



# Mitral Valve Repair: The Chordae Tendineae

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## Abstract

Repair of the mitral valve is the treatment of choice for mitral valve regurgitation when the anatomy is favorable. It is well known that mitral valve repair enjoys better clinical and functional results than any other type of valve substitute. This fact is beyond doubt regardless of the etiology of the valve lesion and is of particular importance in degenerative diseases.

This review analyzes the most important advances in the knowledge of the anatomy, pathophysiology, and chordal function of the mitral valve as well as the different alternatives in the surgical repair and clinical results of the most prevalent diseases of the mitral valve. An attempt has been made to organize the acquired information available in a practical way.

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## Introduction

The mitral valve (MV) is a very complex structure composed of the anterior (AML) and posterior (PML) leaflets, the chordae tendineae (CT), and the papillary muscles (PPMM), all of which work on a very harmonious basis to ensure an appropriate opening and closing of the left atrioventricular orifice. Although the anatomy and function of the CT have been well known for decades, there are still some unknowns regarding their delicate microstructure, which heavily influences their function. This lack of structural knowledge and its functional impact as the consequence of different diseases (rheumatic, degenerative, ischemic, congenital, infectious, etc.) renders the durability of surgical chordal repair uncertain in specific circumstances.

### Anatomy of Chordae Tendineae

The main function of the CT is to transmit the contraction

and relaxation of the PPMM during the cardiac cycle, thus ensuring the closing of the leaflets. There are other important functions like the maintenance of the ventricular architecture and its efficient function in maintaining the cardiac output. The CT must have a high degree of elasticity, strength, and resistance to traction so as to be able to support an approximate load of 75 tons a day in the adult heart. The CT are composed of collagen and elastin fibers in parallel. Millington-Sanders et al. described the composition of the CT in multiple elastin and collagen layers with a central dense collagen and an outer layer of endothelial cells.<sup>1</sup> An experimental study in sheep confirmed that the CT had a central dense zone, a spongiosa, and an endothelial cell lining.<sup>2</sup> More recently, it has been discovered that there are blood vessels in the spongiosa that originate from the PPMM and feed the leaflet tissue. An increase in the collagen synthesis and the proliferation of fibroblasts is a fundamental process in the ability of the CT to resist tension, especially in the marginal CT. Experimental studies have found an

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increased concentration of DNA, elastin, and collagen in the marginal CT in comparison with the medial and basal CT, thus confirming their importance in the maintenance of valvular coaptation and the importance of a constant re-repair with new collagen to avoid mechanical deterioration.<sup>3</sup>

Depending upon their morphology and distribution, the CT have been classified especially according to their site of insertion on the leaflets.<sup>4</sup> There is a wide variety in the distribution, form, and configuration of the CT, and there is no actual consensus on terminology. Each leaflet is supplied by the CT from both PPMM. The anterolateral PM holds the CT for the left half (surgeon's view) of both the AML and PML (A1-left half A2 – P1-left half P2), whilst the posteromedial PM supplies the CT to the right half of both leaflets (A3-right half A2 – P3-right half P2). There are some CT inserted in the free leaflet margin, the so-called marginal or primary CT. They ensure valve coaptation and, therefore, their pathology impacts on their function. In the AML, there are 2-4 thick and resistant CT, called medial CT as they originate in the medial aspect of the ventricular side of the leaflet ("strut chords"), providing resistance to the leaflet at closing during systole and thus avoiding prolapse. These CT have no direct influence on valve coaptation; however, it has recently been discovered that they have an important role in the tunnel-shaped configuration of the valve at the inflow and outflow tracts. In this way, they favor the mitral and aortic flows.<sup>5</sup> Very close to the annulus, with some variations in form and number, are the basal CT, which have the mission of preserving the ventricular architecture and maintaining the PPMM-mitral annular union. The commissural CT are dedicated to valve closure through the coaptation of the valve segments (A1-P1 and A3-P3). It is obvious that every CT has a different mission in valve dynamics, with the marginal CT of the AML and the commissural CT playing the most important role in valve closure. This must be taken into account at the time of surgical valve repair that severing certain CT might have a negative impact on the valve coaptation.

### ***Surgery of Chordae Tendineae***

It is surprising to see that in the majority of current textbooks and publications, some reconstructive techniques that could be considered obsolete are still analyzed. In the last decade, there has been a dramatic change in the CT reconstruction, and classical approaches (shortening, transposition, flip-over, fenestration, etc.) have been replaced by resection and replacement (PTFE) of the CT. However, these classical techniques are still in use and their results are, therefore, analyzed herein.

#### ***1. Chordal Resection***

Resection of the marginal CT, especially those of the PML

and the leaflet segment where they are inserted (quadrangular resection), is the most frequently performed technique, first described by Carpentier et al.<sup>6</sup> It was later modified by the sliding technique, very useful in cases of extensive leaflet resection. The results of this technique are excellent and stable in the long term. It is considered the gold standard in mitral repair for valve regurgitation in degenerative diseases.

Triangular resection of the AML does not yield as satisfactory a result as with quadrangular PML resection. Nonetheless, some authors have reported similar results in the long term with a an actuarial 10-year freedom from reoperation for mitral failure after AML triangular resection of  $93 \pm 5\%$  and  $96 \pm 3\%$  after PML quadrangular resection.<sup>7</sup> Saunders et al. recommend AML triangular resection in the CT disease as the method of repair<sup>8</sup> but a number of surgeons recommend this technique in the cases of Barlow's disease with excess AML tissue or in endocarditis lesions with leaflet involvement<sup>9</sup> In current times, the role of AML resection is challenged by newer techniques<sup>10</sup> and its predictive value might be reinforced or lessened by the use of more accurate imaging techniques like 3D echocardiography.<sup>11</sup>

#### ***2. Chordal Shortening***

This technique consists of incorporating in the PPMM the redundant part of the elongated CT. In general, the PPMM are severed in their middle aspect, where half of the chordal segment is shortened and is thereafter incorporated as the incision in the PPMM is sutured and closed. In 1990, Carpentier et al. published satisfactory long-term results in a series of 89 patients operated on with this technique.<sup>12</sup> Gregori et al. described a technique of chordal shortening by approaching the redundant segment at the level of the AML implantation.<sup>13</sup> This repair technique consists of performing a small incision in the implantation zone of the marginal CT close to the free margin. The elongated CT are sutured to the incision and fixed to the atrial aspect of the AML. Of their 22 patients, two had an early reoperation and there was almost no long-term follow-up. Chordal shortening has worse results than transposition<sup>14</sup> or replacement.<sup>15</sup>

#### ***3. Chordal Transposition***

In this technique, a PML marginal CT with a leaflet segment is inserted and sutured to the prolapsing segment of the AML. It is used for the repair of the rupture or elongation of the AML marginal CT. It is necessary to perform a quadrangular resection of the AML, including the marginal CT, which will be used to replace the ruptured AML CT. This has been popularized as the flip-over technique; it is reproducible and durable in the midterm. Satisfactory results have been described with a 90% freedom from reoperation for mitral failure at 5 years.<sup>15-17</sup> These are better results than chordal shortening. Recent experimental work confirms

the benefits of translocation even in the ischemic setting.<sup>18</sup> Further clinical work, including newer technical options that will stand the test of time, is required to confirm the benefit of chordal transposition.<sup>19, 20</sup>

#### 4. Chordal Replacement

Since the first open heart surgery, a variety of materials have been drawn upon for repair. Artificial materials such as nylon, silk, and Teflon and biological tissues such as autologous and heterologous pericardium have been used for the replacement of the ruptured or elongated CT with suboptimal results. In 1986, Vetter et al.<sup>21</sup> and Revuelta et al.<sup>22</sup> showed that polytetrafluoroethylene sutures (PTFE, WL Gore and Assoc Inc., Flagstaff, Arizona, USA) were effective replacement materials for the CT inasmuch as they acted as a matrix on which a new chord was generated and preserved the same functional properties. This has become an internationally popular and accepted technique for the surgical repair of the CT and is currently deemed the technique of choice for the CT. PTFE neochord is covered by a sheet formed by collagen tissue and endothelial cells; this is a structure similar to that of the native CT and has the advantage that neither calcifies nor ruptures with an additional resistance to infection and low incidence of thromboembolism. The most important drawback of this technique is the difficulty in determining the appropriate length of the neochord. Recent years have witnessed the introduction of some reproducible techniques.<sup>23-25</sup> Long-term results by David et al.<sup>26</sup> were excellent, supporting the use of neochords in degenerative diseases and in fibroelastic deficiency with a small PML. More recently, a systematic review has looked into the evolution of the replacement of the CT in the context of repair,<sup>27</sup> and some other data have supported its use at any leaflet level.<sup>28</sup> The issue of the measurement of the length of PTFE neochords is still a matter of interest.<sup>29</sup>

In Barlow's disease with a very redundant PML, some authors prefer a wide resection and sliding plasty instead of replacing the CT with PTFE. Severe myxomatous mitral regurgitation is traditionally corrected with quadrangular PML resection. Nigro et al.<sup>30</sup> recommended a simple repair of such cases with PTFE and leaflet resection. Approximately, 92% of the operated patients remain asymptomatic with no or mild mitral regurgitation. Duebener et al.<sup>31</sup> reported that PTFE CT replacement allowed for the correction of regurgitation with no ring. In a group of 160 patients operated on with this technique, more than 90% were free of reoperation or significant mitral regurgitation two years after surgery.

#### 5. The Alfieri Technique

The Alfieri technique or edge-to-edge technique was

introduced in 1992.<sup>32</sup> This is a very simple technique of CT repair, especially in complex cases involving the AML or both leaflets when other techniques fail. When there is annular dilatation in Barlow's disease with a redundant tissue, there is a chance of suboptimal results with anatomic techniques. The Alfieri technique or Alfieri stitch is a functional repair. Some authors have shown that this is a stable technique in the short term producing good results in Barlow's disease with reduced morbidity and mortality (hospital survival  $97.5 \pm 2.4\%$ ) with  $94 \pm 4.4\%$  freedom from reoperation and  $90.6 \pm 5.1\%$  freedom from moderate-severe mitral regurgitation in the fifth postoperative year.<sup>33</sup> Alfieri et al.<sup>34</sup> described their experience with the CT repair in 150 patients with degenerative diseases with a 92% freedom from reoperation at nine years. Furthermore, this technique treats successfully the systolic anterior movement (SAM) of the mitral valve following mitral repair.<sup>35</sup>

It is likely that the actual value of the Alfieri stitch has been probably overestimated and that this technique alone is, of course, not appropriate to deal with the vast majority of cases of mitral regurgitation. This was addressed by Alfieri himself in a recent editorial, in which he confirmed the need for a ring annuloplasty to provide the stability of the repair in the long term.<sup>36</sup> It, therefore, seems that this technique, far from being a primary technique, is a part of the surgical armamentarium that helps to complete certain repairs but that should be contemplated as part of some complex repair. In a nutshell, it cannot replace the techniques for anatomic repair.

Currently, the value of the Alfieri technique lies primarily in the fact that it is paving the way for some future catheter-based techniques to approach functional mitral regurgitation. In this regard, the contributions of the Alfieri group ought to be carefully contemplated in the context of on-going clinical trials.<sup>37, 38</sup> The recently published EVEREST II trial is the first trial of some size in which the percutaneous technique is compared to surgery in high-risk patients with acceptable immediate results.<sup>39</sup> In any case, it seems very clear that surgery continues to be the gold standard in surgery for mitral regurgitation despite different considerations given to extremely high-risk patients.<sup>40</sup>

#### 6. Partial Mitral Homograft

In patients with complex chordal involvement, congenital diseases, endocarditis, and degenerative or rheumatic lesions where the marginal and/or commissural CT are ruptured or elongated, they can be repaired with the implantation of a cryopreserved mitral homograft of the involved segment and its subvalvular apparatus. Experimental and clinical results were initially satisfactory<sup>41, 42</sup> and they were later confirmed by Acar and his group<sup>43</sup> in a series of 39 patients who received a partial homograft from 1993. The majority of the study population were rheumatic patients; and at 8 years,



they showed 81% freedom from events and reoperation. This is a useful technique when there is severe commissural involvement as seen in endocarditis or rheumatic disease as Aubert et al. showed in a series of 10 patients.<sup>44</sup>

For all these success stories, the rate of structural failure has been substantial before 10 years and the concept has been revisited. Despite initial additional experiences,<sup>45</sup> results have not met the expectations. This and the scanty experience reported so far render this surgical option less popular than it was 20 years ago (Olivito S, Lalande S, Nappi F, Hammoudi N, D'Alessandro C, Fouret P, Acar C. Structural deterioration of the cryopreserved mitral homograft valve. *J Thorac Cardiovasc Surg* 2011.). As a surgical option, repair of the atrioventricular valves with and without the CT involvement has been positively received by the community in the past two decades in spite of some shortcomings, which must be addressed in the future.<sup>46</sup>

### ***Repair of Chordae Tendineae according to Etiology of Mitral Lesion***

Since the early description of the surgical repair of the mitral valve by Carpentier,<sup>12</sup> it has been clear that not only should we employ different techniques according to the etiology of the valvular lesion but also we should heed the fact that the probability of repair is not the same for different lesions: whilst degenerative lesions have the highest chance of success in surgical repair, rheumatic lesions are the least amenable to repair.

#### ***1. Degenerative Mitral Insufficiency***

Degenerative diseases are the most frequent cause of mitral insufficiency in the so-called developed countries. Over 90% of these lesions can be repaired with the techniques described by Carpentier and others. In degenerative diseases, the mitral valve loses coaptation due to annular dilatation and rupture or elongation of the CT, especially the PML marginal CT. The usual technique is PML quadrangular resection of the prolapsed segment. When the lesion involves more than 1.5 cm of the leaflet, sliding plasty is recommended to reduce the risk of SAM. When the CT belong to the AML, this lesion may be corrected with CT transposition, PTFE neochord replacement, or the Alfieri stitch. As was stated before, the shortening of the CT reduces durability. On the other hand, it should be taken into account that annuloplasty must be a part of any repair procedure. It is likely that other than the type of the ring, the secret of repair is an appropriate repair plus annuloplasty. Every surgeon should use the ring with which he/she feels more comfortable.

Data from large series<sup>47</sup> show that 93% of the patients are free from reoperation for significant mitral insufficiency at 10 years. The risks of reoperation are higher when the lesion involves the AML, when shortening is performed,

when no annuloplasty is performed, and when intraoperative transesophageal echocardiography (TEE) is not used. In the past fifteen years, TEE has emerged as a fundamental tool to address any type of cardiac surgery and with particular emphasis on any type of valve surgery, replacement, or repair.<sup>48</sup> For Gillinov et al.,<sup>47</sup> the resection of the CT and the corresponding PML with an associated annuloplasty yielded optimal results with a 98% durability of repair at 10 years. David et al.<sup>8</sup> reported that the AML prolapse begotten by the marginal CT involvement was the only independent predictor of reoperation at twelve years after mitral repair (AML:  $88 \pm 4\%$  vs. PML:  $96 \pm 2\%$ ). Furthermore, a statistically significant difference ( $p$  value = 0.001) was detected in the freedom from moderate-severe post-repair mitral insufficiency (AML:  $65 \pm 8\%$  vs. PML:  $80 \pm 4\%$  at twelve years).

The main issue in current times with mitral valve repair in degenerative diseases caused by prolapse is that the information collected in the past twenty years confirms surgery as the gold standard. This is a fact. There is a trend towards minimally invasive approaches on the strength of recently published information with very positive results in terms of morbidity and mortality with excellent results at follow-up, comparable to repair performed through median sternotomy. These data bear out the notion that mitral valve repair should perhaps be indicated earlier than current agreement establishes in an attempt to avoid the detrimental effects on cardiac function and decrease the risk of mortality at follow-up without surgical intervention. This has been addressed in recent publications.<sup>49,50</sup>

The above-mentioned comments on the surgical techniques have opened a discussion on the eventual changes that surgery of the mitral valve may see in the future. Minimally invasive mitral valve surgery using peripheral cannulation is a reality and almost a routine in large-volume centers.<sup>51</sup> On the back of these excellent results, a step forward has been proposed by a number of selected institutions. This takes into account the performance of robotically-assisted operations, which have thus far yielded excellent results in experienced hands.<sup>52,53</sup> Hospital mortality is within the range of less than 1% in selected cases and type of disease; and in terms of acute surgical results, robotic surgery seems to match transternal surgery with an appropriate case selection.<sup>52,53</sup>

As the transcatheter techniques for mitral valve repair are in the early phases of experimental and clinical application, the results of surgery for mitral valve repair have vital significance. It is extremely difficult to match surgical results through any approach, transternal or minimally invasive, by transcatheter techniques because of the very low rates of morbidity and mortality and the excellent long-term results regarding freedom from reoperation and the degree of residual mitral insufficiency. Hence, the results of prolapsed repair are bound to be instrumental in setting standards of care against which transcatheter techniques must be compared if

a fair “competition” is to be established in the near future.<sup>54</sup> <sup>55</sup> This is warranted, in great part, on account of the external pressure by the biomedical industry, which allocates massive financial and human resources for developing devices for percutaneous mitral valve repair.

## 2. Rheumatic Mitral Insufficiency

Rheumatic diseases provoke fibrosis and deformity of the subvalvular apparatus, which in turn leads to the CT fusion and rigidity and subsequently loss of valvular mobility (Carpentier type IIIa). More experience is required in the repair of rheumatic valves as it is technically challenging due to the complexity of the subvalvular lesions. In the majority of cases, it is necessary to simultaneously perform a number of reconstructive techniques. However, it is known that the CT repair has worse results than in the case of degenerative diseases.<sup>56</sup> Our own experience with mitral valve repair in rheumatic diseases goes back to 1974 and clinical results have been satisfactory in the long term.<sup>57, 58</sup> The key issue in any repair, including the CT, has been ring annuloplasty, which provides the repair with stability.<sup>58</sup>

## 3. Congenital Mitral Insufficiency

The pathology of the mitral subvalvular apparatus in a number of congenital heart diseases is so diverse that multiple types of repair like the CT shortening, medial splitting of the PPMM, the CT fenestration, and resection or partial mitral homograft have been attempted. Currently, congenital mitral insufficiency due to the CT pathology is better repaired with the Carpentier technique (leaflet and corresponding CT resection), including PTFE CT replacement. Minami et al.<sup>59</sup> reported satisfactory results in the midterm with 89.5% freedom from reoperation and no significant residual mitral regurgitation at 8 years in a series of 39 operated children. It is not recommended to use mitral homografts in this population owing to very early retraction and calcification at a mean follow-up of 4.1 years. In this series by Chauvaud et al., all the patients were reoperated on due to stenosis and insufficiency.<sup>60</sup> In the past few years, the interest in collecting follow-up data in the pediatric population undergoing mitral valve reconstruction for a variety of conditions has yielded interesting results. Most of the time, the disease involves the annulus, and the biodegradable option advocated by Kalangos et al.<sup>61</sup> is a reality and its results must be, accordingly, taken into account. A biodegradable ring for repair is a very attractive option in the growing child, and the results from this experience confirm that outcome is good and the children may grow normally, although reoperation might be expected in the long term. There is also information on the long-term results for pure insufficiency beyond 10 years and this is excellent news in children and young teenagers considering the life expectancy in this population.<sup>62</sup> As all

types of repairs try to avoid replacement, even the Alfieri stitch has been contemplated in congenital mitral disease.<sup>63</sup>

## 4. Ischemic Mitral Insufficiency

Functional ischemic mitral insufficiency is a complex disease with poor prognosis. Its anatomic and pathophysiological mechanisms are still a matter of intense debate despite significant advances in the last decade in the knowledge of this entity. It has been reported a 38% five-year actuarial survival of these patients with 3-4/4 degrees of insufficiency without surgical treatment. In addition to a reduced life expectancy, these patients have a reduced quality of life with multiple admissions for heart failure and an associated very high socioeconomic cost.<sup>64</sup> Myocardial dysfunction due to ischemic heart diseases generates changes in the left ventricular geometry and the components of the mitral valve complex. There is decreased leaflet mobility (Carpentier type IIIb) and annular dilatation, leading to loss of coaptation.<sup>65, 66</sup> The mitral CT represent force vectors deforming the antero-posterior annular distance, increasing the inferior leaflet retraction, increasing the distance between the PPMM, and an increasing the distance between the mitral annulus and the implantation of the PPMM. Furthermore, an increase in the intertrigonal distance and a decrease in the mobility of the left ventricle are also seen.

This type of mitral insufficiency is difficult to repair as some of the mechanisms involved are still not fully known. Some devices designed for annuloplasty (asymmetric rings, cardiac splint, etc.) and the use of prosthetic restrictive rings are bound to improve surgical results. The asymmetric ring specifically addressed the posterior-lateral valve region (posterior commissure and P3) by decreasing the traction (tethering) of the marginal and commissural CT.<sup>67</sup>

Cutting the secondary CT, also known as medial CT, has been attempted to reduce the incidence of residual regurgitation.<sup>68</sup> Be that as it may, this technique does not consistently avoid postoperative regurgitation.<sup>69</sup> At the moment, there still exists controversy with regard to pathophysiology and the optimal management of ischemic mitral regurgitation. Since this seems to be more a ventricular disease than a pure valve disease, the actual role of CT treatment might be of reduced impact as it has already been addressed, together with a number of difficulties in terminology and definitions.<sup>70</sup> It also seems clear now that the results are mostly related to patient factors than to treatment options.<sup>71</sup> Given such contributions, the specific issue of repair versus replacement does not seem be critical in this setting and, as a result, mitral valve replacement and repair are not so different as to refer to repair as the gold standard.<sup>72, 73</sup>

## 5. Functional Mitral Insufficiency

Dilated cardiomyopathy and end-stage heart failure lead



to the most frequent forms of functional mitral regurgitation; this is an independent predictor of mortality. There are multiple surgical options, including valve replacement, and several types of annuloplasty. Restrictive mitral annuloplasty is the most frequently used. This entails the implantation of a semi-flexible complete mitral ring of up to two sizes smaller than the expected size for the regular ring measurements at the level of the intertrigonal distance. This technique was initially described by Bolling et al. in 1995.<sup>74</sup> Since the year 2000, different authors have published clinical results with this downsizing annuloplasty. At twelve-months' follow-up, there was a recurrence of mitral regurgitation degrees 3-4/4 in about 30% of the patients, amounting to 50-70% at five years.<sup>75</sup> This is due to multiple factors, the most important of them being the PML tethering due to the increasing distance from the corresponding PM. Then, despite an initially satisfactory functional result of restrictive annuloplasty, the progressive remodeling of the left ventricle leads to an additional displacement of the PPMM with tethering of the PML and mitral regurgitation. This fact continues to be a critical issue in long-term results and has been addressed in a recent series of 104 patients who underwent repair for non-ischemic dilatation.<sup>76</sup>

Duran introduced the concept of mitral valve repair with a double ring. A flexible annuloplasty ring is performed and a second ring is implanted around the base of both PPMM for approximation. Neochords are also implanted from the PPMM to both trigones. With these techniques, the left ventricular geometry is expected to improve.<sup>77</sup> Furthermore, by keeping the distance between the PPMM constant, it has been suggested that the absorption of energy by the PPMM would be helpful in valve coaptation; this was later tested in the animal model.<sup>78</sup> The scanty literature available confirms good results in the control of regurgitation with the reduction of tethering because the absence of the PPM displacement does not add extra tension on the CT and, therefore, on the leaflets.<sup>79</sup>

## Conclusions

The mitral valve is a complex structure with a number of components. There is a significant amount of accumulated knowledge on the mechanisms whereby regurgitation occurs. Nonetheless, as failure may develop through any of these components, the therapeutic approach to the mitral valve still entails serious difficulties.

In terms of the impact of the CT on the valve function, it is clear that the CT play a fundamental role in leaflet coaptation. Attempts to treat the mitral valve focusing on the subvalvular apparatus and specifically the CT have been numerous and diverse. From the information garnered in the past three decades, it seems clear that the type of disease heavily influences the surgical results. Consequently, degenerative

diseases are associated with optimal results with respect to the treatment of the annulus and the CT.

Other types of CT diseases yield worse results. This is the case of rheumatic valve disease, in which the CT involvement leads to heavy fibrosis and shortening, rendering repair extremely difficult and often necessitating valve replacement. Hence, suboptimal results might be expected, although it is worth trying in younger age groups.

Finally, PTFE neochords have represented a step forward in the repair of the CT according to the type of disease. The option of the CT replacement has been already tested over time and the clinical results are encouraging in the short and mid terms. Ischemic and functional regurgitation are still a matter of intense debate and controversy owing to the multiple factors involved, leaving less room for treating the CT because these are mostly ventricular diseases.

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