THE EVOLUTION OF TRANSCATHETER INTERVENTIONS IN STRUCTURAL CARDIOLOGY

Alkov Ruslan Alimjonovich
Student, Samarkand State Medical University, Samarkand, Uzbekistan
Muxammadjonov Lochinbek Jasurbek o'g'li
Student, Samarkand State Medical University, Samarkand, Uzbekistan
Temirov Muhammad Alisher O'gli
Student, Samarkand State Medical University, Samarkand, Uzbekistan
Boymurodova Oybarchin Saidmurod qizi
Student, Samarkand State Medical University, Samarkand, Uzbekistan

Abstract

Transcatheter structural heart interventions have transformed the management of acquired and congenital cardiovascular disease. Initially developed as alternatives for patients considered unsuitable for surgery, catheter-based procedures have evolved into established treatments across a broad range of surgical-risk groups. Major advances include transcatheter aortic valve replacement (TAVR), transcatheter edge-to-edge repair (TEER), transcatheter mitral and tricuspid valve replacement, left atrial appendage occlusion, and closure of septal defects. This evolution has been driven by improvements in prosthetic design, delivery systems, multimodality imaging, vascular access, and clinical evidence from randomized trials. This review summarizes the historical development of structural interventions, the expansion of TAVR and atrioventricular valve therapies, enabling technologies, current limitations, and emerging directions including artificial intelligence, advanced biomaterials, and earlier intervention.

Keywords: Transcatheter interventions; Structural cardiology; TAVR; TEER; Mitral valve; Tricuspid valve; Percutaneous cardiac procedures.

1. Historical Evolution of Transcatheter Structural Interventions

The development of structural cardiology evolved from early catheter-based procedures for congenital heart disease. In 1966, Rashkind and Miller introduced balloon atrial septostomy for neonates with transposition of the great arteries (Rashkind & Miller, 1966). Percutaneous patent ductus arteriosus closure followed in 1967, while

King and Mills reported the first transcatheter closure of an atrial septal defect in 1976 (Porstmann et al., 1967; King et al., 1976).

The treatment of acquired valve disease subsequently expanded through balloon valvuloplasty. In 1984, Inoue introduced percutaneous balloon mitral commissurotomy for rheumatic mitral stenosis (Inoue et al., 1984). Cribier subsequently developed balloon aortic valvuloplasty in 1986 as a less invasive treatment for severe aortic stenosis (Cribier et al., 1986). Although balloon aortic valvuloplasty provided rapid hemodynamic improvement, restenosis and lack of sustained survival benefit limited its long-term role.

The major turning point occurred in 2002, when Alain Cribier and colleagues performed the first human transcatheter aortic valve implantation in a critically ill patient with severe calcific aortic stenosis (Cribier et al., 2002). This procedure demonstrated that a prosthetic valve could be delivered through a catheter and established the foundation for modern transcatheter valve replacement.

Since then, structural cardiology has progressed from experimental rescue procedures to a multidisciplinary field incorporating advanced imaging, dedicated prosthetic devices, percutaneous vascular access, and evidence-based patient selection.

2. TAVR: From High-Risk Rescue Therapy to Standard Treatment

TAVR represents the most important example of the expansion of transcatheter therapy. Early devices were relatively large, rigid, and difficult to position. Modern systems are smaller, more flexible, and often repositionable.

Two major technological platforms dominate contemporary TAVR. Balloon-expandable systems evolved from the original Cribier-Edwards valve to SAPIEN, SAPIEN XT, SAPIEN 3, and SAPIEN 3 Ultra. Self-expanding systems evolved from CoreValve to the repositionable Evolut R, Evolut PRO, and Evolut FX platforms. Improvements in frame design, sealing skirts, delivery systems, and leaflet materials have reduced vascular complications and paravalvular regurgitation while improving implantation accuracy.

Clinical trials progressively expanded the indication for TAVR. In inoperable patients, PARTNER 1B demonstrated a major reduction in one-year mortality compared with standard therapy, establishing TAVR as a treatment for patients who could not undergo surgery (Leon et al., 2010). PARTNER 1A subsequently demonstrated non-inferiority of TAVR compared with surgical aortic valve replacement (SAVR) in high-risk patients (Smith et al., 2011). The CoreValve High Risk trial similarly demonstrated superiority of self-expanding TAVR over surgery for one-year mortality (Adams et al., 2014).

Evidence then expanded to intermediate-risk patients. PARTNER 2A and SURTAVI demonstrated that TAVR was non-inferior to SAVR for major clinical outcomes in this population (Leon et al., 2016; Reardon et al., 2017). Finally, PARTNER 3 and Evolut Low Risk established the feasibility of TAVR in selected low-risk patients (Mack et al., 2019; Popma et al., 2019). These studies fundamentally changed treatment algorithms by demonstrating that transcatheter therapy was no longer restricted to patients with prohibitive surgical risk.

TAVR has also expanded into anatomically complex populations. Bicuspid aortic valves present challenges because of asymmetric calcification, elliptical annular geometry, and associated aortopathy. Modern CT-based planning has improved patient selection and procedural precision. Valve-in-valve TAVR provides an alternative to redo surgery for failed surgical bioprostheses, although coronary obstruction and residual gradients remain important limitations. Techniques such as BASILICA can reduce the risk of coronary obstruction in selected high-risk anatomies.

Despite its success, TAVR has unresolved limitations. Conduction abnormalities and permanent pacemaker implantation occur more frequently with some self-expanding systems. Paravalvular regurgitation, vascular complications, stroke, subclinical leaflet thrombosis, and uncertainty regarding very long-term valve durability remain clinically important. In younger patients, lifetime management is particularly relevant because future TAVR-in-TAVR procedures may compromise coronary access.

3. Transcatheter Mitral and Tricuspid Interventions

Atrioventricular valve interventions are technically more challenging than aortic valve procedures because the mitral and tricuspid valves have complex, dynamic anatomy and extensive subvalvular structures.

The most established mitral intervention is transcatheter edge-to-edge repair (TEER), based on the surgical Alfieri repair concept. A transseptal catheter delivers a clip that grasps the anterior and posterior mitral leaflets, reducing the regurgitant orifice.

In primary degenerative mitral regurgitation, EVEREST II demonstrated that TEER provided greater procedural safety than surgery, although surgery achieved more complete and durable MR reduction (Feldman et al., 2015). TEER therefore became particularly important for patients with symptomatic severe MR who are at high or prohibitive surgical risk.

The role of TEER in secondary functional MR was clarified by MITRA-FR and COAPT. MITRA-FR failed to demonstrate a significant clinical benefit from TEER plus medical therapy compared with medical therapy alone (Obadia et al., 2018). In contrast, COAPT demonstrated substantial reductions in heart-failure hospitalization and mortality with TEER (Stone et al., 2018). Differences in patient selection, severity of MR, ventricular remodeling, and optimization of medical therapy likely contributed to these contrasting results. The concept of proportionate and disproportionate MR subsequently provided an important framework for interpreting these findings (Grayburn et al., 2019).

Modern TEER systems, including MitraClip G4 and PASCAL, provide improved leaflet grasping and greater anatomical flexibility. However, TEER remains unsuitable for some patients with extensive leaflet destruction, severe calcification, or unfavorable coaptation anatomy.

Transcatheter mitral valve replacement (TMVR) is being developed for patients who cannot undergo TEER. Major challenges include stable anchoring within the dynamic mitral annulus, prevention of left ventricular outflow tract obstruction, and thrombotic complications. CT-based prediction of the neo-LVOT is therefore an essential component of procedural planning.

Tricuspid intervention has similarly expanded. Tricuspid TEER devices such as TriClip and PASCAL can reduce severe tricuspid regurgitation with relatively low procedural morbidity. In the TRILUMINATE Pivotal trial, TEER improved quality of life and reduced TR severity, although a significant reduction in one-year mortality or heart-failure hospitalization was not demonstrated (Sorajja et al., 2023).

Dedicated transcatheter tricuspid valve replacement represents the next stage of development. The EVOQUE system demonstrated substantial reduction of TR and improvements in functional outcomes in the TRISCEND II trial (Kodali et al., 2024). These developments suggest a broader transition from transcatheter repair toward complete valve replacement.

4. Other Structural Interventions and Enabling Technologies

Beyond valve replacement and repair, several catheter-based procedures have become established components of structural cardiology. Transcatheter ASD closure using self-expanding occluders has largely replaced surgery in anatomically suitable secundum ASD patients. PFO closure has also become an important option for selected patients with cryptogenic ischemic stroke. RESPECT, CLOSE, and REDUCE demonstrated reductions in recurrent ischemic stroke in appropriately selected patients receiving PFO closure compared with antiplatelet therapy alone (Saver et al., 2017; Mas et al., 2017; Søndergaard et al., 2017).

Left atrial appendage occlusion (LAAO) provides another important alternative to long-term anticoagulation in selected patients with atrial fibrillation. PROTECT AF and PREVAIL demonstrated that Watchman implantation could provide stroke prevention comparable to warfarin, while PRAGUE-17 demonstrated non-inferiority compared with direct oral anticoagulants in high-risk patients (Reddy et al., 2014; Osmancik et al., 2020).

Transcatheter pulmonary valve replacement has reduced the need for repeated surgical intervention in patients with right ventricular outflow tract dysfunction following congenital heart surgery. Similarly, transcatheter paravalvular leak closure can treat prosthetic valve regurgitation and avoid high-risk redo surgery in selected patients (Cheatham et al., 2007).

The rapid expansion of these procedures has been enabled by technological advances. Early TAVR required large 22–24 Fr delivery systems, whereas modern platforms use substantially smaller expandable or low-profile systems. Multidetector CT has become central to pre-procedural planning, allowing precise assessment of annular dimensions, coronary height, vascular access, calcification, and potential obstruction.

Intraprocedural imaging has also evolved from conventional fluoroscopy toward three-dimensional transesophageal echocardiography and intracardiac echocardiography. These modalities improve visualization during TEER, septal closure, LAAO, and other complex interventions. Percutaneous closure devices have further reduced the need for surgical vascular cutdown and contributed to shorter hospital stays.

Artificial intelligence and computational modeling represent the next technological step. Automated CT segmentation, finite element analysis, patient-specific simulations, and digital-twin models may eventually predict device positioning, paravalvular leak, conduction disturbances, and LVOT obstruction before the procedure begins.

Conclusion

The evolution of structural cardiology represents a transition from surgical and palliative treatment toward minimally invasive, evidence-based intervention. TAVR has progressed from an experimental procedure for inoperable patients to an established alternative to surgery across multiple risk categories. TEER and emerging mitral and tricuspid replacement technologies have expanded catheter-based treatment to atrioventricular valve disease, while LAAO, septal closure, pulmonary valve replacement, and paravalvular leak closure have broadened the structural intervention spectrum.

This transformation has been driven by improvements in prosthetic engineering, delivery systems, vascular access, multimodality imaging, and randomized clinical evidence. Future progress will depend on solving remaining problems of valve durability, conduction disturbances, coronary access, complex anatomy, and healthcare accessibility. Integration of artificial intelligence, computational modeling, advanced biomaterials, and individualized Heart Team decision-making is likely to define the next phase of structural cardiology.

References

1. Adams, D. H., Popma, J. J., Reardon, M. J., Hermiller, J. B., Yakubov, S. J., Liang, Q., ... & Deeb, G. M. (2014). Transcatheter aortic-valve replacement with a self-expanding prosthesis. *New England Journal of Medicine*, 370(19), 1790-1798.
2. Capodanno, D., Petronio, A. S., Prendergast, B., Eltchaninoff, H., Vahanian, A., Modine, T., ... & Tamburino, C. (2019). Standardized definitions in transcatheter aortic valve tissue failure: consensus document from the Heart Valve Society. *European Heart Journal*, 40(5), 439-455.
3. Cheatham, J. P., Hellenbrand, W. E., Zahn, E. M., Jones, T. K., Berman, D. P., Vincent, J. A., & McElhinney, D. B. (2007). Clinical application of the Melody transcatheter pulmonary valve in the US Investigational Device Exemption study. *Journal of the American College of Cardiology*, 50(14), 1350-1359.
4. Cribier, A., Savin, T., Saoudi, N., Rocha, P., Berland, J., & Letac, B. (1986). Percutaneous balloon valvuloplasty: a new treatment for calcific aortic stenosis. *The Lancet*, 327(8472), 63-67.
5. Cribier, A., Eltchaninoff, H., Bash, A., Borenstein, N., Tron, C., Bauer, F., ... & Leon, M. B. (2002). Percutaneous transcatheter implantation of an aortic valve prosthesis for calcific aortic stenosis: first human case description. *Circulation*, 106(24), 3006-3008.
6. Dotter, C. T., & Judkins, M. P. (1964). Transluminal treatment of arteriosclerotic obstruction: description of a new technic and a preliminary report of its application. *Circulation*, 30(5), 654-670.
7. Feldman, T., Kar, S., Elmariah, S., Smart, S. C., Trento, A., Siegel, R. J., ... & Mauri, L. (2015). Randomized comparison of percutaneous repair and surgical repair of the mitral valve: 5-year results of EVEREST II. *Journal of the American College of Cardiology*, 66(19), 2075-2084.
8. Forrest, J. K., Deeb, G. M., Yakubov, S. J., Gada, H., Mumtaz, M. A., Ramlawi, B., ... & Reardon, M. J. (2023). 4-Year outcomes of transcatheter vs surgical aortic valve replacement in low-risk patients. *Journal of the American College of Cardiology*, 82(22), 2111-2123.
9. Genereux, P., Webb, J. G., Pibarot, P., Redfors, B., Alu, M. C., Smith, C. R., ... & Leon, M. B. (2024). Transcatheter aortic valve replacement in asymptomatic severe aortic stenosis: Primary results of the EARLY TAVR trial. *New England Journal of Medicine*, 391(21), 1971-1983.
10. Grayburn, P. A., Sannino, A., & Packer, M. (2019). Proportionate and disproportionate functional mitral regurgitation: a new conceptual framework that reconciles the results of the MITRA-FR and COAPT trials. *JACC: Cardiovascular Imaging*, 12(2), 353-362.

11. Grüntzig, A. (1978). Transluminal dilation of coronary-artery stenosis. *New England Journal of Medicine*, 298(2), 101-102.
12. Inoue, K., Owaki, T., Nakamura, T., Kitamura, F., & Miyamoto, N. (1984). Clinical application of transvenous mitral commissurotomy by a new balloon catheter. *The Journal of Thoracic and Cardiovascular Surgery*, 87(3), 394-402.
13. Jilaihawi, H., Kashif, M., Fontana, G., White, A., Thomas, D., Shiota, T., ... & Makkar, R. R. (2012). Cross-sectional computed tomographic assessment improves accuracy of aortic annular sizing for transcatheter aortic valve replacement and reduces the incidence of paravalvular aortic regurgitation. *Journal of the American College of Cardiology*, 59(14), 1275-1286.
14. Kapadia, S. R., Makkar, R., Leon, M. B., Abdel-Wahab, M., Rinaldi, M. J., Massberg, S., ... & Linke, A. (2022). Cerebral embolic protection during transcatheter aortic-valve replacement. *New England Journal of Medicine*, 387(14), 1253-1263.
15. King, T. D., Thompson, S. L., Steiner, C., & Mills, N. L. (1976). Secundum atrial septal defect: nonoperative closure during cardiac catheterization. *JAMA*, 235(23), 2506-2509.
16. Kodali, S., Hahn, R. T., Davidson, C. J., Narang, A., Zahr, F., Chadderdon, S., ... & TRISCEND II Investigators. (2024). Transcatheter tricuspid-valve replacement in severe tricuspid regurgitation: The TRISCEND II randomized trial. *New England Journal of Medicine*, 391(22), 2085-2097.
17. Leon, M. B., Smith, C. R., Mack, M., Miller, D. C., Moses, J. W., Svensson, L. G., ... & PARTNER Trial Investigators. (2010). Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. *New England Journal of Medicine*, 363(17), 1597-1607.
18. Leon, M. B., Smith, C. R., Mack, M. J., Makkar, R. R., Svensson, L. G., Kodali, S. K., ... & PARTNER 2 Investigators. (2016). Transcatheter or surgical aortic-valve replacement in intermediate-risk patients. *New England Journal of Medicine*, 374(17), 1609-1620.
19. Mack, M. J., Leon, M. B., Smith, C. R., Miller, D. C., Moses, J. W., Tuzcu, E. M., ... & PARTNER Trial Investigators. (2015). 5-year outcomes of transcatheter aortic valve replacement or surgical aortic valve replacement for high surgical risk patients with aortic stenosis (PARTNER 1): a randomised controlled trial. *The Lancet*, 385(9986), 2477-2484.
20. Mack, M. J., Leon, M. B., Thourani, V. H., Makkar, R., Kodali, S. K., Russo, M., ... & PARTNER 3 Investigators. (2019). Transcatheter aortic-valve replacement with a balloon-expandable valve in low-risk patients. *New England Journal of Medicine*, 380(18), 1695-1705.

21. Mas, J. L., Derumeaux, G., Guillon, B., Massazier, E., Hosseini, H., Mechtouff, L., ... & CLOSE Investigators. (2017). Patent foramen ovale closure or anticoagulation vs. antiplatelets after cryptogenic stroke. *New England Journal of Medicine*, 377(11), 1011-1021.
22. Obadia, J. F., Messika-Zeitoun, D., Leurent, G., Iung, B., Bonnet, G., Piriou, N., ... & MITRA-FR Investigators. (2018). Percutaneous repair or medical treatment for secondary mitral regurgitation. *New England Journal of Medicine*, 379(24), 2297-2306.
23. Osmancik, P., Herman, D., Neuzil, P., Hala, P., Taborsky, M., Kala, P., ... & PRAGUE-17 Trial Investigators. (2020). Left atrial appendage occlusion versus direct oral anticoagulants in high-risk patients with atrial fibrillation. *Journal of the American College of Cardiology*, 75(25), 3122-3135.
24. Otto, C. M., Nishimura, R. A., Bonow, R. O., Carabello, B. A., Erwin, J. P., Gentile, F., ... & Toly, V. B. (2021). 2020 ACC/AHA Guideline for the management of patients with valvular heart disease: executive summary. *Circulation*, 143(5), e35-e71.
25. Popma, J. J., Deeb, G. M., Yakubov, S. J., Mumtaz, M., Gada, H., O'Hair, D., ... & Evolut Low Risk Trial Investigators. (2019). Transcatheter aortic-valve replacement with a self-expanding valve in low-risk patients. *New England Journal of Medicine*, 380(18), 1706-1715.
26. Porstmann, W., Wierny, W., & Warnke, H. (1967). Der Verschluss des Ductus arteriosus persisten ohne Thorakotomie. *Thoraxchirurgie Vaskuläre Chirurgie*, 15(2), 199-203.
27. Rashkind, W. J., & Miller, W. W. (1966). Creation of an atrial septal defect without thoracotomy: a palliative approach to complete transposition of the great arteries. *JAMA*, 196(11), 991-992.
28. Reardon, M. J., Van Mieghem, N. M., Popma, J. J., Kleiman, N. S., Søndergaard, L., Mumtaz, M., ... & SURTAVI Investigators. (2017). Surgical or transcatheter aortic-valve replacement in intermediate-risk patients. *New England Journal of Medicine*, 376(14), 1321-1331.
29. Reddy, V. Y., Sievert, H., Holmes, D., Doshi, S. K., Neuzil, P., Trause, D., ... & PROTECT AF and PREVAIL Investigators. (2014). Left atrial appendage closure vs warfarin for stroke prevention in atrial fibrillation: 5-year outcomes of PREVAIL and PROTECT AF. *JAMA*, 312(19), 1988-1998.
30. Saver, J. L., Carroll, J. D., Thaler, D. E., Smalling, R. W., MacDonald, L. A., Marks, D. S., & Tirschwell, D. L. (2017). Long-term outcomes of patent foramen ovale closure or medical therapy after stroke. *New England Journal of Medicine*, 377(11), 1022-1032.

31. Smith, C. R., Leon, M. B., Mack, M. J., Miller, D. C., Moses, J. W., Svensson, L. G., ... & PARTNER Trial Investigators. (2011). Transcatheter versus surgical aortic-valve replacement in high-risk patients. *New England Journal of Medicine*, 364(23), 2187-2198.
32. Søndergaard, L., Kasner, S. E., Rhodes, J. F., Andersen, G., Iversen, H. K., Nielsen-Kudsk, J. E., ... & REDUCE Clinical Study Investigators. (2017). Patent foramen ovale closure or antiplatelet therapy for cryptogenic stroke. *New England Journal of Medicine*, 377(11), 1033-1042.
33. Sorajja, P., Whisenant, B., Hamid, N., Naik, H., Makkar, R., Tadros, P., ... & TRILUMINATE Pivotal Investigators. (2023). Transcatheter repair for patients with severe tricuspid regurgitation. *New England Journal of Medicine*, 388(20), 1833-1842.
34. Stone, G. W., Lindenfeld, J., Abraham, W. T., Kar, S., Lim, D. S., Mishell, J. M., ... & COAPT Investigators. (2018). Transcatheter mitral-valve repair in patients with heart failure. *New England Journal of Medicine*, 379(24), 2307-2318.