

2019

Conduction abnormalities after transcatheter aortic valve replacement

S. Kanjanauthai

K. Bhasin

L. Pirelli

Zucker School of Medicine at Hofstra/Northwell, lpirelli@northwell.edu

C. A. Kliger

Zucker School of Medicine at Hofstra/Northwell, ckliger@northwell.edu

Follow this and additional works at: <https://academicworks.medicine.hofstra.edu/articles>

 Part of the [Cardiology Commons](#)

Recommended Citation

Kanjanauthai S, Bhasin K, Pirelli L, Kliger CA. Conduction abnormalities after transcatheter aortic valve replacement. . 2019 Jan 01; 13(1):Article 4801 [p.]. Available from:

<https://academicworks.medicine.hofstra.edu/articles/4801>. Free full text article.

This Article is brought to you for free and open access by Donald and Barbara Zucker School of Medicine Academic Works. It has been accepted for inclusion in Journal Articles by an authorized administrator of Donald and Barbara Zucker School of Medicine Academic Works. For more information, please contact academicworks@hofstra.edu.

Conduction Abnormalities After Transcatheter Aortic Valve Replacement

Somsupha Kanjanauthai, MD, Kabir Bhasin, MD, Luigi Pirelli, MD, and Chad A Kliger, MD

Valve and Structural Heart Center, Lenox Hill Heart and Lung, New York, NY

Abstract

Transcatheter aortic valve replacement (TAVR) has been established as a therapeutic option for patients with severe symptomatic aortic stenosis who are of intermediate or higher surgical risk. Several periprocedural complications are reduced with newer transcatheter heart valve generations; however, conduction abnormalities and the need for permanent pacemaker implantation have remained unchanged and are the most frequent TAVR complications. The close relationship of the atrioventricular node and left bundle branch to the subaortic region explains these potential conduction abnormalities. This article highlights conduction abnormalities after TAVR with a focus on basic conduction system anatomy in relation to the aortic valve, the mechanism, incidence, predisposing factors for occurrence, impact on mortality and finally, proposed treatment algorithms for management.

Keywords

Conduction abnormalities, left bundle branch block, pacemaker implantation, right bundle branch block, sudden cardiac death, transcatheter aortic valve replacement

Disclosure: CK receives speaking honorarium from Medtronic and Siemens Healthineers. All other authors have no conflicts of interest to declare.

Received: June 30, 2018 **Accepted:** October 23, 2018 **Citation:** *US Cardiology Review*, 2019;13(1):21–9. **DOI:** <https://doi.org/10.15420/usc.2018.7.2>

Correspondence: Chad A Kliger, Director, Valve and Structural Heart Center, Lenox Hill Heart and Lung, 130 East 77th Street, Suite 4th Floor, New York, NY 10075, USA. E: ckliger@northwell.edu

Open Access: This work is open access under the CC-BY-NC 4.0 License which allows users to copy, redistribute and make derivative works for non-commercial purposes, provided the original work is cited correctly.

Transcatheter aortic valve replacement (TAVR) has been established as a therapeutic option for patients with severe symptomatic aortic stenosis who are considered to be of intermediate, high or prohibitive surgical risk.^{1–5} As a result of favorable TAVR outcomes and substantial improvements in transcatheter heart valve (THV) technologies and implantation techniques, the feasibility of broadening applications to the low-risk population is being evaluated.

Despite periprocedural complications being reduced with newer THV generations, the occurrence of conduction abnormalities and the need for permanent pacemaker implantation (PPI) remain the most frequent complications.^{6,7} Rates of PPI have not been significantly reduced but rather, with some technologies, have increased.⁸ The long-term implications of PPI in the TAVR patient population remain unclear, and applicability in low-risk patients is a further consideration. In addition, short-term implications may jeopardize the minimalist TAVR approach, with increased use of electrophysiological studies and continuous EKG monitoring devices (i.e. Holter monitors, event monitors, or implantable loop recorders), and subsequent prolonged length of hospital stay.^{9–12}

This article highlights conduction abnormalities after TAVR with a focus on basic conduction system anatomy in relation to the aortic valve, the

mechanism, incidence, predisposing factors for occurrence, impact on mortality, and finally, proposed treatment algorithms for management.

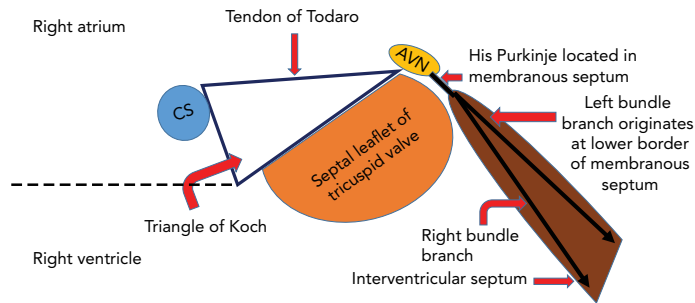
Anatomy of the Conduction System

The atrioventricular node (AVN) is located within the triangle of Koch, which is demarcated by the tendon of Todaro, the septal leaflet attachment of the tricuspid valve, and the orifice of the coronary sinus (*Figure 1*). The AVN continues as the His bundle, tracking through the septum leftward to the central fibrous body. The central fibrous body is the area within the heart where the membranous septum (MS), the atrioventricular valves, and the aortic valve join in continuity. The left bundle branch exits within this area between the non-coronary cusp (NCC) and right coronary cusp (RCC) leaflets and travels along the septal surface of the left ventricular septum.^{13,14} The close relationship of the AVN and left bundle branch to the subaortic region explains the potential conduction abnormalities after percutaneous THV insertion.

Conduction Abnormalities after Surgical Aortic Valve Replacement

The most common conduction abnormality after surgical aortic valve replacement (SAVR) is left bundle branch block (LBBB). The incidence of new LBBB after SAVR has been reported to range from 6% to 32%.^{15–17} It is caused by injury to the conduction system at the interleaflet

Figure 1: Schematic Illustration of Intracardiac Anatomy and Relationship to Atrioventricular Node



triangle of the NCC/RCC leaflets from direct surgical trauma during decalcification, mechanical compression, hemorrhage, or ischemia.^{15–17} New LBBB after SAVR was found to be associated with worse 1-year survival, when compared with cases where LBBB did not develop.^{15,18}

SAVR can be performed by using either stented or stentless biological prostheses. Stented biological prostheses can be implanted in a supra-annular or intra-annular position; the valve does not generate a radial force that compresses the conduction system if implanted in a supra-annular position. Stentless valve prostheses are designed to achieve a more physiological flow pattern and superior hemodynamics in comparison with stented valves.¹⁹ Some generations of stentless valves require only one suture line to secure the valve.¹⁹

Recent technological developments have led to an alternative, minimally-invasive option that avoids the placement of sutures, known as sutureless or rapid-deployment aortic valves (Su-AVR). Su-AVR, which combines features of both SAVR and TAVR, requires removal/decalcification of native leaflets, but depends on its intra-annular stent design with oversizing to anchor the prosthesis.²⁰ Conduction abnormalities associated with this valve type are more similar to with TAVR than SAVR.²¹

Conduction Abnormalities After Transcatheter Aortic Valve Replacement

TAVR prostheses are placed in an intra-annular position in closer proximity to the AVN and left bundle branch. In contrast to surgical valves, they are anchored into the aortic annulus and their stent frames generate a radial force expansion that may compress the conduction system.²¹ Slight oversizing is necessary in implant technique to secure the THV and reduce paravalvular regurgitation; however, excessive oversizing can result in increased compression of the conduction system.²² Overall, TAVR patients have a higher incidence of conduction abnormalities than patients who have conventional SAVR.²¹

Incidence of New-onset Left Bundle Branch Block and Permanent Pacemaker Insertion

New-onset LBBB is the most frequent complication after TAVR.⁶ The incidence of new-onset LBBB ranges from 4% to 57%, with the rate of PPI ranging from 2% to 51%.^{23,24} The incidence of both new-onset LBBB and PPI are higher after implantation with the self-expanding CoreValve® system (MCV, Medtronic) than with the balloon-expandable SAPIEN or SAPIEN XT systems (ESV, Edwards Lifesciences); new-onset LBBB

and PPI are 35–65% and 28%, and 3–30% and 6%, for MCV and ESV, respectively.^{25–34} Table 1 summarizes studies with their associated LBBB and PPI rates. The higher incidence of PPI in the MCV compared with the ESV has been confirmed in a randomized controlled trial.³⁵

Overall, LBBB leads to an increased likelihood of new PPI early after TAVR.³⁶ However, one-fifth to nearly half of new-onset LBBB is temporary.³⁷ Testa et al. studied 1,060 patients treated with MCV; 43.0% developed LBBB after TAVR, and this figure decreased to 27.3% at discharge and remained stable at 30 days.²⁵ Urena et al. reported the rate of new-onset LBBB to be approximately 20.0% after TAVR with ESV and that 50.0% of new-onset LBBB resolved within a few days after TAVR, leading to a rate of new-onset persistent LBBB of approximately 10.0%.³⁸ In another study, Franzoni et al. showed a higher incidence of LBBB following MCV (50.0%) than ESV (13.5%), which reduced by discharge to 32.2% for MCV and 8.6% for ESV, respectively.³⁹

LBBB is also a predictor of late PPI after hospital discharge.^{40,41} In a recent meta-analysis, a higher rate of PPI at 1-year follow up was observed among patients with new-onset LBBB, compared with those who did not develop LBBB.⁴¹ The frequency of LBBB after TAVR has decreased significantly over time, especially with MCV THVs. This has been largely attributed to operator experience and the subsequent reduction in implantation depth.⁴² Nevertheless, the incidence of PPI has remained unchanged over time and has not been affected by operator experience.⁴² When interrogation of permanent pacemakers are performed, approximately 50% of patients are continuously paced, 25% are intermittently paced, and 25% have adequate atrioventricular conduction without the necessity of pacing.³⁷ The patient population with persistent LBBB who require PPI and have identifiable need upon follow-up interrogation still require improved understanding.

Newest Third-generation Transcatheter Heart Valves

Increased rates of PPI, ranging from 12.4% to 25.5%, have been reported with the use of the newest third-generation ESV SAPIEN 3, when compared with previous generations.^{43–49} This finding has been attributed to the incorporation of an external fabric cuff in the inferior part of the valve, intended to minimize paravalvular leak. Moreover, different stent expansion patterns of the SAPIEN 3 compared with the SAPIEN XT may play a role.⁵⁰ In SAPIEN XT, the expansion area increased from the inflow level, reaching its peak at the outflow level; in contrast, the SAPIEN 3 has its largest expansion at the left ventricular outflow tract (LVOT) end, causing elevated localized pressure within the LVOT and thus higher rates of atrioventricular conduction disturbances.⁵⁰ A higher (>70% aortic extension) valve depth implantation of this newest-generation THV may decrease PPI risk.^{43,44} Also, the next-generation self-expanding MCV Evolut Pro has been designed with an external pericardial wrap with the intention of reducing paravalvular leak. Early PPI rates in the first 60 patients were reported at 30 days at 11.7%.⁵¹ Although 6-month data suggest no significant change in PPI, data for this THV are limited.

Impact of Transcatheter Aortic Valve Replacement-induced Left Bundle Branch Block on Mortality

LBBB has been associated with increased morbidity and mortality in a broad population of patients, from healthy individuals to patients who have had MI and have established heart failure.^{52,53} However,

Table 1: Summary of Studies Showing the Incidence of LBBB and PPI Following TAVR and Respective Association with Mortality

Author	Patients (n)	Valve Type	Incidence of LBBB (%)	Incidence of PPI (%)	Risk Factors for LBBB/PPI	Association of TAVR-induced LBBB/PPI and Mortality
Chamandi et al. 2018 ⁹⁰	1,629	45% ESV 55% MCV	N/A	19.8% at 30 days post-TAVR (26.9% of MCV, 10.9% of ESV)	N/A	PPI was associated with an increased risk of heart failure rehospitalization and lack of LVEF improvement, but not mortality
Fadahuni et al. 2016 ⁷⁶ (STS/ACC TVT registry)	9,785	ESV MCV	N/A	6.7% at 30 days post-TAVR (25.0% of MCV and 4.3% of ESV)	PPI: age, prior conduction defect, use of self-expanding valve, large prosthesis, valve oversizing	PPI was associated with increased mortality and a composite of mortality or heart failure admission at 1 year
Mauri et al. 2016 ⁴⁷	229	ESV3	N/A	14.4%	PPI: deep THV implantation, higher LVOT calcium in the area below LCC and RCC, pre-existing RBBB	N/A
Van der Boon et al. 2015 ⁴²	549	ESV MCV	New-onset LBBB 33.7%	13.3% (7.6% of TAVR-induced LBBB patients underwent PPI)	LBBB: Use of MCV, transfemoral approach, deep THV implantation	N/A
Nazif et al. 2015 ⁷³ (PARTNER trial and registry)	1,973	ESV	N/A	8.8%	PPI: RBBB, prosthesis/LVOT diameter, LVEDD	PPI was associated with higher repeat hospitalization and mortality or repeat hospitalization at 1 year
Urena et al. 2014 ⁸⁸	668	ESV	New-onset LBBB 19.2% Persistent LBBB 11.8%	N/A Higher rate of PPI in LBBB group	LBBB: Transapical approach, a 29-mm valve	LBBB did not increase the risk of global or cardiovascular mortality or rehospitalization at 1 year
Nazif et al. 2014 ⁵⁸ (PARTNER trial and registry)	1,307	ESV	New-onset LBBB 10.5%	N/A Higher rate of PPI in LBBB group	LBBB: Prior CABG	LBBB was not associated with 1-year mortality, cardiovascular mortality, repeat hospitalization, stroke, or MI
Testa et al. 2013 ²⁵	818	MCV	Persistent LBBB 27.4%	N/A Higher rate of PPI at 30 days in persistent LBBB group	PPI: Deep THV implantation (>8 mm)	LBBB was not associated with increased all-cause mortality, cardiac mortality, hospitalization for heart failure at 30 days or 1 year.
Franzoni et al. 2013 ³⁹	238	63.4% ESV 36.6% MCV	New-onset LBBB 26.5% (13.5% ESV, 50.0% MCV) Persistent LBBB: 8.6% ESV, 32.2% MCV	12.7%	LBBB: Use of MCV	LBBB was not associated with overall or cardiovascular mortality
Houthuizen et al. 2012 ²⁶	679	57% MCV 43% ESV	New-onset LBBB 34.3%	N/A	N/A	LBBB increased all-cause mortality
Urena et al. 2012 ³³	202	ESV	New-onset LBBB 30.2%	N/A	LBBB: Baseline QRS, deep THV implantation	LBBB was not associated with mortality at 1 year
De Carlo et al. 2012 ²⁷	275	MCV	New-onset LBBB 26.9%	24%	PPI: Deep THV implantation, RBBB, left anterior hemiblock, longer PR interval	PPI did not affect 1-year survival
Aktug et al. 2012 ²⁸	139	ESV MCV	New-onset LBBB 29.0% (38.0% in MCV, 16.0% in ESV) Persistent LBBB 12.9%	17.2% (28.0% MCV, 5.0% ESV)	LBBB: Deep THV implantation, use of MCV	N/A

Table 1: Continued

Author	Patients (n)	Valve Type	Incidence of LBBB (%)	Incidence of PPI (%)	Risk Factors for LBBB/PPI	Association of TAVR-induced LBBB/PPI and Mortality
Layne et al. 2012 ³⁴	125	ESV	New-onset LBBB 4%	4%	N/A	N/A
Khawaja et al. 2011 ³¹	243	MCV	New-onset LBBB 61%	33.3%	PPI: Periprocedural AVB, balloon predilatation, CoreValve prosthesis, increased interventricular septum diameter, prolonged QRS	N/A
Baan et al. 2010 ⁷⁷	34	MCV	New-onset LBBB 65%	20.5% (7/34 patients)	LBBB: Deep THV implantation PPI: Pre-existing conduction abnormalities, narrow LVOT, postprocedural small EOA, more mitral annular calcification	N/A
Piazza et al. 2010 ³²	91	MCV	New-onset LBBB 54%	19%	LBBB: Male sex, pre-existing RBBB, depth of implantation, actual diameter of inflow portion of CoreValve frame PPI: Baseline QRS, septal wall thickness	N/A

AVB = atrioventricular block; CABG = coronary artery bypass graft; EOA = effective orifice area; ESV = Edwards SAPIEN valve; LBBB = left bundle branch block; LCC = left coronary cusp; LVEDD = left ventricular end-diastolic dimension; LVEF = left ventricular ejection fraction; LVOT = left ventricular outflow tract; MCV = Medtronic CoreValve; PARTNER = Placement of Aortic Transcatheter Valves; PPI = permanent pacemaker implantation; RBBB = right bundle branch block; RCC = right coronary cusp; STS/ACC TVT = Society of Thoracic Surgeons/American College of Cardiology Transcatheter Valve Therapy; TAVR = transcatheter aortic valve replacement; THV = transcatheter heart valve.

there are conflicting data about the impact of new-onset LBBB on mortality in post-TAVR patients. Several studies have failed to show the relationship between new-onset LBBB and mortality.^{25,27,32–34,38,54–58} In an analysis from the Placement of Aortic Transcatheter Valves (PARTNER) trial, persistent new-onset LBBB occurred in 10.5% of cases and was not associated with all-cause mortality, cardiovascular mortality, stroke, or MI. However, it was associated with a higher rate of repeat hospitalizations, PPI, and lack of improvement in left ventricular ejection fraction (LVEF).⁵⁸ On the other hand, a large multicenter registry study by Houthuizen et al. reported that TAVR-induced LBBB is one of the strongest predictors of all-cause mortality in TAVR patients,²⁶ and can neutralize the benefit of TAVR. A meta-analysis by Regueiro et al. confirmed a higher risk of cardiac death in patients with TAVR-induced LBBB after 1 year of follow up.⁴¹

Possible mechanisms of increased mortality for patients with TAVR-induced LBBB are progression to high-grade atrioventricular blocks (HAVB), and the development of dyssynchrony associated with the LBBB.²⁶ LBBB causes left ventricular dyssynchrony, which has a similar effect to chronic right ventricular pacing and can lead to reduction in left ventricular function and remodeling.^{59,60} Patients who develop left ventricular dysfunction from dyssynchrony are also susceptible to ventricular tachyarrhythmias, which could be another possible explanation for higher mortality in patients with TAVR-induced LBBB.²⁶ One case report of a patient without pre-existing conduction abnormalities who died suddenly in the early phase after discharge, showed autopsy findings of a THV that had compressed the atrioventricular conduction system at the septum.⁶¹ Microscopic examination confirmed necrosis of the His bundle and left bundle branch as a result of mechanical compression, supporting progression to HAVB as a possible mechanism of sudden cardiac death (SCD).⁶¹

Advanced heart failure and SCD account for two-thirds of cardiac deaths in post-TAVR patients.⁶² LVEF \leq 40% and new-onset persistent LBBB

following TAVR were independently associated with an increased risk of SCD.⁶² Patients with new-onset persistent LBBB and QRS duration $>$ 160 ms had a greater SCD risk and most of them died within 6 months of TAVR.⁶² No increased risk of SCD was observed in patients with new-onset persistent LBBB and pacemaker implanted before hospital discharge, suggesting HAVB as the main cause of SCD in these patients.⁶² The ongoing Ambulatory Electrocardiographic Monitoring for the Detection of High-Degree Atrio-Ventricular Block in Patients With New-onset Persistent Left Bundle Branch Block After Transcatheter Aortic Valve Implantation (MARE) study, with continuous EKG recording (up to 3 years) in patients with new-onset persistent LBBB following TAVR should provide more information on this issue.

Mechanism and Risk Factors of TAVR-induced LBBB, HAVB, and PPI

Atrioventricular conduction disorders and LBBB occur after both TAVR and SAVR as a result of the close proximity of the AVN and left bundle branch to the aortic valve.¹³ The His bundle is located between the MS and the posterior crest of the muscular septum; the lower end of MS is an anatomic landmark for the left ventricular exit point of the His bundle.¹³ Consequently, the MS length represents the distance between the aortic annulus and the His bundle. Hamdan et al. evaluated 73 patients with severe aortic stenosis who underwent contrast-enhanced CT before TAVR and found that MS length was the most powerful predictor of HAVB and PPI.⁶³ Short MS, insufficient distance between MS length and implantation depth, and the presence of calcification in the basal septum facilitate mechanical compression of the conduction tissue by the TAVR prosthesis.⁶³ On the other hand, a longer MS length may allow accommodation of more device penetration without causing conduction abnormalities.⁶³

LBBB may develop before actual insertion of the valve device in $>$ 50% of cases. This can be caused by contact of the guidewire or compression of the LVOT by balloon dilatation.^{29,56} Patient- and procedure-related

factors such as septal wall thickness, NCC thickness, depth of valve implantation within the LVOT, post-implantation dilatation, and large size and type of THV predicts LBBB or new conduction abnormalities after TAVR.^{38,54–56,64} Deep THV implants, greater than or equal to 6 mm, are associated with increased conduction abnormalities and pacemaker rate.^{39,65,66} Moreover, higher ratio between prosthesis valve size and the annulus, (that is, oversizing) in the MCV is considered to be a predictor of new LBBB.³⁹

Mauri et al. identified risk factors for PPI following TAVR with a balloon-expandable (SAPIEN 3) THV to be a high LVOT calcium volume in the area below the left coronary cusp and RCC, pre-existing right bundle branch block (RBBB), and lower implantation depth (Table 2).⁶⁷ Tarantini et al. described a relationship between implantation depth and PPI rate after SAPIEN 3 implantation and proposed an implantation technique aimed at a maximum LVOT extension of the stent frame of less than 8 mm, which would result in a ventricular portion of approximately 40.0% depending on prosthesis size.⁴⁴ Subsequent studies showed that implantation techniques aimed at a ventricular portion of <30.0% and <25.5% were the best discriminatory thresholds for reduced PPI risk.^{43,67} Optimal implantation depths for MCV and ESV are between 3 mm and 6 mm and 80% aortic:20% ventricular, respectively.

The radial force from the THV must be sufficient to ensure valve anchoring, but not interfere with the AVN and disturb the electrical conduction system.⁶⁸ Radial force produced by the MCV and ESV was studied by Tzamtzis et al.⁶⁹ In self-expanding THVs, the radial force is dependent on the diameter of LVOT.⁶⁹ However, the radial force in the balloon-expandable THVs is associated with a more complex mechanism that involves the geometric and material properties of the stent, of the balloon and of the host tissue, as well as the technical aspects of the balloon inflation procedure.⁶⁹

Pre-existing Right Bundle Branch Block in Patients Undergoing Transcatheter Aortic Valve Replacement

Data from the Copenhagen City Heart Study demonstrated that RBBB was associated with an increased risk for all-cause mortality and adverse cardiovascular outcomes in the general population.⁷⁰ A large meta-analysis of 19 prospective cohort studies confirmed the same findings; RBBB was associated with an increased risk of mortality in the general population and in patients with heart disease.⁷¹ RBBB is a well-recognized risk factor for PPI or late bradycardia in post-TAVR patients.^{24,72,73} Watanabe et al. evaluated the prognostic effect of pre-existing RBBB in patients undergoing TAVR in a substudy of the Optimized Transcatheter Valvular Intervention (OCEAN-TAVI) registry, which used the SAPIEN XT prosthesis.⁷⁴ Of 749 patients, 102 (13.6%) had pre-existing RBBB, and this group had a higher incidence of PPI than the group without RBBB (17.6% versus 2.9%).⁷⁴ Patients with RBBB demonstrated an increased risk of cardiovascular mortality after TAVR, and were at higher risk of cardiac death if discharged without pacemakers (HR 2.6).⁷⁴ A recent study showed a similar result; RBBB was present on baseline EKG in approximately 10% of patients and associated with higher 30-day rates of PPI and death.⁷⁵ Patients with pre-existing RBBB should be carefully monitored to detect fatal arrhythmic events after discharge and may require prolonged hospitalization.

Table 2: Risk Factors for TAVR-induced LBBB and PPI

Risk Factors for TAVR-induced LBBB	Risk Factors for Pacemaker Insertion (PPI)
Patient Characteristics	
Baseline QRS duration	Age
–	Male sex
–	Baseline conduction disturbances (i.e. RBBB)
Anatomical Considerations	
Short membranous septum	Short membranous septum
Increased septal wall thickness	Narrow LVOT
Presence of calcification in the basal septum	High LVOT calcium volume below the LCC and RCC
Increased non-coronary cusp thickness	Large annular size
–	Mitral annular calcification
Procedural Characteristics	
Higher ratio between THV size and annulus (oversizing)	Higher ratio between THV size and annulus (oversizing)
Deep THV implantation	Deep THV implantation
Post-dilatation	Intraprocedural atrioventricular block
Type of THV (self- > balloon-expandable)	Type of THV (self- > balloon-expandable)

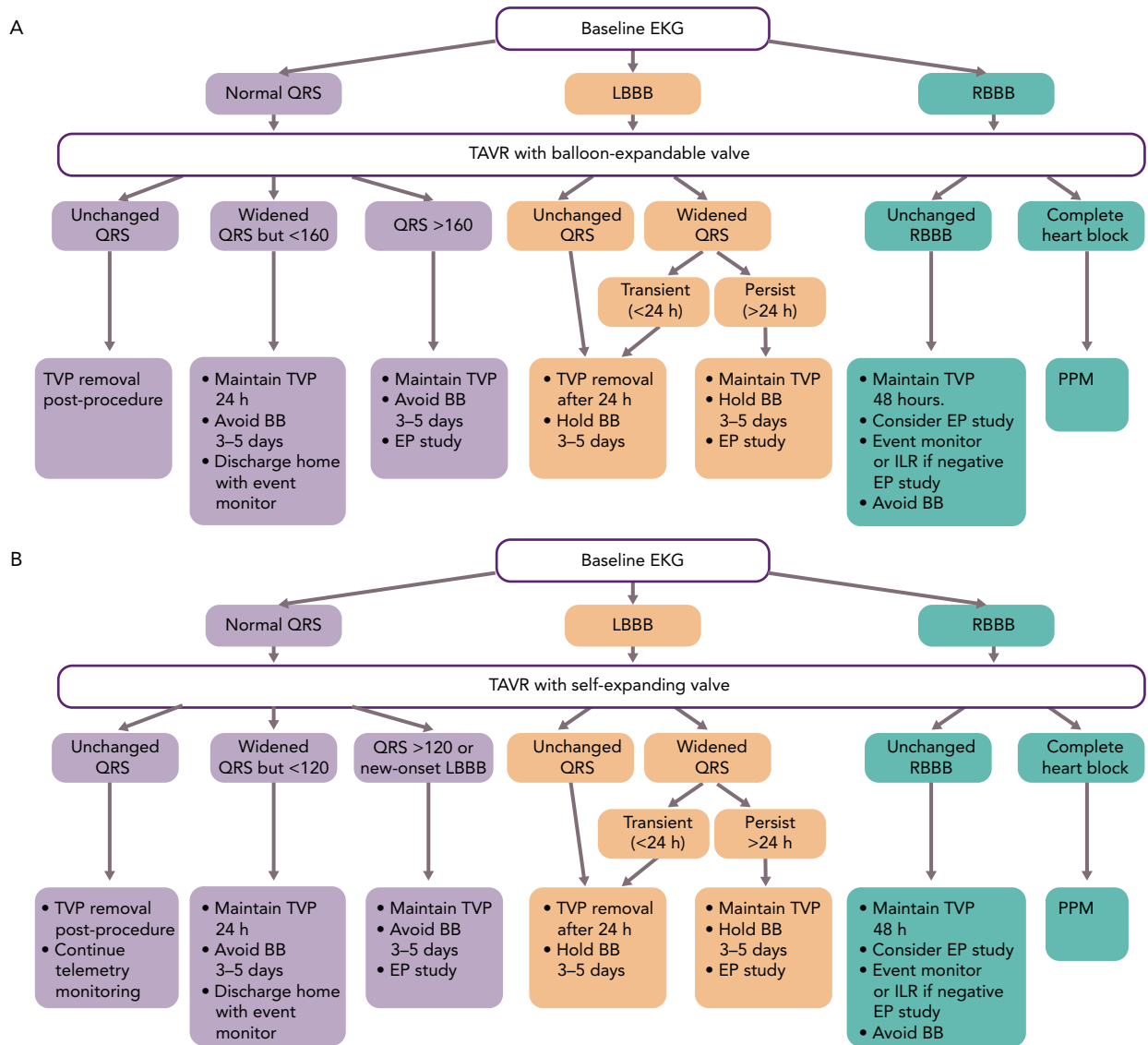
LBBB = left bundle branch block; LCC = left coronary cusp; LVOT = left ventricular outflow tract; PPI = permanent pacemaker implantation; RBBB = right bundle branch block; RCC = right coronary cusp; TAVR = transcatheter aortic valve replacement; THV = transcatheter heart valve.

Predictors and Outcomes of Permanent Pacemaker Implantation Following TAVR

Positive predictors of PPI post-TAVR are age, male sex, baseline conduction disturbances, intraprocedural atrioventricular block (AVB), narrow LVOT, the severity of mitral annular calcification, and use of self-expanding valve (Table 2).^{24,76,77} Patients who received PPI were more likely to have larger THVs implanted, higher oversizing, larger left ventricular internal diastolic dimensions, larger aortic valve annular size, larger aortic valve area, and lower aortic valve mean gradient.⁷⁶ Moreover, septal bulge can result in a smaller LVOT and increased prosthesis:LVOT diameter ratio, which increases risk of PPI.⁷³ PPI was associated with longer hospital and intensive care unit stays,^{73,76} and significantly increased cost associated with TAVR.^{78–80} Most studies reported a median time of 3 days from TAVR to PPI, and almost 90% of PPIs were performed within 7 days of TAVR.^{73,76,81,82} It is believed that conduction abnormalities occurring at a later time are a result of edema and late expansion of the THV prosthesis.^{83,84}

Chronic right ventricular pacing causes electrical and mechanical dyssynchrony, and has been associated with a deleterious effect on left ventricular function and an increased risk of heart failure hospitalizations in patients with pre-existing heart failure.^{85–87} Among TAVR patients, several studies have shown a negative effect of PPI on left ventricular function at both short- and long-term follow up.^{30,81,88–90} A retrospective cohort study of patients undergoing TAVR at 229 sites in the US was performed using the Society of Thoracic Surgeons/American College of Cardiology Transcatheter Valve Therapy (STS/ACC TVT) registry and the Centers for Medicare and Medicaid Services database. The study found that PPI was required within 30 days of TAVR in 6.7% of cases and varied

Figure 2: Treatment Algorithms for Management of Conduction Abnormalities Following Transcatheter Aortic Valve Replacement



A: Treatment algorithms for management of conduction abnormalities following TAVR with balloon-expandable valves. B: Treatment algorithms for management of conduction abnormalities following TAVR with self-expanding valves. BB = beta-blocker; EP = electrophysiology; ILR = implantable loop recorder; LBBB = left bundle branch block; PPM = permanent pacemaker; RBBB = right bundle branch block; TVP = transvenous pacemaker.

among those receiving self-expanding THVs (25.1%) versus balloon-expanding THVs (4.3%).⁷⁶ Early PPI is a common complication following TAVR and was associated with higher mortality and composite endpoint of mortality or heart failure admission at 1 year.⁷⁶

Conversely, another recent multicenter study showed PPI was associated with an increased risk of heart failure rehospitalization and lack of LVEF improvement, but not total mortality or cardiac mortality, after a median 4-year follow up.⁹⁰ A meta-analysis by Regueiro et al. also failed to show any association between PPI and mortality (total and cardiovascular),⁴¹ which was similar to the Surgical Replacement and Transcatheter Aortic Valve Implantation (SURTAVI) trial that did not show any effect of new PPI post-TAVR on 2-year mortality.⁴

A study from the PARTNER trial and registry confirmed PPI after TAVR had higher rates of repeat hospitalization and a longer duration of hospitalization, but did not show any association with 1-year mortality.⁷³ Whether more long-term follow-up is needed to better evaluate this risk of PPI on post-TAVR mortality is yet to be determined, particularly as the therapy extends to low-risk aortic stenosis patients.

Management of Conduction Abnormalities After Transcatheter Aortic Valve Replacement

Toggweiler et al. evaluated a cohort of 1,064 patients who underwent TAVR; 6.7% of patients developed delayed HAVB, of which most cases occurred within the first 48 hours, and 2.3% had HAVB at 3-8 days post-TAVR.⁹¹ The rates of delayed HAVB in patients with complete RBBB,

LBBB, and without bundle branch block (BBB) are 27%, 11%, and 2%, respectively.⁹¹ A first-degree AVB was associated with a higher probability of subsequent HAVB.⁹¹ Overall, the presence of conduction disorders (BBB, first-degree AVB, or bradycardia in patients with AF) on the EKG post-TAVR had high sensitivity (99.0%) and negative predictive value (99.7%) for the occurrence of delayed HAVB.⁹¹ The authors propose a treatment algorithm for the management of conduction abnormalities post-TAVR (Figure 2).

Without Conduction Disorders

Patients without new BBB and first-degree AVB did not develop HAVB at 30 days post-TAVR.⁹¹ Moreover, the rate of HAVB was low in patients with AF without BBB or bradycardia.⁹¹ The temporary venous pacemaker (TVP) can be removed immediately post-procedure, and telemetry monitoring and a daily 12-lead EKG can be continued. Patients without new BBB and first-degree AVB may be candidates for early discharge.

With a New Left Bundle Branch Block or First-degree Atrioventricular Block

The risk of HAVB is highest in patients with pre-existing RBBB, followed by those with LBBB, and first-degree AVB. It is recommended that TVP is maintained in patients with RBBB and LBBB, and that telemetry monitoring and a daily 12-lead EKG is continued. Avoid atrioventricular nodal blocking agents. In patients with a balloon-expandable THV, consider electrophysiology study if there is a worsening PR interval or the PR interval is >200 ms, or QRS duration is >160 ms in the first 48 hours. However, if the PR interval is stable and QRS duration is <160 ms in the

first 48 hours, patients can be discharged home with an event monitor. In patients with a self-expandable THV, consider electrophysiology study with development of a new LBBB. A HV interval >65 ms may be suggestive of a significant conduction abnormality and warrant PPI; patients with a HV interval <65 ms can be discharged home with an event monitor. High-risk patients, such as those with baseline RBBB and bifascicular blocks, may warrant long-term monitoring with an implantable loop recorder if early event monitoring is unremarkable.

With Post-procedural High-grade Atrioventricular Block

PPI is indicated for either third-degree or advanced second-degree AVB at any anatomic level, which is not expected to resolve, or in the presence of sinus node dysfunction and documented symptomatic bradycardia.⁹²

TAVR represents a valid option for treatment of severe symptomatic aortic stenosis. Post-TAVR conduction abnormalities are still a common complication following both self- and balloon-expandable THVs. Predictors of TAVR-induced LBBB and PPI depend on baseline patient characteristics such as preoperative EKG pattern, anatomy of the AVN, His bundle, and surrounding structures, as well as intra-procedural technical factors.

There is no consensus on how to prevent and/or treat post-TAVR conduction abnormalities. Protocols vary among operators and valve centers. New generation THVs and modified techniques for valve implantation may help to reduce the prevalence of PPI. Further studies are required to validate and establish universal algorithms to manage conduction abnormalities following TAVR, irrespective of the prosthesis type. ■

- Leon MB, Smith CR, Mack M, et al. Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. *N Engl J Med* 2010;363:1597–607. <https://doi.org/10.1056/NEJMoa1008232>; PMID: 20961243.
- Smith CR, Leon MB, Mack MJ, et al. Transcatheter versus surgical aortic-valve replacement in high-risk patients. *N Engl J Med* 2011;364:2187–98. <https://doi.org/10.1056/NEJMoa1103510>; PMID: 21639811.
- Adams DH, Popma JJ, Reardon MJ, et al. Transcatheter aortic-valve replacement with a self-expanding prosthesis. *N Engl J Med* 2014;370:1790–8. <https://doi.org/10.1056/NEJMoa1400590>; PMID: 24678937.
- Reardon MJ, Van Mieghem NM, Popma JJ, et al. Surgical or Transcatheter Aortic-Valve Replacement in Intermediate-Risk Patients. *N Engl J Med* 2017;376:1321–31. <https://doi.org/10.1056/NEJMoa1700456>; PMID: 28304219.
- Leon MB, Smith CR, Mack MJ, et al. Transcatheter or surgical aortic-valve replacement in intermediate-risk patients. *N Engl J Med* 2016;374:1609–20. <https://doi.org/10.1056/NEJMoa1514616>; PMID: 27040324.
- van der Boon RM, Nuis RJ, Van Mieghem NM, et al. New conduction abnormalities after TAVI – frequency and causes. *Nat Rev Cardiol* 2012;9:454–63. <https://doi.org/10.1038/nrcardio.2012.58>; PMID: 22547171.
- Urena M, Rodes-Cabau J. Conduction abnormalities: the true Achilles' heel of transcatheter aortic valve replacement? *JACC Cardiovasc Interv* 2016;9:2217–9. <https://doi.org/10.1016/j.jcin.2016.09.040>; PMID: 27832847.
- Urena M, Rodes-Cabau J. Managing heart block after transcatheter aortic valve implantation: from monitoring to device selection and pacemaker indications. *Eurointervention* 2015;11(Suppl W):W101–5. <https://doi.org/10.4244/EIJV11SWA30>; PMID: 26384171.
- Kappetein AP, Head SJ, Genereux P, et al. Updated standardized endpoint definitions for transcatheter aortic valve implantation: the Valve Academic Research Consortium-2 consensus document. *J Am Coll Cardiol* 2012;60:1438–54. <https://doi.org/10.1016/j.jacc.2012.09.001>; PMID: 23036636.
- Barbanti M, Capranzano P, Ohno Y, et al. Early discharge after transfemoral transcatheter aortic valve implantation. *Heart* 2015;101:1485–90. <https://doi.org/10.1136/heartjnl-2014-307351>; PMID: 26076940.
- Durand E, Eltchaninoff H, Canville A, et al. Feasibility and safety of early discharge after transfemoral transcatheter aortic valve implantation with the Edwards SAPIEN-XT prosthesis. *Am J Cardiol* 2015;115:1116–22. <https://doi.org/10.1016/j.amjcard.2015.01.546>; PMID: 25726383.
- Noad RL, Johnston N, McKinley A, et al. A pathway to earlier discharge following TAVI: assessment of safety and resource utilization. *Catheter Cardiovasc Interv* 2016;87:134–42. <https://doi.org/10.1002/ccd.26005>; PMID: 26010269.
- Piazza N, de Jaegere P, Schultz C, et al. Anatomy of the aortic valvar complex and its implications for transcatheter implantation of the aortic valve. *Circ Cardiovasc Interv* 2008;1:74–81. <https://doi.org/10.1161/CIRCINTERVENTIONS.108.780858>; PMID: 20031657.
- Kawashima T, Sato F. Visualizing anatomical evidences on atrioventricular conduction system for TAVI. *Int J Cardiol* 2014;174:1–6. <https://doi.org/10.1016/j.ijcard.2014.04.003>; PMID: 24750717.
- El-Khally Z, Thibault B, Staniloae C, et al. Prognostic significance of newly acquired bundle branch block after aortic valve replacement. *Am J Cardiol* 2004;94:1008–11. <https://doi.org/10.1016/j.amjcard.2004.06.055>; PMID: 15476613.
- Van Mieghem NM, Head SJ, de Jong W, et al. Persistent annual permanent pacemaker implantation rate after surgical aortic valve replacement in patients with severe aortic stenosis. *Ann Thorac Surg* 2012;94:1143–9. <https://doi.org/10.1016/j.athoracsur.2012.04.038>; PMID: 22698776.
- Habicht JM, Scherr P, Zerkowski HR, Hoffmann A. Late conduction defects following aortic valve replacement. *J Heart Valve Dis* 2000;9:629–32. PMID: 11041175.
- Tjang YS, van Hees Y, Korfer R, et al. Predictors of mortality after aortic valve replacement. *Eur J Cardiothorac Surg* 2007;32:469–74. <https://doi.org/10.1016/j.ejcts.2007.06.012>; PMID: 17658266.
- Ennker J, Albert A, Ennker IC. Stentless aortic valves. Current aspects. *HSR Proc Intensive Care Cardiovasc Anesth* 2012;4:77–82. PMID: 23439732.
- van Boxel AG, Houthuizen P, Hamad MA, et al. Postoperative conduction disorders after implantation of the self-expandable sutureless Perceval S bioprosthesis. *J Heart Valve Dis* 2014;23:319–24. PMID: 25296456.
- Regeer MV, Merckstein LR, de Weger A, et al. Left bundle branch block after sutureless, transcatheter, and stented biological aortic valve replacement for aortic stenosis. *Eurointervention* 2017;12:1660–6. <https://doi.org/10.4244/EIJ-D-15-00256>; PMID: 28106000.
- Blanke P, Willson AB, Webb JG, et al. Oversizing in transcatheter aortic valve replacement: a commonly used term but a poorly understood one: dependency on definition and geometrical measurements. *J Cardiovasc Comput Tomogr* 2014;8:67–76. <https://doi.org/10.1016/j.jcct.2013.12.020>; PMID: 24582045.
- Bax JJ, Delgado V, Bapat V, et al. Open issues in transcatheter aortic valve implantation. Part 2: procedural issues and outcomes after transcatheter aortic valve implantation. *Eur Heart J* 2014;35:2639–54. <https://doi.org/10.1093/eurheartj/ehu257>; PMID: 25062953.
- Siontis GC, Juni P, Pilgrim T, et al. Predictors of permanent pacemaker implantation in patients with severe aortic stenosis undergoing TAVR: a meta-analysis. *J Am Coll Cardiol* 2014;64:129–40. <https://doi.org/10.1016/j.jacc.2014.04.033>; PMID: 25011716.
- Testa L, Latib A, De Marco F, et al. Clinical impact of persistent left bundle-branch block after transcatheter aortic valve implantation with CoreValve Revalving System. *Circulation* 2013;127:1300–7. <https://doi.org/10.1161/CIRCULATIONAHA.112.001099>; PMID: 23443735.
- Houthuizen P, Van Garsse LA, Poels TT, et al. Left bundle-branch block induced by transcatheter aortic valve implantation increases risk of death. *Circulation* 2012;126:720–8. <https://doi.org/10.1161/CIRCULATIONAHA.112.101055>; PMID: 22791865.
- De Carlo M, Giannini C, Bedogni F, et al. Safety of a conservative strategy of permanent pacemaker implantation after transcatheter aortic CoreValve implantation. *Am Heart J* 2012;163:492–9. <https://doi.org/10.1016/j.ahj.2011.12.009>; PMID: 22424022.
- Aktug O, Dohmen G, Brehmer K, et al. Incidence and predictors of left bundle branch block after transcatheter aortic valve implantation. *Int J Cardiol* 2012;160:26–30. <https://doi.org/10.1016/j.ijcard.2011.03.004>; PMID: 21458085.
- Nuis RJ, Van Mieghem NM, Schultz CJ, et al. Timing and potential mechanisms of new conduction abnormalities during the implantation of the Medtronic CoreValve System in patients with aortic stenosis. *Eur Heart J* 2011;32:2067–74. <https://doi.org/10.1093/eurheartj/ehr110>; PMID: 21622979.
- Tzikas A, van Dalen BM, Van Mieghem NM, et al. Frequency of conduction abnormalities after transcatheter aortic valve implantation with the Medtronic-CoreValve and the effect on left ventricular ejection fraction. *Am J Cardiol* 2011;107:285–9. <https://doi.org/10.1016/j.amjcard.2010.09.015>; PMID: 21129715.

31. Khawaja MZ, Rajani R, Cook A, et al. Permanent pacemaker insertion after CoreValve transcatheter aortic valve implantation: incidence and contributing factors (the UK CoreValve Collaborative). *Circulation* 2011;123:951–60. <https://doi.org/10.1161/CIRCULATIONAHA.109.927152>; PMID: 21339482.
32. Piazza N, Nuis RJ, Tzikas A, et al. Persistent conduction abnormalities and requirements for pacemaking six months after transcatheter aortic valve implantation. *EuroIntervention* 2010;6:475–84. <https://doi.org/10.4244/EUJ30V6I4A80>; PMID: 20884435.
33. Urena M, Mok M, Serra V, et al. Predictive factors and long-term clinical consequences of persistent left bundle branch block following transcatheter aortic valve implantation with a balloon-expandable valve. *J Am Coll Cardiol* 2012;60:1743–52. <https://doi.org/10.1016/j.jacc.2012.07.035>; PMID: 23040577.
34. Laynez A, Ben-Dor I, Barbash IM, et al. Frequency of conduction disturbances after Edwards SAPIEN percutaneous valve implantation. *Am J Cardiol* 2012;110:1164–8. <https://doi.org/10.1016/j.amjcard.2012.05.057>; PMID: 22770935.
35. Abdel-Wahab M, Mehilli J, Frerker C, et al. Comparison of balloon-expandable vs self-expandable valves in patients undergoing transcatheter aortic valve replacement: the CHOICE randomized clinical trial. *JAMA* 2014;311:1503–14. <https://doi.org/10.1001/jama.2014.3316>; PMID: 24682026.
36. Barbanti M, Gulino S, Costa G, Tamburino C. Pathophysiology, incidence and predictors of conduction disturbances during Transcatheter Aortic Valve Implantation. *Expert Rev Med Devices* 2017;14:135–47. <https://doi.org/10.1080/17434440.2017.1282819>; PMID: 28092726.
37. Boerlage-Van Dijk K, Kooiman KM, Yong ZY, et al. Predictors and permanency of cardiac conduction disorders and necessity of pacing after transcatheter aortic valve implantation. *Pacing Clin Electrophysiol* 2014;37:1520–9. <https://doi.org/10.1111/pace.12460>; PMID: 25040838.
38. Urena M, Webb JG, Cheema A, et al. Impact of new-onset persistent left bundle branch block on late clinical outcomes in patients undergoing transcatheter aortic valve implantation with a balloon-expandable valve. *JACC Cardiovasc Interv* 2014;7:128–36. <https://doi.org/10.1016/j.jcin.2013.08.015>; PMID: 24440024.
39. Franzoni I, Latib A, Maisano F, et al. Comparison of incidence and predictors of left bundle branch block after transcatheter aortic valve implantation using the CoreValve versus the Edwards valve. *Am J Cardiol* 2013;112:554–9. <https://doi.org/10.1016/j.amjcard.2013.04.026>; PMID: 23726173.
40. Auffret V, Puri R, Urena M, et al. Conduction disturbances after transcatheter aortic valve replacement: current status and future perspectives. *Circulation* 2017;136:1049–69. <https://doi.org/10.1161/CIRCULATIONAHA.117.028352>; PMID: 28893961.
41. Regueiro A, Abdul-Jawad Altisent O, Del Trigo M, et al. Impact of new-onset left bundle branch block and periprocedural permanent pacemaker implantation on clinical outcomes in patients undergoing transcatheter aortic valve replacement: a systematic review and meta-analysis. *Circ Cardiovasc Interv* 2016;9:e003635. <https://doi.org/10.1161/CIRCINTERVENTIONS.115.003635>; PMID: 27169577.
42. van der Boon RM, Houhuizen P, Urena M, et al. Trends in the occurrence of new conduction abnormalities after transcatheter aortic valve implantation. *Catheter Cardiovasc Interv* 2015;85:E144–52. <https://doi.org/10.1002/ccd.25765>; PMID: 25504891.
43. De Torres-Alba F, Kaleschke G, Diller GP, et al. Changes in the pacemaker rate after transition from Edwards SAPIEN XT to SAPIEN 3 transcatheter aortic valve implantation: the critical role of valve implantation height. *JACC Cardiovasc Interv* 2016;9:805–13. <https://doi.org/10.1016/j.jcin.2015.12.023>; PMID: 27017367.
44. Tarantini G, Mojoli M, Purita P, et al. Unravelling the (arte) fact of increased pacemaker rate with the Edwards SAPIEN 3 valve. *EuroIntervention* 2015;11:343–50. https://doi.org/10.4244/EIJY14M11_06; PMID: 25405801.
45. Webb J, Gerosa G, Lefevre T, et al. Multicenter evaluation of a next-generation balloon-expandable transcatheter aortic valve. *J Am Coll Cardiol* 2014;64:2235–43. <https://doi.org/10.1016/j.jacc.2014.09.026>; PMID: 25456759.
46. Murray MI, Geis N, Plegler ST, et al. First experience with the new generation Edwards Sapien 3 aortic bioprosthesis: procedural results and short term outcome. *J Interv Cardiol* 2015;28:109–16. <https://doi.org/10.1111/joic.12182>; PMID: 25689554.
47. Binder RK, Stortecky S, Heg D, et al. Procedural results and clinical outcomes of transcatheter aortic valve implantation in Switzerland: an observational cohort study of Sapien 3 versus Sapien XT transcatheter heart valves. *Circ Cardiovasc Interv* 2015;8. <https://doi.org/10.1161/CIRCINTERVENTIONS.115.002653>; PMID: 26453687.
48. Schymik G, Lefevre T, Bartorelli AL, et al. European experience with the second-generation Edwards SAPIEN XT transcatheter heart valve in patients with severe aortic stenosis: 1-year outcomes from the SOURCE XT Registry. *JACC Cardiovasc Interv* 2015;8:657–69. <https://doi.org/10.1016/j.jcin.2014.10.026>; PMID: 25946437.
49. Gilard M, Eltchaninoff H, Lung B, et al. Registry of transcatheter aortic-valve implantation in high-risk patients. *N Engl J Med* 2012;366:1705–15. <https://doi.org/10.1056/NEJMoa1114705>; PMID: 22551129.
50. Kazuno Y, Maeno Y, Kawamori H, et al. Comparison of SAPIEN 3 and SAPIEN XT transcatheter heart valve stent-frame expansion: evaluation using multi-slice computed tomography. *Eur Heart J Cardiovasc Imaging* 2016;17:1054–62. <https://doi.org/10.1093/ehjci/jew032>; PMID: 27002141.
51. Forrest JK, Mangi AA, Popma JJ, et al. Early Outcomes With the Evolut PRO Repositionable Self-Expanding Transcatheter Aortic Valve With Pericardial Wrap. *JACC Cardiovasc Interv* 2018;11:160–8. <https://doi.org/10.1016/j.jcin.2017.10.014>; PMID: 29348010.
52. Zannad F, Huelvel E, Dickstein K, et al. Left bundle branch block as a risk factor for progression to heart failure. *Eur J Heart Fail* 2007;9:7–14. <https://doi.org/10.1016/j.ejheart.2006.04.011>; PMID: 16890486.
53. Zhang ZM, Rautaharju PM, Soliman EZ, et al. Mortality risk associated with bundle branch blocks and related repolarization abnormalities (from the Women's Health Initiative [WHI]). *Am J Cardiol* 2012;110:1489–95. <https://doi.org/10.1016/j.amjcard.2012.06.060>; PMID: 22858187.
54. Gutierrez M, Rodes-Cabau J, Bagur R, et al. Electrocardiographic changes and clinical outcomes after transapical aortic valve implantation. *Am Heart J* 2009;158:302–8. <https://doi.org/10.1016/j.ahj.2009.05.029>; PMID: 19619709.
55. Sinhal A, Altwegg L, Pasupati S, et al. Atrioventricular block after transcatheter balloon expandable aortic valve implantation. *JACC Cardiovasc Interv* 2008;1:305–9. <https://doi.org/10.1016/j.jcin.2007.12.009>; PMID: 19463318.
56. Piazza N, Onuma Y, Jesserun E, et al. Early and persistent intraventricular conduction abnormalities and requirements for pacemaking after percutaneous replacement of the aortic valve. *JACC Cardiovasc Interv* 2008;1:310–6. <https://doi.org/10.1016/j.jcin.2008.04.007>; PMID: 19463319.
57. Godin M, Eltchaninoff H, Furuta A, et al. Frequency of conduction disturbances after transcatheter implantation of an Edwards Sapien aortic valve prosthesis. *Am J Cardiol* 2010;106:707–12. <https://doi.org/10.1016/j.amjcard.2010.04.029>; PMID: 20723650.
58. Nazif TM, Williams MR, Hahn RT, et al. Clinical implications of new-onset left bundle branch block after transcatheter aortic valve replacement: analysis of the PARTNER experience. *Eur Heart J* 2014;35:1599–607. <https://doi.org/10.1093/eurheartj/ehu376>; PMID: 24179072.
59. Yu CM, Chan JY, Zhang Q, et al. Biventricular pacing in patients with bradycardia and normal ejection fraction. *N Engl J Med* 2009;361:2123–34. <https://doi.org/10.1056/NEJMoa0907555>; PMID: 19915226.
60. Vernooij K, Verbeek XA, Peschar M, et al. Left bundle branch block induces ventricular remodelling and functional septal hypoperfusion. *Eur Heart J* 2005;26:91–8. <https://doi.org/10.1093/eurheartj/ehi008>; PMID: 15615805.
61. Saji M, Murai T, Tobaru T, et al. Autopsy finding of the Sapien XT valve from a patient who died suddenly after transcatheter aortic valve replacement. *Cardiovasc Interv Ther* 2013;28:267–71. <https://doi.org/10.1007/s12928-012-0153-9>; PMID: 23277347.
62. Urena M, Webb JG, Eltchaninoff H, et al. Late cardiac death in patients undergoing transcatheter aortic valve replacement: incidence and predictors of advanced heart failure and sudden cardiac death. *J Am Coll Cardiol* 2015;65:437–48. <https://doi.org/10.1016/j.jacc.2014.11.027>; PMID: 25660921.
63. Hamdan A, Guetta V, Klempfner R, et al. Inverse relationship between membranous septal length and the risk of atrioventricular block in patients undergoing transcatheter aortic valve implantation. *JACC Cardiovasc Interv* 2015;8:1218–28. <https://doi.org/10.1016/j.jcin.2015.05.010>; PMID: 26292585.
64. Roten L, Wenaweser P, Delacretaz E, et al. Incidence and predictors of atrioventricular conduction impairment after transcatheter aortic valve implantation. *Am J Cardiol* 2010;106:1473–80. <https://doi.org/10.1016/j.amjcard.2010.07.012>; PMID: 21059439.
65. Guetta V, Goldenberg G, Segev A, et al. Predictors and course of high-degree atrioventricular block after transcatheter aortic valve implantation using the CoreValve Revalving System. *Am J Cardiol* 2011;108:1600–5. <https://doi.org/10.1016/j.amjcard.2011.07.020>; PMID: 21880290.
66. Lenders GD, Collas V, Hernandez JM, et al. Depth of valve implantation, conduction disturbances and pacemaker implantation with CoreValve and CoreValve Accutrak system for Transcatheter Aortic Valve Implantation, a multi-center study. *Int J Cardiol* 2014;176:771–5. <https://doi.org/10.1016/j.ijcard.2014.07.092>; PMID: 25147076.
67. Mauri V, Reimann A, Stern D, et al. Predictors of permanent pacemaker implantation after transcatheter aortic valve replacement with the SAPIEN 3. *JACC Cardiovasc Interv* 2016;9:2200–9. <https://doi.org/10.1016/j.jcin.2016.08.034>; PMID: 27832845.
68. Jilalawi H, Chin D, Vasa-Nicotera M, et al. Predictors for permanent pacemaker requirement after transcatheter aortic valve implantation with the CoreValve bioprosthesis. *Am Heart J* 2009;157:860–6. <https://doi.org/10.1016/j.ahj.2009.02.016>; PMID: 19376312.
69. Tzamtzis S, Viquerat J, Yap J, et al. Numerical analysis of the radial force produced by the Medtronic-CoreValve and Edwards-SAPIEN after transcatheter aortic valve implantation (TAVI). *Med Eng Phys* 2013;35:125–30. <https://doi.org/10.1016/j.medengphy.2012.04.009>; PMID: 22640661.
70. Bussink BE, Holst AG, Jespersen L, et al. Right bundle branch block: prevalence, risk factors, and outcome in the general population: results from the Copenhagen City Heart Study. *Eur Heart J* 2013;34:138–46. <https://doi.org/10.1093/eurheartj/ehs291>; PMID: 22947613.
71. Xiong Y, Wang L, Liu W, et al. The prognostic significance of right bundle branch block: a meta-analysis of prospective cohort studies. *Clin Cardiol* 2015;38:604–13. <https://doi.org/10.1002/clc.22454>; PMID: 26436874.
72. Chorianopoulos E, Krumsdorf U, Plegler ST, et al. Incidence of late occurring bradyarrhythmias after TAVI with the self-expanding CoreValve® aortic bioprosthesis. *Clin Res Cardiol* 2012;101:349–55. <https://doi.org/10.1007/s00392-011-0398-9>; PMID: 22179559.
73. Nazif TM, Dizon JM, Hahn RT, et al. Predictors and clinical outcomes of permanent pacemaker implantation after transcatheter aortic valve replacement: the PARTNER (Placement of Aortic Transcatheter Valves) trial and registry. *JACC Cardiovasc Interv* 2015;8:60–9. <https://doi.org/10.1016/j.jcin.2014.07.022>; PMID: 25616819.
74. Watanabe Y, Kozuma K, Hioki H, et al. Pre-existing right bundle branch block increases risk for death after transcatheter aortic valve replacement with a balloon-expandable valve. *JACC Cardiovasc Interv* 2016;9:2210–6. <https://doi.org/10.1016/j.jcin.2016.08.035>; PMID: 27832846.
75. Auffret V, Webb JG, Eltchaninoff H, et al. Clinical impact of baseline right bundle branch block in patients undergoing transcatheter aortic valve replacement. *JACC Cardiovasc Interv* 2017;10:1564–74. <https://doi.org/10.1016/j.jcin.2017.05.030>; PMID: 28734885.
76. Fadahunsi OO, Olowoyeye A, Ukaigwe A, et al. Incidence, predictors, and outcomes of permanent pacemaker implantation following transcatheter aortic valve replacement: analysis from the U.S. Society of Thoracic Surgeons/American College of Cardiology TVT Registry. *JACC Cardiovasc Interv* 2016;9:2189–99. <https://doi.org/10.1016/j.jcin.2016.07.026>; PMID: 27832844.
77. Baan J Jr, Yong ZY, Koch KT, et al. Factors associated with cardiac conduction disorders and permanent pacemaker implantation after percutaneous aortic valve implantation with the CoreValve prosthesis. *Am Heart J* 2010;159:497–503. <https://doi.org/10.1016/j.ahj.2009.12.009>; PMID: 20211315.
78. Chevrel K, Brunn M, Cadier B, et al. Cost of transcatheter aortic valve implantation and factors associated with higher hospital stay cost in patients of the FRANCE (French Aortic National CoreValve and Edwards) registry. *Arch Cardiovasc Dis* 2013;106:209–19. <https://doi.org/10.1016/j.acvd.2013.01.006>; PMID: 23706367.
79. Babaliaros V, Devireddy C, Lerakis S, et al. Comparison of transfemoral transcatheter aortic valve replacement performed in the catheterization laboratory (minimalist approach) versus hybrid operating room (standard approach): outcomes and cost analysis. *JACC Cardiovasc Interv* 2014;7:898–904. <https://doi.org/10.1016/j.jcin.2014.04.005>; PMID: 25086843.
80. Reynolds MR, Magnuson EA, Lei Y, et al. Cost-effectiveness of transcatheter aortic valve replacement compared with surgical aortic valve replacement in high-risk patients with severe aortic stenosis: results of the PARTNER (Placement of Aortic Transcatheter Valves) trial (Cohort A). *J Am Coll Cardiol* 2012;60:2683–92. <https://doi.org/10.1016/j.jacc.2012.09.018>; PMID: 23122802.
81. Urena M, Webb JG, Tamburino C, et al. Permanent pacemaker implantation after transcatheter aortic valve implantation: impact on late clinical outcomes and left ventricular function. *Circulation* 2014;129:1233–43. <https://doi.org/10.1161/CIRCULATIONAHA.113.005479>; PMID: 24370552.
82. Buellesfeld L, Stortecky S, Heg D, et al. Impact of permanent pacemaker implantation on clinical outcome among patients undergoing transcatheter aortic valve implantation. *J Am Coll Cardiol* 2012;60:493–501. <https://doi.org/10.1016/j.jacc.2012.03.054>; PMID: 22726632.
83. Steinberg BA, Harrison JK, Frazier-Mills C, et al. Cardiac conduction system disease after transcatheter aortic valve replacement. *Am Heart J* 2012;164:664–71. <https://doi.org/10.1016/j.ahj.2012.07.028>; PMID: 23137496.
84. Akin I, Kische S, Schneider H, et al. Surface and intracardiac ECG for discriminating conduction disorders after CoreValve implantation. *Clin Res Cardiol* 2012;101:357–64. <https://doi.org/10.1007/s00392-011-0400-6>; PMID: 22179507.
85. Curtis AB, Worley SJ, Adamson PB, et al. Biventricular pacing for atrioventricular block and systolic dysfunction. *N Engl J Med* 2013;368:1585–93. <https://doi.org/10.1056/NEJMoa1210356>; PMID: 23614585.
86. Steinberg JS, Fischer A, Wang P, et al. The clinical implications of cumulative right ventricular pacing in the multicenter automatic defibrillator trial II. *J Cardiovasc Electrophysiol* 2005;16:359–65. <https://doi.org/10.1046/j.1540->

- 8167.2005.50038.x; PMID: 15828875.
87. Moss AJ, Zareba W, Hall WJ, et al. Prophylactic implantation of a defibrillator in patients with myocardial infarction and reduced ejection fraction. *N Engl J Med* 2002;346:877–83. <https://doi.org/10.1056/NEJMoa013474>; PMID: 11907286.
 88. Hoffmann R, Herpertz R, Lotfipour S, et al. Impact of a new conduction defect after transcatheter aortic valve implantation on left ventricular function. *JACC Cardiovasc Interv* 2012;5:1257–63. <https://doi.org/10.1016/j.jcin.2012.08.011>; PMID: 23257374.
 89. Dizon JM, Nazif TM, Hess PL, et al. Chronic pacing and adverse outcomes after transcatheter aortic valve implantation. *Heart* 2015;101:1665–71. <https://doi.org/10.1136/heartjnl-2015-307666>; PMID: 26261157.
 90. Chamandi C, Barbanti M, Munoz-Garcia A, et al. Long-term outcomes in patients with new permanent pacemaker implantation following transcatheter aortic valve replacement. *JACC Cardiovasc Interv* 2018;11:301–10. <https://doi.org/10.1016/j.jcin.2017.10.032>; PMID: 29413244.
 91. Toggweiler S, Stortecky S, Holy E, et al. The Electrocardiogram after transcatheter aortic valve replacement determines the risk for post-procedural high-degree AV Block and the need for telemetry monitoring. *JACC Cardiovasc Interv* 2016;9:1269–76. <https://doi.org/10.1016/j.jcin.2016.03.024>; PMID: 27339844.
 92. Epstein AE, DiMarco JP, Ellenbogen KA, et al. 2012 ACCF/AHA/HRS focused update incorporated into the ACCF/AHA/HRS 2008 guidelines for device-based therapy of cardiac rhythm abnormalities: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines and the Heart Rhythm Society. *J Am Coll Cardiol* 2013;61:e6–75. <https://doi.org/10.1016/j.jacc.2012.11.007>; PMID: 23265327.