The problem is not what you see on intraoperative echocardiography; it is what you do not see. Intraoperative transesophageal echocardiography and 3-dimensional (3D) echocardiography provide useful information for the surgeon performing mitral valve surgery, but they are not indispensable. We should consider the outstanding results of the pioneer of mitral valve repair, Professor Alain Carpentier. A report of very late results (>20 years) of the earliest series (1970–1984) of mitral valve repair is informative.1 Even without the availability of intraoperative transesophageal echocardiography, the late results were outstanding. At 20 years, freedom from reoperation was 96.9% for patients with posterior leaflet prolapse and 86.2% for patients with anterior prolapse. At the last follow-up (median, 17 years) 15% had moderate or worse mitral regurgitation. An experienced mitral valve surgeon can achieve durable high-quality results without any echocardiography, so 3D echocardiography is not essential.

Response by Tsang and Lang on p 658

What is essential for mitral valve surgery? The fundamental elements from the surgical standpoint are the same whether the procedure is performed through a sternotomy or a minimally invasive incision or is robotically assisted. Achieving good surgical exposure is paramount.2 Numerous surgical techniques, including the type and location of venous cannulation, the atrial incision, retraction of the atrial wall, sutures to help rotate the valve and improve visualization, and occasionally the use of an instrument pushing from outside the heart to facilitate exposure of commissures or the anterior leaflet, are routine practice to optimally visualize the valve. Unless the surgeon is expert in the first step of the procedure, results will be compromised. A perfect 3D echocardiography image of the valve will not compensate for poor exposure. Although real-time 3D color echocardiography is useful, there is nothing more realistic than real-time 3D color visualization through 2.5-power loupes by the operating surgeon. In addition, the entire subvalvular apparatus can be examined by the surgeon, including subtle pathology of the chords and leaflet that may not be apparent on 3D echocardiography. Three-dimensional echocardiography can visualize the valve during the entire cardiac cycle, but for patients with mitral regurgitation, the surgeon is concerned primarily with the appearance and function of the valve in systole. Inspection of the valve with the saline test, that is, pressurizing the left ventricle with saline (or cardioplegia), is therefore paramount. Once the ventricle is pressurized, the abnormal areas of coaptation become evident. Along with exposure and careful inspection, a thorough understanding of the pathology such as the Carpentier

The opinions expressed in this article are not necessarily those of the editors or of the American Heart Association.

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classification of types I, II, IIIa, and IIIb is mandatory.\textsuperscript{3} Beyond this basic understanding, the surgeon needs to be aware that mixed pathologies may occur, and some patients have \textgreater\ 1 disease process and lesion. These valves may have a confusing combination of prolapse in 1 area, restriction in another, and annular dilatation.

Overreliance on intraoperative 3D echocardiography findings is a potential pitfall. Resection or other reconstruction will change how the valve looks, how it closes, and how it functions, and the annuloplasty ring changes valve orifice and therefore coaptation. For instance, the most basic mitral valve repair, resection of a P2 prolapsed segment, may significantly alter the valve. The indentations that separate the scallops (P1 from P2 and P2 from P3) may open and become more prominent after resection. Echocardiography may not have detected a jet from these indentations, but after resection, a jet may appear, potentially causing residual mitral regurgitation. Residual mitral regurgitation is uncorrected from the repair, whereas recurrent mitral regurgitation refers to mitral regurgitation that develops later after repair. The use of artificial chords (neochords) without resection will also change the way the valve closes and may make other valve lesions more prominent, which may lead to residual mitral regurgitation.\textsuperscript{4, 5} The neochords may be too short (leading to restricted leaflet motion) or too long (leading to residual prolapse) with residual mitral regurgitation. Recent experience using foldoplasty without resection also changes the look and function of the valve leaflets.\textsuperscript{6, 7} Considering the variety of lesions, it is essential that the surgeon understand more than the basics of mitral valve repair to achieve a good track record because advanced techniques may be required unexpectedly if the echocardiography does not identify associated pathology.\textsuperscript{8}

The lesion must be thoroughly repaired. When the leaflet is reconstructed, the surface should be made as smooth as possible so that the opposite leaflet does not coapt against an irregular surface, leading to residual small jets of mitral regurgitation. The height of the leaflets and size of the annuloplasty need to be precise to avoid systolic anterior motion.\textsuperscript{9, 10} An effective orifice of the mitral valve must be maintained without creating mitral stenosis. It is essential that the saline test be performed after repair. Postrepair testing may reveal small residual jets that require attention, leaflet asymmetry with maldistribution of stress, residual prolapse, restriction, or stenosis from the technique. The overall appearance of the valve is important. If \textgreater\ 50\% of the visible area is posterior leaflet during the saline test, then the likelihood of systolic anterior motion is high. With the use of the saline test after repair, very rarely should surprises be seen with intraoperative transesophageal echocardiography when weaning from cardiopulmonary bypass.

Preoperative echocardiography can identify patients with very complex pathology that will pose a challenging repair such as those with endocarditis or Barlow disease with bileaflet prolapse or ruptured chords. An important pitfall, however, is 3D echocardiography oversimplification of the pathology. This has not been the subject of reviews, surgical series, or echocardiography articles but is not uncommon in a busy valve repair practice. The following case is used to illustrate some of those pitfalls.

**Case Example**

A 50-year-old man was diagnosed with a new murmur and fatigue. Evaluation identified severe mitral regurgitation, ruptured chords involving the middle scallop (P2) of the posterior leaflet, normal left ventricular function, and trivial tricuspid regurgitation. It was anticipated that this would be a straightforward mitral valve repair, with the chances for repair approaching 100\% (We never quote a patient a 100\% chance for success). Intraoperative 3D echocardiography (Figure 1 and Movie I in the online-only Data Supplement) clearly demonstrated ruptured chords involving P2 by both 2-dimensional and 3D images (Figure 2 and Movie II in the online-only Data.
Supplement). Additional views from 3D echocardiography indicated no associated anterior leaflet pathology (Figure 3A–3C and Movie IIIA–IIIC in the online-only Data Supplement). The surgical findings confirmed extensive ruptured P2 chords that were managed with a conventional trapezoid resection and posterior leaflet reconstruction to adjust the height of the leaflet to one half of the height of the anterior leaflet. The resected P2 segment was very tall (25 mm by intraoperative measurement) and bulky. The repair was tested, and an isolated area of prolapse at A1 near the border with A2 had been hidden and not appreciated on echocardiography because it coapted against the large prolapsing P2 segment (Figure 4 and Movie IV in the online-only Data Supplement). There was an isolated, very thin, elongated chord to this segment.

There were several options to deal with this problem. One decision was to ignore the prolapse. Reports have indicated that with a mild amount of prolapse of the anterior leaflet, annuloplasty alone will lead to better coaptation of the anterior and posterior leaflet and reduce the mitral regurgitation.11 In the near term, that may have been sufficient. However, others have pointed out that some patients with abnormal chords may be prone to recurrent mitral regurgitation in this setting, so this should be applied only selectively.3,12,13 Others have reported mitral valve repair results for type II prolapse with initially satisfactory results but poor long-term results that can be caused by recurrent prolapse.14 We are careful to address all lesions to avoid these type of results. Despite reassurance from the preoperative and intraoperative 3D echocardiography that there was an isolated P2 lesion, the judgment was made that there would be a significant risk for recurrent mitral regurgitation if the valve were left alone because of the asymmetrical prolapse, which would place high tension on the thin chord.

Several possible techniques are available to treat this isolated segment. These include insertion of a single artificial chord, localized triangular resection of the prolapsing segment of the anterior leaflet, chord transfer, and edge-to-edge approximation (Alfieri repair). Normal secondary chords to the midbody of the P2 segment had been preserved in this patient, so chord transfer to the localized segment was chosen.15 Surprisingly, there was mild residual mitral regurgitation at the area of prolapse, and instead, edge-to-edge approximation (Alfieri repair) from the localized segment to the posterior leaflet was performed.16 Postpump echocardiography indicated no residual mitral regurgitation and a mean gradient of 4 mm Hg across the mitral valve; these findings were unchanged on predischarge echocardiography (Figure 5 and Movie V in the online-only Data Supplement).

This case illustrates that 3D echocardiography can easily identify the predominant pathology. Previously published reports confirm that 3D echocardiography and the surgical findings correlate well and that 3D is more accurate than 2-dimensional echocardiography.17–20 However, an overreliance on 3D can be hazardous. Reports generally observe a 90% to 95% correlation with surgical findings, not 100%.18–20 More subtle pathologies may be overlooked or their potential importance underestimated. The patient in the example above may have fared well in the near term with just a P2 resection and reconstruction (the indentations between P1 and P2 and between P2 and P3 were also closed during the procedure) but would have had a significant risk for recurrent mitral regurgitation because of the pathology that had been missed on 3D echocardiography. There is no substitute for a careful surgical assessment of all segments and the subvalvular apparatus and appropriate management of associated lesions.
The deficiencies of transesophageal echocardiography and 3D echocardiography are exemplified by this case. First, the predominant pathology was evident, but the bulky prolapsing leaflet tissue obscured associated areas of pathology. Mixed lesions may be even more difficult to interpret on preoperative studies. Second, leaflet tissue may be resected, reconstructed, folded, or transferred from one area to another, and the leaflets may be sewn together (Alfieri repair). The preoperative image may no longer be helpful as this mechanical rearrangement takes place. Finally, a variety of shapes and sizes of annuloplasty are added that can affect the amount of coaptation and potentially cause systolic anterior motion.

Why Is This Important?
Mitral valve repair is still an art, not the science we would like it to be. Routine success at mitral repair requires experience. There is a heterogeneous rate of mitral valve repair among hospitals and among surgeons. According to the Society of Thoracic Surgeons data, the median number of mitral valve operations per year was only 5 (range, 1–166) and the mean rate of mitral valve repair was only 41% (Figure 6).

Increased surgeon volume was associated a higher probability of repair. In addition, a higher hospital volume (>40 per year) of mitral surgeries was associated with a higher repair rate. The shortcomings of mechanical mitral valve replacement (thromboembolism, need for anticoagulation, occasional need for emergency reoperation) or bioprostheses (durability) are well known. Nevertheless, adherence to guidelines suggesting early referral for repair is low, in part because the rate of repair is considered to be too low in some centers.

A concern with too much credence on 3D echocardiography results is that it can lead to an oversimplified approach to the patient, and a simple repair, when a more complex repair may be the better option, potentially may direct the patient to a low-volume center, and the unexpected finding may lead to a replacement for the patient. Adams and Anyanwu suggested that patients needing a simpler repair (such as those with posterior leaflet prolapse) may be repaired with “almost certain” success by an “experienced cardiac surgeon.” This is making the assumption, however, that the preoperative study is accurate enough that that determination can be made with certainty. They note that more complex pathologies (eg,
Barlow disease) could be repaired by a “reference” surgeon with a high-volume mitral valve repair practice with almost certainty, whereas it would be unlikely to be repaired by surgeons with less experience. The burden is on the echocardiographer to make that judgment and to direct the patient to the appropriate center. In England, Bridgewater et al28 went so far as to make explicit suggestions for criteria about surgical training, the use of intraoperative echocardiography, and surgery for associated atrial fibrillation. In a controversial recommendation, they suggested volume thresholds so that surgeons undertaking mitral repair surgery should be doing >25 repairs each year and that hospitals undertaking mitral repair should be doing >50 repairs each year. Furthermore, they suggested an audit of the surgeons performing mitral repair, including an analysis of mortality, residual regurgitation at discharge, later recurrence of regurgitation, and reoperation rates. They suggested transparency of those results with access by both the cardiologists and potential patients.

### Summary
The pathology of mitral regurgitation can be complex. Increasingly, surgeons are called on to operate early in the course of the disease, even on asymptomatic patients, and to ensure a ≥90% chance for repair with no residual or recurrent mitral regurgitation.29 The mortality rate should also be <1% for most patients with mitral valve repair, and morbidity should be uncommon. Although the bar is set high today, some also expect to achieve these results with minimally invasive or robotically assisted approaches (although an analysis from the Society of Thoracic Surgeons database indicated that the risk for perioperative stroke may be twice as high as with conventional surgery).30 Preoperative and intraoperative echocardiography results are the important pivot point in decision making. There is a veritable love affair with 3D echocardiography in the imaging community. It has some advantages. It is easier to read, instantly provides views that the surgeon can understand, and accurately portrays the valve in systole and diastole. It has significant drawbacks. The subvalvular apparatus is not easily examined. More subtle yet important aspects of pathology may be difficult to appreciate. With this incomplete information, a less experienced surgeon may settle for a repair that addresses the major part of the pathology but may leave behind untreated pathology. This may lead to an unacceptably high rate of residual or recurrent mitral regurgitation, or the unexpected pathology may lead to replacement.

Therefore, like all advances in technology, 3D echocardiography needs to be kept in perspective. It may improve the interpretation of the pathology of mitral regurgitation and may help many surgeons in their efforts to repair the valve. It should not, however, be viewed as the ultimate means to facilitate mitral valve repair. That is still the optic nerve, cerebellum, and cerebral cortex of the operating surgeon.

### Disclosures
Dr McCarthy is the inventor of the MC3 Tricuspid Annuloplasty ring and dETlogix Ring and is the coinventor of the Carpentier-McCarthy-Adams IMR ETlogix Annuloplasty Ring and receives royalties for those products. In addition, he is a consultant to Edwards Lifesciences, LLC (Irvine, CA).

### References
We have the greatest respect for the surgical skills of Dr McCarthy and agree that mitral valve (MV) repair in his hands and in those of other world-class MV surgeons is very successful and likely not improved by the use of 3-dimensional echocardiography (3DE). However, not all surgeons are as skilled, so the use of 3DE-derived measurements and images can only enhance the success of these surgeons.

True, 3DE cannot predict the changes that occur after MV repair that may lead to residual regurgitation, but neither can the surgeon because, like 3DE, the surgeon is not a fortune teller. It is also true that 3DE cannot replace superb surgical exposure, but that is not its role. What 3DE can do is allow dynamic visualization of the entire MV apparatus throughout the cardiac cycle, which is superior to the deflated, motionless MV visualized under surgical loupes. Intraoperative inspection for pathology is not physiological and can be misleading because it is performed after emptying the heart of blood and inserting a syringe full of saline between the flaccid MV leaflets to simulate ventricular systole. The case study presented to argue against the use of 3DE is illustrative of not what 3DE misses but of the importance of the use of quantitative tools to analyze 3DE data to understand the complete anatomy and to avoid missing secondary lesions, especially in the presence of mixed pathologies. Finally, while not quite a love affair, the use of 3DE during MV repair is the start of a meaningful friendship.
Three-dimensional Echocardiography Is Not Essential for Intraoperative Assessment of Mitral Regurgitation

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Dr. Tsang and Dr. Lang provide an outstanding review of the benefits of 3-D echocardiography. The crux of the question for discussion, however is, "Is 3-D Echo Essential for Intraoperative Assessment of Mitral Regurgitation?" Before surgery, clinicians should already understand the MR mechanism(s), the lesions, and the severity as that impacts decisions regarding timing of surgery, choice of surgeon, and surgical approach. Intraoperatively, however, 3-D echo is not as valuable as the experience of the surgeon. An analogy would be the suggestion that perfect high-definition three-dimensional photography makes plastic surgery simple and reproducible. We have seen results in Hollywood stars demonstrating that is not true! We have seen patients after mitral valve repair, even with the use of intraoperative 3-D echo, with a less than ideal outcome.

I am a fan of 3-D echo, and I use it routinely during mitral valve surgery. I am a proponent of surgeons evolving away from mitral valve repair as an artistic, plastic surgery type procedure to create more predictable results provided by more cardiac surgeons. However, in this manuscript they point out that there are "still immeasurable variables" impacting the success of repair. Some may be subtle and not detected by 3D echo such as prominent clefts between the scallops, small areas of prolapse, and the quality and height of valve tissue that impacts surgical decision-making regarding adjusting leaflet height, size of the ring and choice of technique. Therefore, ultimately, I agree with Dr. Tsang and Dr. Lang that ideal repairs require not only accurate imaging but also an experienced surgeon.
Movie Legend

**Movie 1:** Ruptured chords involving P2 by both 2-D and 3-D images. Best viewed with Windows Media Player.

**Movie 2:** Additional views from 3-D echo indicate no associated anterior leaflet pathology. Best viewed with Windows Media Player.

**Movie 3 A, B, C:** Additional 3-D echo views showing no anterior leaflet pathology. Best viewed with Windows Media Player.

**Movie 4:** An isolated area of prolapse at A1 near the border with A2 was hidden and not appreciated on echo as it coapted against the large prolapsing P2 segment. Best viewed with Windows Media Player.

**Movie 5:** Post-pump echo indicating no residual mitral regurgitation and a mean gradient of 4mmHg across the mitral valve. Best viewed with Windows Media Player.