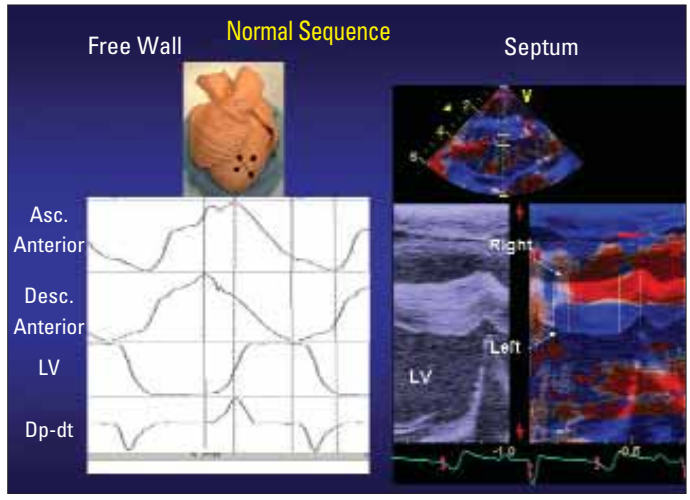

Figure 4. Upper left shows a diagram of the heart with the positions of the sonomicrometer crystals, one of which is deep in endocardium. Lower left shows that lengthening of the descending anterior fibers is beginning while the ascending anterior fibers are still shortening; the left ventricular pressure and dP/dt tracings indicate the timing. The solid line shows the beginning and ending of the descending shortening and the hatched lines show the ascending segment. Upper right panel shows the section examined by the ultrasound probe, with the region of interest at the left and right parts of the septum. The lower right panel shows the septum at higher magnification, and the timing lines parallel those in the free wall in the sonomicrometer tracings. Strain in the right (red) and left (blue) side of the septum. M-mode shows displacement of the left and right side of the septum towards their respective ventricular chambers. Note a) delay of initiation of ascending segment and right septal motion, b) lengthening of descending segment during isovolumic phase following ejection and continuing displacement of the right side of the septum towards the right ventricular cavity, despite beginning of left ventricular cavity expansion. This displacement corresponds to the sonomicrometer tracings that display widening of the descending segment while the ascending segment continues to shorten.

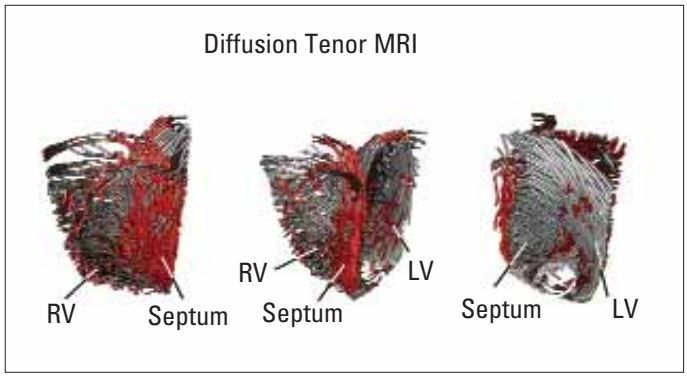

Figure 5. Fiber tracking performed in the LV's and RV's of the human heart using regularized tensor diffusion MRI visualization techniques. The geometry of the fibers of both RV's and LV's and the septum is shown and the continuity of the LV fibers with the septum can be seen. The transverse fiber orientation of the RV free wall is also evident. The left figure shows the RV and septum, the center figure shows the septum in a transverse view, and the right image shows the left side of septum. Note the fiber angulation mirrors the muscle fiber orientation in Figure 1. (Reprinted with permission of Lawrence National Berkley Laboratory Publications)

LV-left ventricle, RV-right ventricle, MRI-magnetic resonance imaging

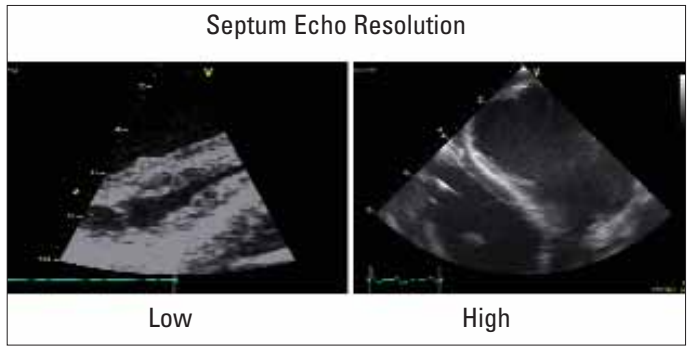

Figure 6A. Septum low and high resolution echo recording image showing the mid hyperecogenic- mid septal line

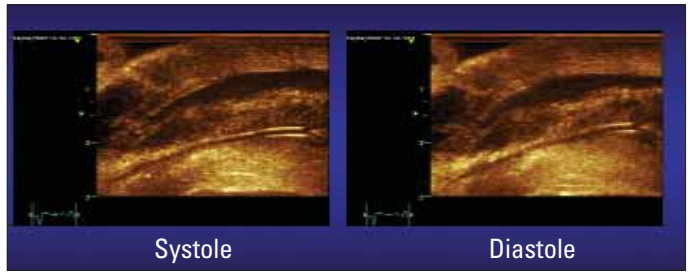

Figure 6B. High- resolution image of septum line that has space or plane between the bands of muscle on either side of this dimension. The right ventricle is above. Note that the endocardial muscle region (below) is homogeneous and dense, while the epicardium region (above toward the RV outer wall) is more transparent, thereby reflecting how the echocardiographic beam traverses muscle fiber orientation planes that exist orthogonal or parallel to its direction. This plane separates the inner and outer segments undergoing reciprocal clockwise and counterclockwise twisting motions when the heart is ejecting and filling.

The RV free wall is a component of the basal loop in the ventricular myocardial band containing predominantly a transverse fibers, which compress the cavity in a bellows like fashion while contracting, an action that is not directly related to those oblique fibers comprising the septum that normally twist during contraction. The importance of the septum versus the free wall was defined by several studies showing that right ventricular performance is not significantly impaired following either cauterization of the entire free wall (23) or replacement of the free wall with patch material, (24) so long as the septum is intact. Conversely, right ventricular failure became accentuated if the septum was either cauterized, made ischemic by embolization after right coronary artery occlusion, or damaged by pulmonary hypertension (25).

Fiber orientation defines the extent of ventricular deformation responsible for strain and thickening, to achieve blood ejection in systole and suction filling in diastole. Tagged images by magnetic resonance imaging (MRI) show the mechanism is through twisting of fibers to eject, followed by untwisting to fill (26) reflecting the "wringing of a cloth" functional concept defined in 1681 by Borelli (9). Moreover the echocardiographic studies show a sequential action of the left, followed by the right side of the septum (Fig. 4) Additionally, RV free wall contraction causes transverse narrowing and relaxation causes widening of these structures, with minimum external wall changes during systole and diastole. Conversely, MRI studies confirm the primary events involving septal muscle are chamber shortening and lengthening caused by twisting and thickening that produce ejection, and untwisting and lengthening for suction filling. Recent functional reports by Klima (27) have confirmed these predominant septal events. The current clinical significance of septal dysfunction is linked to functional performance differences that impair right ventricular efficiency when the twisting capacity of the septum is impaired by lesions that result in septal stretch, which include dilation by valve insufficiency, heart failure, ischemia, and left bundle branch block that is an excitation-contraction delay. Moreover, the stretched septum loses its sequential action and thickens to compress, but not in a twisting motion that is needed for ejection into increased pulmonary vascular resistance (Fig. 7).

The importance of these observations relates to how the efficiency of ejection is impacted by the vector forces needed for ejection into the right and left sides, since the outflow vascular beds offer different resistances. The oblique orientation of muscle fibers of the LV free wall and septum allow the wringing or twisting required to eject blood into high systemic vascular resistance. In contrast, pulmonary vascular resistance is one sixth of systemic resistance, so that the compressive force of transverse constriction, or bellows-like activity from the RV free wall, is sufficient for RV ejection under normal conditions. The effectiveness of this compressive capacity following only free wall contraction is readily evident clinically since postoperative septal dysfunction often follows conventional methods of myocardial protection. (1, 6) Under these circumstances, the normally contracting free wall provides enough compression by transverse circumferential narrowing to maintain normal right-sided hemodynamic function. Therefore, despite septal hypokinesia, akinesia, or dyskinesia or paradox, postoperative right-sided hemodynamics remains normal if the pulmonary vascular resistance is low. Conversely, right ventricular failure supervenes following surgical induction of septum dysfunction if there is pulmonary hypertension from raised pulmonary

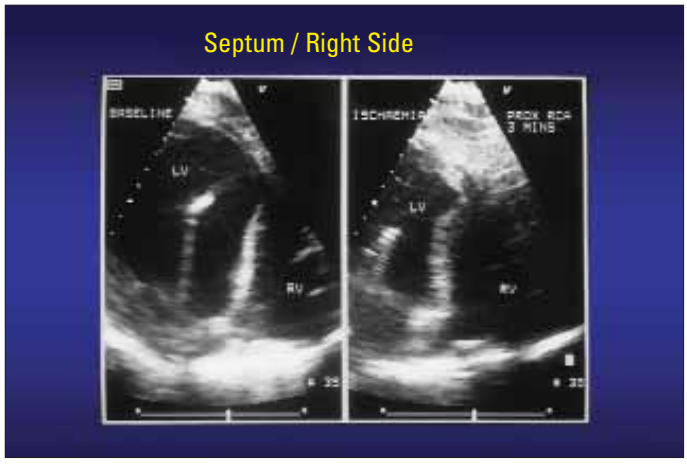

Figure 7. Transesophageal echocardiogram showing bowing or stretch of septum to left side after right coronary artery occlusion with intact pericardium, as shown by Brooks (42). Similar displacement occurs with septum paradox following cardiac surgery.
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vascular resistance, a hemodynamic event caused either by primary pulmonary arterial vasoconstriction, or from a secondary increase due to left ventricular failure. Whereas RV function was adequate preoperatively because septum twist was available to properly ensure cardiac output, postoperative septal dysfunction now causes RV failure because of loss of the predominant functional capacity of the septum to twist and thereby ensure RV ejection.

Sonomicrometry studies

Sonomicrometry experiments confirm the commonality of an oblique orientation of septal fiber architecture with those of the LV free wall (Fig. 3) (19) , but crystal shortening only reflects local dimensional changes in the limited regions that were studied. However, recording of the maximal extent of regional shortening likely reflects the composite transmural ventricular twisting movement that is responsible for ejection and suction. Recognition of the importance of oblique angulations comprising the septal descending and ascending segments influences understanding of their helical arrangement and subsequent twisting motion. These findings have enormous impact because they imply that the septum is the "lion of right ventricular function" (21), since septal twisting is essential when pulmonary vascular resistance is increased.

Sonomicrometer crystal studies of the circumferential base have shown that shortening develops before the septum fully contracts, so that the major contribution of the free wall fibers occurs during the phase of isometric contraction (28). In 1914, Wiggers (29) found the isometric phase was unaltered by afterloading the RV, because the pulmonary valve did not open during free wall contraction. Conversely, the pre-ejection phase was enhanced when inotropic stimulation directly affected the circumferential free wall muscle (29). Furthermore, information gleaned from crystal observation of delayed shortening in the RVOT is 1) consistent with the aberrant oblique fibers described by Torrent Guasp, and 2) confirms the clinical observations of Francis Fontan, who suggested that intraoperative RVOT pacing may impede RV ejection by prematurely obstructing the outflow tract.

Pathophysiology of RV dysfunction

The structure and function interaction of the septum and free wall is key to understanding why the septal contribution to biventricular events is important in congenital heart disease. Septum dysfunction can be the consequence of either left-sided (aortic insufficiency, LV outflow tract obstruction, mitral regurgitation, etc.) or right-sided (pulmonary stenosis, pulmonary insufficiency, atrial septal defect, RV dysplasia, etc.) lesions. The vital importance of correct fiber orientation for proper septal function stems from our prior experience with septal dysfunction that occurs when the oblique fibers are made more transverse by stretch secondary to LV dilation from cardiomyopathy. Echocardiographic studies in these patients confirm septal dysfunction by stretch and displacement into the RV. More importantly, echocardiography confirms the resumption of normal septum function after LV restoration returning the septum to its central anatomic position (30). Such observations imply that the stretched septum is more vulnerable to ischemic damage, perhaps explaining the increased susceptibility to paradoxical motion in the large number of valve patients undergoing this adverse septum change in the recent report of over 3000 patients (6). This adverse functional septal effect on left-sided stretch was described by Bernheim in 1910 (31). Conversely, right-sided ventricular dilation from either pressure or volume overload will stretch the free wall, increase chamber size, and bow the septum to the left side creating septal hypokinesis, akinesia or dyskinesia and limit its functional contribution to left and right-sided outputs. Perhaps the most obvious, but often unrecognized example was reported by Dexter, when he described the "reverse Bernheim effect" after closing large atrial septal defects causing RV volume overload; left-sided performance improved as the bowed septum became a functional midline structure (32).

Right ventricular dilatation and septum displacement may ultimately lead to annular dilation of the tricuspid valve and alteration of the papillary muscle geometry (to be considered in the next section). The resultant tricuspid insufficiency is often progressive and leads to further decline in RV efficiency. Further decline and compromise of RV function occurs in those patients with elevated pulmonary vascular resistance because of loss of septal function.

The occurrence of septal dysfunction that results from congenital heart disease becomes accentuated if the methods of myocardial protection during surgical correction do not prevent septum stunning. For example, patients with preoperative pulmonary hypertension and normal septal function may develop sudden acute right ventricular failure following successful correction of the underlying congenital heart defect. This septum injury causes hypokinesis or even more advanced damage, but the effects of this injury is not apparent if initial pulmonary artery pressure is not markedly elevated. However, RV failure develops after postoperative episodes of acute pulmonary vasospasm as the septum cannot twist to ensure RV output. Loss of septal twisting places the hemodynamic burden upon the RV free wall, whose function is predominantly a compressive force due to the working transverse muscle from the basal loop. Unfortunately, free wall transverse constriction may be insufficient to generate output against high pulmonary vascular resistance, an action that requires a septum that twists to ensure efficient RV performance.

Septum and atrio-ventricular (A-V) valve function

There is close relationship between the septum and tricuspid and mitral valve function, since the septum anchors the A-V valve annulus and competence is restricted if it stretches during ventricular dilation. The coaptation of valve leaflets is also affected by tethering as a consequence of ventricular stretch. If the attached papillary muscles are displaced in the direction of septal bulging into the opposite ventricular chamber, pre-systolic regurgitation can occur as shown in Figure 8 that displays the underlying anatomic reasons. Mitral regurgitation is evident on the left side as the posterior medial papillary muscle is displaced toward the right side in patients with left bundle branch block. This displacement is sometimes architecturally remedied by biventricular pacing that causes early septal contraction to return in a midline position and thus alters this spatially adverse tethering defect (33). Moreover, A-V valve insufficiency is accentuated by impaired function of the interconnected papillary muscles after septal motion is altered, thereby worsening RV failure.

Septum malfunction and intraoperative findings

The impact of septal malfunction and its role in RV failure is not initially clear from intraoperative visualization of the RV free wall, since the septum is not seen unless viewed by echocardiography. The right ventricular free wall usually contracts normally immediately after removal of the aortic clamp following surgical repair, the right coronary artery is open and the free wall is soft and decompressed. This visual appearance differs from prior descriptions of absence of free wall activity following right ventricular cauterization, and aneurysmal changes after coronary occlusion or free wall / septal separation. Septal malfunction becomes enhanced when bypass is stopped; decreasing free wall contraction develops as the RV chamber is rapidly filled and must now eject against increased pulmonary artery pressure. Right ventricular free wall bulging often appears, when right ventricular dysfunction is severe, and this secondary event is due to the associated, but unrecognized underlying abnormal septal motion.

Right ventricular failure may be severe enough to deliver insufficient blood to the left ventricle, and the left ventricle is consequently under-filled and thereby cannot deliver adequate cardiac output. Belief that the left ventricle is functioning properly during such profound depression is an incorrect analysis, since right ventricular failure camouflages left ventricular dysfunction because of under-filling of the LV chamber. Severity of left ventricular function becomes apparent only when right ventricular output is sufficient to test the left ventricular Starling mechanism so that global dysfunction may escape detection.

The early phases of this surgical predicament are sometimes compounded by the erroneous conclusion that the decompressed RV was well protected but quickly uncovered after high afterload is imposed. The treatment strategies are most often directed at the symptomatic secondary effects of a stretched RV free wall as a sign of RV failure, rather than focused upon the septum that is the primary cause of RV dysfunction. This attitude reflects incorrect reasoning because surgically induced septal dysfunction raises morbidity and mortality when there is preexisting pulmonary hypertension, and reflects an adverse event that may be prevented as described below.

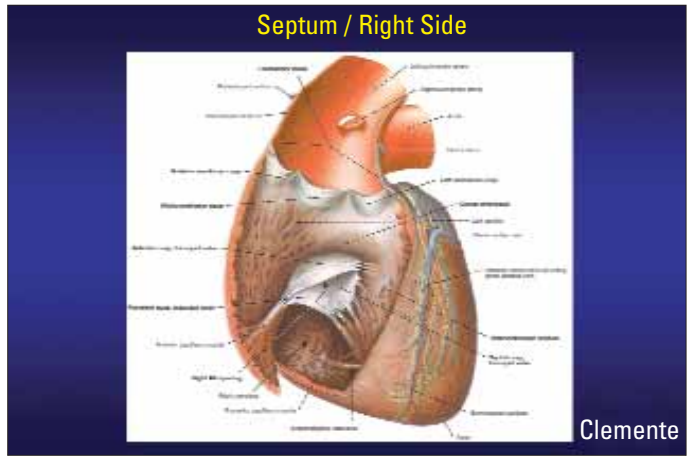

Figure 8. Intraventricular appearance of the septum, attachments of the posterior papillary muscles to the septum wall, and septum cusps to the tricuspid valve. Note that leftward bowing of septum will produce traction upon septum cusp leaflets and alter leaflet coaptation.
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Clinical septum dysfunction and its prevention

Calibration

Quantification of septum dysfunction is done by echocardiography, and Table 1 displays the gradation of septal motion, its movement, and the degree of thickening observed from transesophageal studies that are becoming routine during cardiac procedures. Damage is graded on a progressive scale that correlates the extent of a) contractile motion (normal, mild to severe hypokinesia, akinesia and dyskinesia) , with b) movement (that extends from normal up until thinning with paradoxical motion), and c) observed thickening. For example, muscle motion is expressed as thinning during paradoxical motion with dyskinesia. From a functional standpoint, contractile motion is the most important element rather than the amount of septal thickening, since contractile motion is vital to generating cardiac output during ejection. Conversely, thickening is a less critical variable, and its presence may become quite confusing when evaluating how septal function influences cardiac performance. Two examples are provided which amplify this point and relate to a) left bundle branch block (LBBB) or ventricular asynchrony in heart failure and b) to the recent post operative report in 3292 patients (6). First, normal septal function involves a twisting motion, and this movement disappears during asynchronous contraction during heart failure, and becomes delayed during LBBB. As a result, contractile dysfunction relates to loss of sequential thickening within the asynergically contracting muscle that thickens in an uncoordinated way and thereby provides limited contribution to cardiac performance. Second, normal thickening was observed in the septum that displayed paradoxical motion in the postoperative report by Reynolds (6) (personal communication). However, the thickened septum, bulged into the right side, expresses an aneurysm-like

physiology, which simultaneously detracts rather than contributes to organized and efficient ejection.

Incidence of septal dysfunction and responsible factors

Postoperative septal dysfunction is a frequent result of open- heart surgical repair, and Table 2 summarizes the reported incidence that varies between 30% and 100% in six different centers. Within this cohort, Akins (34) observed a marked contrast between the 100% incidence of septal dysfunction after CABG on bypass compared to 0% incidence after only left anterior descending grafting during off-pump coronary bypass. Echocardiographic evaluation from many centers over a long time interval (1-5) has recognized that septal dysfunction has become an expected postoperative finding after cardiac surgery, as recently reported from a single center that evaluated 3,292 patients (6): paradoxical septal motion was observed in 46-60% of patients with valve disease, and observed after coronary revascularization (CABG) in 34% on bypass, and in 19% of off-pump CABG procedures. The origin in bypass cases was ascribed to differences in the duration of aortic clamping (6).

In the past, the culprit appeared to be cardioplegia, as this septal abnormality was more common after crystalloid approaches, using either antegrade or retrograde delivery (5, 35). Conversely, more normal septal function follows blood cardioplegia, especially with continuous infusion whenever possible (35). The higher incidence of paradoxical septal motion in valve disease versus CABG procedures must be related to either anatomic or physiologic reasons. We previously observed that stretching of the septum in valvular heart disease alters sequential contraction, therefore, establishing a more vulnerable state (perhaps simulating the similar susceptible subendocardial muscle in coronary patients that are ischemic before undergoing different protection methods). Our early evaluation of the importance of protection methods on septal function comes from a limited report of only 11 patients that underwent prolonged aortic clamping for CABG and left ventricular restoration (30) and displayed good postoperative septal contraction that existed despite preoperative bulging, when the integrated cardioplegic approach (defined below) was employed and endoventricular-ventricular rebuilding was done in the beating ventricle. These early observations, suggest that maintenance of normal septal contraction or septal recovery should become the indicator of adequate myocardial protection since normal septum function resulted despite prolonged duration of aortic clamping. Adverse hemodynamic alterations are less likely during off-pump LAD grafting, perhaps explaining the 0% incidence reported by Akins (34) versus a 19% incidence (6) after multiple grafting, which requires more cardiac retraction for exposure of circumflex marginal and posterior vessels. This proposed perfusion/pressure relationship was evaluated in OPCAB patients that undergo intra-aortic balloon counterpulsation; the mechanically augmented diastolic pressure reduced hemodynamic changes during cardiac retraction for exposure and improved clinical results (36).

Table 1. Echocardiography criteria for septal dysfunction (7), where septum motion, movement and thickening are described as shown in image

Septal Wall Motion	Movement	Thickening
Grade I (Normal)	Normal	>30%
Grade II (Mild HK)	↓	10-30%
Grade III (Severe HK)	↓___ ↓___ ↓	<10%
Grade IV (Akinesis)	None	None
Grade V (Dyskinesis)	Moves out during systole	Thins during systole

Table 2. Postoperative septal dysfunction as reported in enclosed studies

Study	Year	Number of patients	Incidence, %
Aikins (34)	1984	11	100
		11 (no CPB)†	0
Schroeder* (1)	1987	324	70
Feneley (2)	1987	16	57
Lehmann (3)	1990	21	100
Wranne (4)	1997	19	86
Chouraqui** (5)	1997	21	33
Reynolds (6)	2007	2972	40

† LAD graft only
* 20% persist for 1 year
** Normal Thallium scan in paradoxical patients
CPB - cardiopulmonary bypass, LAD - left anterior descending artery

Prevention

Temporary ischemia and subsequent reperfusion or septal stunning is the principal mechanism responsible for septum dysfunction, as these events follow aortic cross-clamping and reperfusion, or occur after perfusion pressure is reduced during cardiac retraction and reperfusion follows return of hemodynamic function when normal cardiac position is restored. A prerequisite is absence of an excitation-contraction abnormality like left bundle branch block, asynchrony with congestive heart failure with asynergy and late septal contractile stimulation. This conclusion about stunning is amplified by review of how different cardioplegia methods alter this adverse consequence (5, 35), as well as from observations regarding a distinct relationship to the duration of aortic clamping (6). These causative observations, coupled with capacity of a stretched chamber to enhance vulnerability, as occurs in patients with dilated hearts secondary to valvular heart disease or dilated cardiomyopathy sets the stage for evaluating whether septal dysfunction can be avoided by altering the methods of myocardial protection during surgery.

The effects of the integrated blood cardioplegia method that we initially introduced in 1995 has been previously reviewed in a study of 1492 patients (from 4 centers) (37, 38). We will now present recent data on septal function in a consecutive series of 119 cardiac surgical patients (from one center) where the echocardiographic criteria of septal function described in Table 1 were used.

The "integrated blood cardioplegia" method synthesizes the benefits of different protection approaches, rather than rigidly adhering to one method and then pitting it against another technique. For example, warm blood cardioplegia induction is used

and a warm blood cardioplegia reperfusate is given before removing the aortic clamp, but intermittent cold blood cardioplegia is employed during periods of ischemia. Delivery methods include antegrade, retrograde, and simultaneous antegrade and retrograde perfusion as previously described (37). Continuous cold infusion of a non-cardioplegic solution with citrate phosphate dextrose (CPD), trishydroxylmethylaminomethane (THAM), magnesium and mannitol is delivered for nourishment during construction of proximal anastomoses and while placing sutures into the valve annulus, as ischemia is not needed because visualization is not impaired at these times (39). The cardioplegia solutions are fully described in our prior publications (38), and glutamate and aspartate supplementation is used in warm solutions to enhance oxidative metabolism (40). Cardioplegia is delivered as soon as total bypass insures adequate venous drainage by collapse of the pulmonary artery, and CPB is discontinued within 5-10 minutes after removing the aortic clamp while delivering a small dose of dopamine (2.5 micrograms/kg/min) to improve calcium flux efficiency. The strategies for delivery of this integrated method in different lesions are fully described elsewhere (38, 39).

This integrated method was applied in a consecutive series of 119 patients undergoing a spectrum of procedures that include CABG (n=85 or 71.4%), or valve procedures, left ventricular restoration and aortic arch procedures (n=34 or 28.6%), with a cross clamp time averaging 58.4±22.8 minutes, ranging from 24-157 minutes. Septum wall movement was scored as described in Table 1, and averaged 1.2 pre operatively (indicating normal to slight hypokinesia). The post operative score was 1.1 (Table 3), demonstrating this method avoided septal damage. Figure 9 documents a consistent finding in patients that undergo left ventricular restoration and simultaneous CABG; preoperative bulging septum recovers its normal function following application of our method of protection and returns to the mid line by the SVR procedure (41).

Right ventricular failure did not develop in any of these 119 patients, and the normally contracting septum is considered the central reason for this outcome (41).

This demonstration of normal septum function following integrated blood cardioplegia application differs from conventional reports (1-6), and implies that our technique avoids reperfusion damage. Septal motion must be routinely monitored during cardiac procedures and becomes an indicator of adequate cardiac protection. Our analysis does not imply that others must use the integrated method, but rather documents the importance of using echocardiography to determine if a normal preoperative septum develops dysfunction postoperatively. Demonstration of septal damage implies inadequate myocardial protection. Selection of alternative protection methods is determined by the surgeon, but acceptance of septal damage is an unsatisfactory end-point for any methods that render approximately 40% of ventricular muscle mass dysfunctional following correction of the cardiac lesion.

Conclusions

Postoperative septal dysfunction is the underlying reason for right heart failure after cardiac surgery because this adverse event impairs the twisting function that is essential for RV ejection against increased pulmonary vascular resistance. Cardiac structure / function relationships show the septum is spatially composed of helical oblique fibers responsible for developing this twisting action, rather than circumferential fibers that predominantly constitute the RV free wall and constrict or compress the chamber for a bellows effect. The septum constitutes approximately 40% of the mass of the heart and myocardial stunning is the genesis of its dysfunction in the absence of a excitation-contraction abnormality. Routine monitoring of septal function is essential during cardiac surgery, and evidence of septal dysfunction should lead to reevaluation of protection methods. Integrated blood cardioplegia prevents septal dysfunction after cardiac surgery and recognition of this finding should encourage evaluation of its widespread use or earmark selection of another technique that avoids this preventable myocardial injury.

Table 3. Postoperative septum function is 138 consecutive patients, displaying the score (as calibrated from Figure 1), and showing mean and range of intervals of aortic clamping

Integrated blood cardioplegia score	
Number of patients	119*
Preoperative	1.2
Postoperative	1.1
Aortic clamp time, min	58.4 ± 22.8 (24-157)

• * - consecutive patients
• No right heart failure

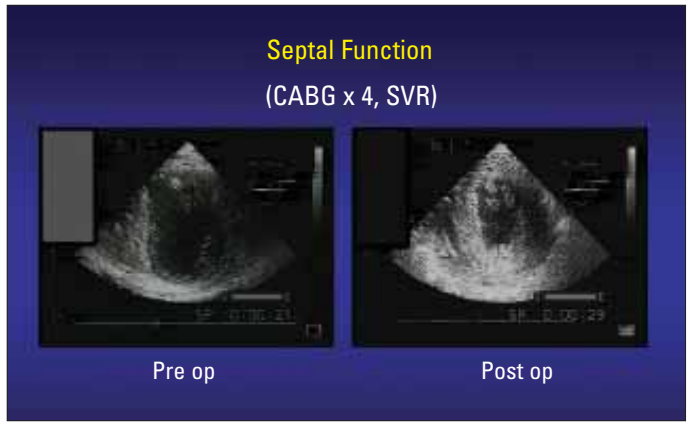

Figure 9. Recovery of septum function after left ventricular restoration (SVR) and simultaneous coronary artery bypass suregry (CABG); preoperative bulging septum recovers its normal function following application of our method of protection and returns to the mid line by the SVR procedure.
preop - preoperative, postop - postoperative

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