Transcatheter aortic valve implantation: past, present and future

Transcatheter aortic valve implantation is one of the most significant technological advances in cardiovascular medicine. It offers a safe alternative in high risk cardiac patients with proven durability, economical viability and survival advantage. Current trials may expand its application in intermediate or low risk groups.

In recent decades we have seen a significant increase in global life expectancy. The incidence of cardiovascular conditions such as valvular heart disease is particularly prevalent in the ageing population and therefore rising as the age profile of the population changes. The prevalence of aortic stenosis in octogenarians is approximately 40% (Malhotra, 2012) and in one study the incidence of 'critical' aortic valve stenosis in Europe was 2.9% in those aged between 75 and 86 years. This is a particularly important health issue because the prognosis of these conditions is poor: survival after the onset of symptoms in aortic stenosis is 50% at 2 years, which emphasizes the need for early diagnosis and timely intervention (Lindroos et al, 1993).

Although conventional surgical aortic valve replacement still remains the gold standard for low to moderate risk patients with aortic stenosis, transcatheter aortic valve implantation is a less invasive alternative and has now become the treatment of choice in patients who are deemed high risk for surgical aortic valve replacement or those who are inoperable. This review discusses the historical background, indications and technical aspects of the transcatheter aortic valve implantation procedure.

Transcatheter valvular interventions (of which transcatheter aortic valve implantation is one procedure) represent one of the most significant technological advances made in cardiovascular medicine in the last decade. The first-in-man transcatheter aortic valve implantation was performed in Rouen in 2002 by Professor Alain Cribier (Cribier et al, 2002). Thereafter rapid uptake of this technique has led to more than 200 000 cases being performed globally. First generation devices, the Medtronic CoreValve and Edwards Sapien, have demonstrated improved short- and long-term clinical outcomes when compared with medical management in inoperable aortic stenosis patients and outcomes similar to surgical aortic valve replacement in high-risk patients (Leon et al, 2010; Smith et al, 2011).

Despite transcatheter aortic valve implantation being performed in older, higher risk populations, the length of hospital stay is currently similar to that for surgical aortic valve replacement and is decreasing (Ludman et al, 2015). As such, transcatheter aortic valve implantation may provide economic advantages in both the hospital and post-discharge setting (Awad et al, 2014). Trials of transcatheter aortic valve implantation have demonstrated device durability and sustained improvement in prognosis (Kapadia et al, 2015).

Long-term results of the PARTNER A trial have shown that transcatheter aortic valve implantation in high-risk patients achieved similar long-term clinical outcomes to patients undergoing surgical aortic valve replacement (Sehatzadeh et al, 2013). Furthermore, the results from the more recent CoreValve US Pivotal Trial, which studied long-term outcomes in patients who received the self-expanding CoreValve compared to surgical aortic valve replacement, indicated that patients in the transcatheter aortic valve implantation group had a better survival than those undergoing surgical aortic valve replacement. At 2 years the mortality rate was 22.2% for transcatheter aortic valve implantation *vs* 28.6% for surgical aortic valve replacement (Reardon et al, 2015).

Case selection and the evolution of the 'heart team'

The concept of the 'heart team' has evolved with transcatheter aortic valve implantation (*Figure 1*). The heart team assesses each patient individually and undertakes a detailed appraisal of the treatment options available. The approach is tailored for each patient, allowing careful risk stratification and assessment of the potential benefits of each possible therapeutic intervention. This multidisciplinary approach is now considered to be the standard of care and the European Society of Cardiology (Joint Task Force on the Management of Valvular Heart Disease of the European Society of Cardiology (ESC) et al, 2012) has recommended that transcatheter aortic valve implantation should only be performed under the auspices of a multidisciplinary heart team, which includes cardiologists, cardiac surgeons,

Dr Freidoon Keshavarzi is Consultant Interventional Cardiologist in the Cardiology Department, University Hospital of South Manchester, Manchester

Professor Philip MacCarthy is Consultant Interventional Cardiologist in the Department of Cardiology, King's College Hospital, London SE5 9RS

Correspondence to: Dr F Keshavarzi (freidoonkeshavarzi@nhs.net)

Figure 1. The composition of the 'heart team'.

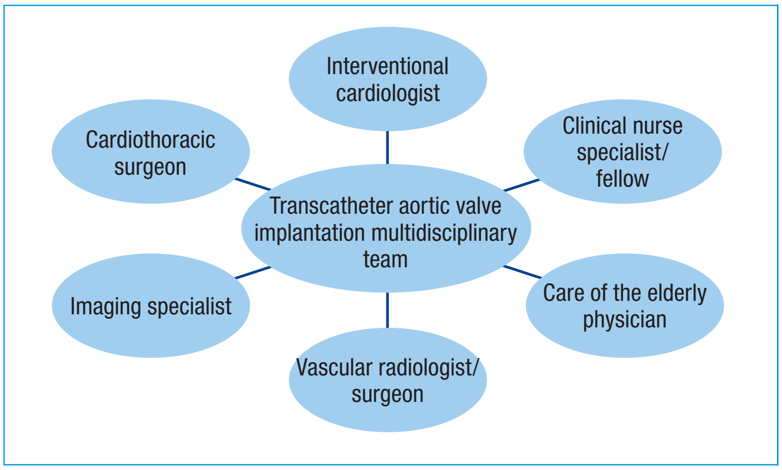


Figure 2. Potential access routes for transcatheter aortic valve implantation procedures.

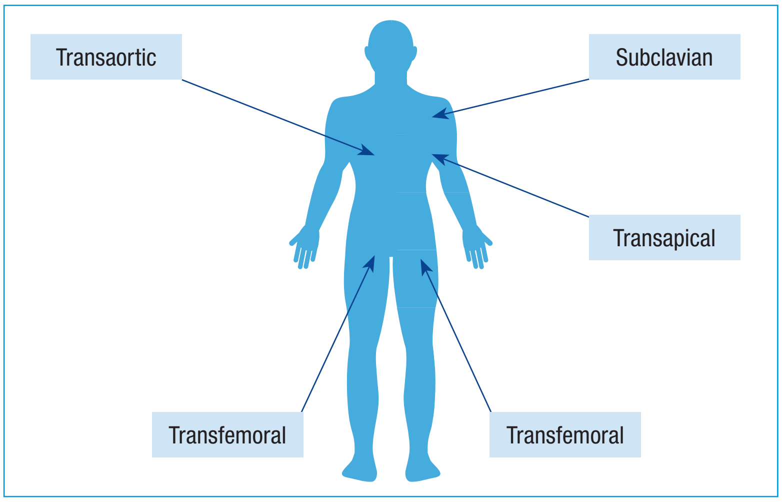
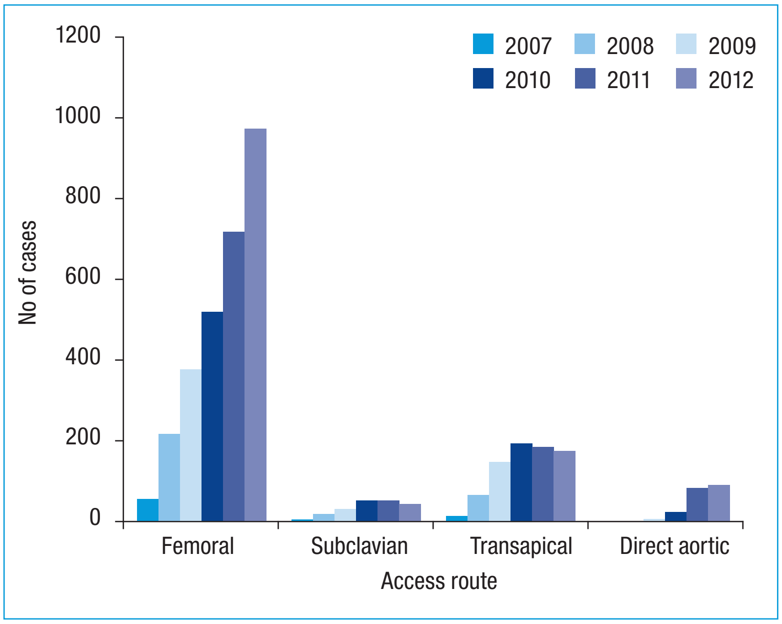


Figure 3. Transcatheter aortic valve implantation access route choice in the UK. Data from the UK TAVI registry (Ludman et al, 2012).



imaging experts, care of the elderly physicians and other specialists if necessary.

Before acceptance by the heart team for transcatheter aortic valve implantation, patients undergo a variety of imaging investigations to assess their suitability for transcatheter intervention. In general, these investigations include a functional assessment of the valve (including valve stress echocardiography if needed) and three-dimensional transoesophageal echocardiography. Three-dimensional computed tomography angiography is also used to assess the valve anatomy and vascular access.

Technical aspects of the transcatheter procedure

Vascular access

Careful assessment of the femoral and/or iliac artery calibre, tortuosity and calcification is essential. Computed tomography imaging and/or angiography play a key role in this regard. Broadly, there are two possible access approaches for transcatheter aortic valve implantation: femoral and non-femoral. Non-femoral approaches include transapical, transaortic, subclavian and carotid (*Figure 2*). Transfemoral access is the most commonly used (>75% of all cases) (*Figure 3*), followed by transapical (Bax et al, 2014). To fulfil the criteria for the transfemoral approach the minimal femoral and iliac artery diameter (for currently available transcatheter aortic valve implantation delivery systems) should be at least 5.5 mm. Even if this calibre of vessel is exceeded, the transfemoral approach may still be challenging in heavily calcified and/or tortuous vessels.

Transapical or transaortic access is used in patients not suitable for the transfemoral approach but is more invasive, and outcomes and long-term survival are less good.

Importance of imaging

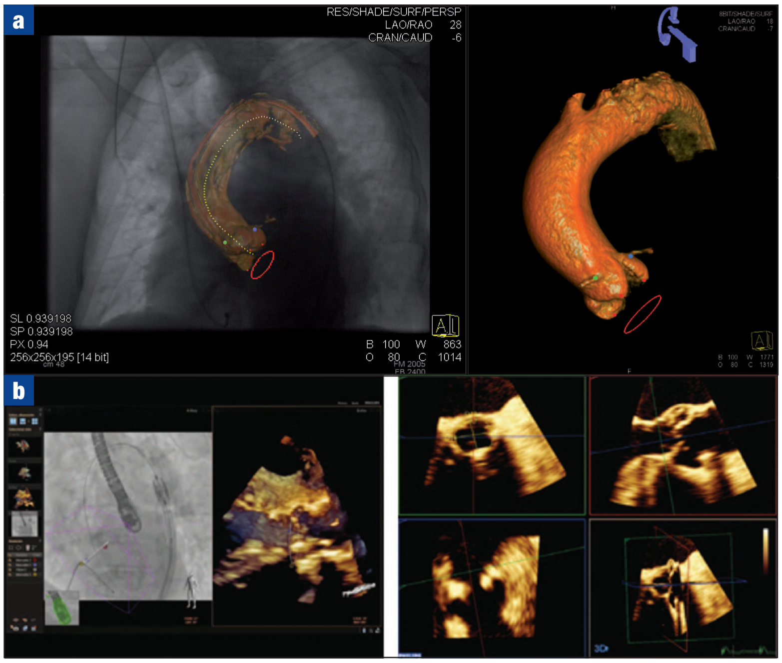
Imaging modalities play a vital role in planning for transcatheter aortic valve implantation procedures, not only in case selection and device sizing, but also peri-procedurally. Contemporary practice in most transcatheter aortic valve implantation centres includes using three-dimensional computed tomography, echocardiography or both to allow accurate preoperative aortic annulus measurements, to visualize the aortic root and to help define the appropriate vascular access site.

Key steps in preoperative imaging include assessment of: aortic valve morphology, distribution and extent of valve calcification, annular dimensions, distance of the coronary ostia to the aortic annulus, peripheral artery diameter, calcification and tortuosity. Multi-modality imaging methods provide reliable, reproducible aortic measurements, translating into accurate device sizing and ultimately optimal valve positioning.

Multi-detector computed tomography is increasingly used because of its capability for three-dimensional determination of the non-circular nature of the aortic annulus, geometry of the aortic valve and/or root as well as the extent and location of aortic valve calcification (Delgado et al, 2010) (*Figure 4*).

Figure 4. Three-dimensional computed tomography reconstruction scan of the aorta and iliofemoral arteries.

Figure 5. Sophisticated imaging techniques exist that facilitate valve positioning and deployment. **a.** Computed tomography **b.** Echonavigator.



Transoesophageal echocardiography can give similar information about the aortic valve and root to that provided by computed tomography, but it is more operator-dependent. Transoesophageal echocardiography can be used peri-procedurally, providing real-time information about valve positioning, aetiology of immediate complications and assessment of para-valvular leak after device deployment.

Novel adjunctive imaging modalities, when used in addition to computed tomography and transoesophageal echocardiography, provide real-time three-dimensional information to enhance accuracy and reduce procedure time. One such example is 'Echonavigator', a co-registration system which acts by fusing live fluoroscopy and echo for intuitive guidance during the transcatheter aortic valve implantation procedure. Another example is Dyna-CT, which uses intraoperative rotational angiography thus enabling three-dimensional reconstruction of the aortic root (*Figure 5*).

Rapid ventricular pacing

One of the early conceptual advances that was fundamental to the transcatheter aortic valve implantation procedure was the realization that rapid ventricular pacing (rate 180–220 bpm) effectively temporarily eradicates cardiac output, allowing controlled intervention to the native aortic valve (whether this be balloon valvuloplasty or insertion of a prosthetic device). Moreover, rapid pacing is surprisingly well tolerated and can even be performed in the conscious, sedated patient. In the transcatheter aortic valve implantation procedure this requires insertion of a right ventricular temporary pacing wire, although this can be achieved via the left ventricle guide wire on which the transcatheter aortic valve implantation device is delivered.

The newer, self-expanding transcatheter aortic valve implantation devices do not require rapid pacing although the ability to rapid pace is useful if absolute stability is required at certain moments during deployment.

It is good practice to keep rapid pacing duration to a minimum because significant periods of hypotension could harm other organs (e.g. kidneys or brain) although the exact impact of rapid pacing has not been fully elucidated (Selle et al, 2014).

Balloon aortic valvuloplasty

Balloon aortic valvuloplasty was first described as a standalone procedure in 1986 but its application became limited following evidence that revealed that it had no mortality benefit and poor long-term outcome. However, balloon aortic valvuloplasty has been an important step in transcatheter aortic valve implantation procedures, opening the native aortic valve to 'prepare' it for the transcatheter aortic valve implantation device and with the emergence of transcatheter aortic valve implantation, balloon aortic valvuloplasty has made a comeback. The key difference is that the modern balloon aortic valvuloplasty technique is done in a more controlled way with rapid pacing. Moreover, modern balloons make it a safer and more reproducible technique. While balloon aortic valvuloplasty still does not give lasting results, it can be used as a 'bridge' to surgical aortic valve replacement or transcatheter aortic valve implantation in very unstable patients (Ben-Dor et al, 2010), as a palliative measure or as a 'diagnostic trial' in complex patients to assess whether relieving aortic stenosis improves symptoms (Ben-Dor et al, 2013; Saia et al, 2013).

Device type

The two 'mainstream' transcatheter aortic valve implantation devices are the balloon-expandable Sapien (Edwards LifeSciences) and the self-expanding CoreValve (Medtronic) (*Table 1*).

The original Edwards Sapien valve was a balloon expandable device that had a stainless steel support frame with a bovine pericardial valve within it. This device was implanted via a transfemoral or transapical/transaortic approach. The newer Sapien XT (made of a cobalt–chromium alloy) was delivered on a more sophisticated, lower-profile delivery system and was associated with fewer vascular events than the original Edwards Sapien valve (PARTER II study). The third generation of the Sapien valve (Sapien 3) is now in use in Europe and has an additional outer skirt to minimize paravalvular regurgitation. It also has the advantage of an even smaller and 'double flexing' delivery system.

The CoreValve (Medtronic) is a self-expanding valve consisting of a nitinol stent with a porcine pericardial valve within. The CoreValve is available in the greatest range of sizes (18–29 mm) and can be deployed without rapid pacing, although pacing can be used if needed. The newest iteration is the Evolut R device, which is more predictable to deploy.

The ideal transcatheter aortic valve implantation valve would be low profile, minimize paravalvular leak and would be fully repositionable and retrievable. Newer generation devices have gone some way to achieving this goal but still have technical limitations. They include:

The Lotus valve (Boston Scientific)

Pre-mounted on its delivery system, the Lotus valve can be retrieved, repositioned and redeployed any time before release. It is delivered via the transfemoral or transaortic approach and consists of a woven nitinol frame with valve leaflets of bovine pericardium. On deployment, it shortens in a controlled way, providing significant radial strength.

The JenaValve (Jenavalve Production Ltd)

A self-expanding valve consisting of a nitinol stent. It has three 'feelers', which clip the native valve leaflets enabling the operators to accurately position the prosthesis in the anatomically correct position. Rapid pacing is not required during prosthesis positioning and release. At present it is only available for non-transfemoral access routes.

The Symetis Acurate (Symetis SA, Switzerland)

Another self-expanding nitinol stent valve with porcine pericardial leaflets which is now available for both the transapical and transfemoral approaches.

The Portico (St Jude Company)

A nitinol self-expanding re-sheathable device which consists of bovine pericardial leaflets. It is similar to the CoreValve and provides open stent cell design to allow access to coronary arteries.

The Engager (Medtronic)

Another nitinol self-expanding valve, again with bovine pericardial leaflets. It uses a support arm, which anchors over the native leaflets to improve stability and optimal alignment. Designed for the transapical and direct aortic approach, it may be more suitable for patients with a dilated aortic root or pure aortic regurgitation.

The Direct Flow (Direct Flow Medical)

A self-expanding valve with a novel 'double ring' design which is repositionable and, owing to its speed of deployment, does not require rapid pacing.

Given the rapid advances in technology in this field, valve designs are sure to improve in the coming years.

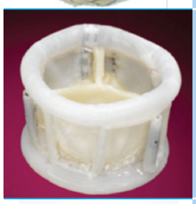
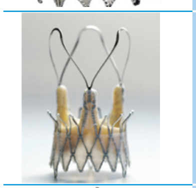
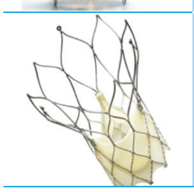
Potential complications

Like any interventional procedure, transcatheter aortic valve implantation has potential complications which have been well characterized over the past decade. The frequency of all complications is decreasing significantly, partly because of operator and centre experience and partly because of advances in technology, both in device and delivery system design, and in imaging techniques, which improve case selection. Complications include:

Renal impairment

Post transcatheter aortic valve implantation renal impairment is associated with increased in-hospital mortality. Preoperative chronic kidney disease, anaemia and diabetes have been identified as predictors of post-transcatheter aortic valve implantation acute kidney injury (Elhmidi et al, 2011). The precise aetiology of transcatheter aortic valve implantation-related renal impairment is not known, but the procedure creates a significant post-procedural inflammatory response, more so with the transapical approach, and this may play a part (Dworakowski et al, 2011; Wendler and MacCarthy, 2013).

Table 1. Composite features of the commonest transcatheter aortic valve implantation valve prostheses

	Device (manufacturer)	Mechanism of deployment	Access route	Treatable aortic annulus size
	CoreValve Evolut R (Medtronic Inc.)	Self-expanding nitinol frame	Transfemoral, trans-subclavian (14F [true outer 18F])	18–30 mm
	Sapien XT/Sapien 3 (Edwards Lifesciences)	Balloon expandable	Transfemoral, transapical (24F)	18–28 mm (TOE), 20.5–295 mm
	Lotus Valve (Boston Scientific)	Braided nitinol wire mechanically expanded on implantation	Transfemoral, transaortic (18-20F)	19–27 mm
	Direct Flow (Direct Flow Medical)	Aortic and ventricular 'inflatable' rings with strut framework	Transfemoral (18F)	19–28 mm
	JenaValve (JenaValve Technology)	External frame – self-expanding	Transapical (32F), transfemoral (18F)	21–27 mm
	Engager (Medtronic Inc.)	Self-expanding nitinol frame with support 'arms'	Transapical, transaortic (29F)	21–26.7 mm
	Acurate TA (Symetis)	Self-expanding nitinol frame	Transapical (28F sheathless)	21–27 mm
	Portico (St Jude Medical)	Self-expanding nitinol frame	Transfemoral (18F), transapical (24F sheathless)	19–21 mm

Results from the large FRANCE 2 registry demonstrate that the extent of renal impairment before transcatheter aortic valve implantation predicts 30-day and 1-year outcomes (Oguri et al, 2015).

Vascular injury

The overall risk of significant vascular damage has decreased with lower profile valve delivery systems, but remains ~ 10%. Fully percutaneous techniques, including ultrasound-guided puncture of the femoral artery and the use of pre-closure suture systems (such as the ProGlide), have refined the technique. An awareness of potential problems with check angiography and 'cross-over' access from the contralateral side has improved safety in this regard, but vascular radiologists and surgeons are integral members of the broader transcatheter aortic valve implantation team.

Paravalvular aortic regurgitation

Paravalvular regurgitation was common with earlier valve designs and was the result of incomplete apposition of the prosthesis to the aortic annulus. The principal contributing mechanisms were an undersized prosthesis, suboptimal positioning or challenging anatomy of the aortic root and valve (e.g. eccentric or heavy calcification). Initially this was not thought to be a major limitation but data from the PARTNER A study first identified that the presence of anything other than very mild paravalvular regurgitation predicted a poor outcome. Since then, many studies have shown that paravalvular aortic regurgitation predicts increased mortality (Lerakis et al, 2013; Dworakowski et al, 2014) and have emphasized that it should be minimized or avoided if at all possible. This has been addressed by more sophisticated aortic annulus sizing (with three-dimensional imaging modalities) to more accurately size the valve prosthesis and with device technology itself (e.g. the addition to 'sealing' skirts to the frame of the valve, as with the Sapien 3). Moreover, judicious use of post-dilatation can also decrease paravalvular aortic regurgitation. Further studies are needed to verify exactly why paravalvular aortic regurgitation has such a negative effect on survival.

Permanent pacemaker requirement

The risk of significant conduction disturbance following transcatheter aortic valve implantation is approximately 10–25%. The incidence is variable for different devices, with a higher pacemaker requirement with some valves than others (Bleiziffer et al, 2010; Ferreira et al, 2010). This has been addressed with device design and also positioning within the native aortic valve. There is some evidence to suggest that a higher prosthesis implantation lessens the incidence of complete heart block (Bleiziffer et al, 2010).

Tachyarrhythmias can also occur, the commonest being new-onset atrial fibrillation, which also impacts on prognosis after transcatheter aortic valve implantation (Amat-Santos et al, 2012; Ludman et al, 2015).

Stroke

The incidence of stroke after transcatheter aortic valve implantation is reported as being between 1.7 and 8.4% depending on the clinical definition. In the PARTNER A study, the risk of stroke with transcatheter aortic valve implantation was 5.5% *vs* 2.4% with surgical aortic valve replacement (Leon et al, 2010). A similar stroke rate was reported in the Core Valve US Pivotal Trial High Risk Study (Barker and Reardon, 2014). However, in the ADVANCE registry (1015 enrolled patients) the stroke risk was lower at 2.9% at 30 days. It is possible that strokes after transcatheter aortic valve implantation differ in nature from those after surgical aortic valve replacement, with showers of cerebral emboli at different points during the transcatheter aortic valve implantation procedure causing a more diffuse brain injury, manifest as a more subtle cognitive impairment (rather than an overt neurological event such as a hemiplegia). This may make these events difficult to diagnose and indeed adjudicate in clinical trials.

There are a number of cerebral 'embolic protection/deflection' devices currently available to reduce the risk of cerebral micro-embolization. The application of these devices requires extra caution and is only advised in certain high risk groups of patients. Whether these devices cause a reduction in clinical neurological events has yet to be proven and studies are ongoing (Buchanan et al, 2013).

Post-procedural management

Close monitoring of haemodynamic status, fluid balance and vascular access sites within the first 24–48 hours post-procedure is essential to identify and rectify early complications. There is now a drive to simplify the transcatheter aortic valve implantation procedure, with less use of central jugular lines and urinary catheters. Many centres now perform transcatheter aortic valve implantations under conscious sedation rather than general anaesthetic. Patients often have complex drug regimens (including antiplatelet and anticoagulant medicines), which need to be reintroduced cautiously. The optimum antiplatelet regimen after transcatheter aortic valve implantation remains controversial although a single antiplatelet agent seems to suffice in the absence of other indications.

Early patient mobilization and discharge planning are key to preventing hospital-acquired infection and minimizing length of stay.

What does the future hold for transcatheter aortic valve implantation?

Transcatheter aortic valve implantation is now an established mainstream technique and there is no doubt its use will continue to increase worldwide with newer, smaller devices.

Currently, a large proportion of transcatheter aortic valve implantation procedures are performed under general anaesthesia. As clinical experience increases, there will be a trend toward conscious sedation (already widely used in many European countries) with local anaesthesia and less invasive anaesthetic protocols may enhance procedural safety and enable earlier discharge post-procedure.

Newer generations of valves may allow safe treatment of intermediate and even low risk patients with aortic stenosis. Low profile, durable devices may decrease the current limitations, which include vascular and access site complications as well as paravalvular leak, stroke and the need for permanent pacing.

The indications for transcatheter aortic valve implantation are expanding. Newer devices are allowing treatment of more challenging anatomy (e.g. functionally bicuspid valves) and treating intermediate risk patients is currently being explored. The NOTION (Nordic Aortic Valve Intervention) Trial is the first all-comers cohort study to randomize low-risk patients to either transcatheter aortic valve implantation or surgical aortic valve replacement and demonstrated no significant difference between transcatheter aortic valve replacement and surgical aortic valve replacement for the composite end point of death from any cause, stroke or myocardial infarction at 1 year (Thyregod et al, 2015).

The use of transcatheter aortic valve implantation in intermediate risk patients will be defined by upcoming trials including UK-TAVI, SURTAVI and PARTNER 2 and this evidence base will dictate the position of transcatheter aortic valve implantation and surgical aortic valve replacement in the modern era.

Novel off-label indications other than aortic stenosis for transcatheter valve implantation are emerging. Valve-in-valve therapy for failing surgical bioprostheses offers an excellent alternative to high-risk re-do surgical aortic valve replacement and is now widely used. Transcatheter therapy for pure aortic regurgitation is also being explored with certain newer devices. Mitral valve-in-valve or valve-in-annuloplasty-ring implantation in high risk patients with previous mitral valve repair or replacement is now routinely performed.

The next frontier for transcatheter valve therapy is fully percutaneous mitral valve implantation and several mitral devices have already been implanted in first-in-man studies.

Conclusions

Transcatheter aortic valve implantation is now an established technique for the treatment of aortic stenosis in high risk and inoperable surgical patients. Technological advances and increased clinical experience have made the procedure safe and largely reproducible and the major limitations are being successfully addressed. The future indications for transcatheter valve implantation will expand to more complex anatomy and probably include intermediate risk patients. Moreover, patients with failing surgical bioprostheses, aortic regurgitation and those with mitral valve disease are likely to benefit from this technological revolution. Future devices will be smaller, repositionable and retrievable with a lower tendency to leave paravalvular regurgitation or conduction disturbance. While the expansion of the technique should be cautious and in-line with a growing, robust evidence base, there is no doubt that transcatheter aortic valve implantation and transcatheter valve therapy in general is yet to fulfil its full potential. **BJHM**

Figure 3 *is reproduced courtesy of Peter Ludman,* Figure 5a *is reproduced courtesy of Siemens and* Figure 5b *is reproduced courtesy of Philips. Images in* Table 1 *are reproduced courtesy of Medtronic Inc, Edwards Lifesciences, Sadra Medical, Inc./Boston Scientific, Direct Flow Medical, Inc., JenaValve™ Technology, Symetis SA and St Jude Medical.*
Conflict of interest: none.

KEY POINTS

- Transcatheter aortic valve implantation has become the 'standard of care' for the treatment of high risk and surgically inoperable patients with symptomatic aortic stenosis.
- Technological advances and increased clinical experience have made the procedure safe and largely reproducible and the major limitations are being successfully addressed.
- Transcatheter aortic valve implantation can also be safely used in intermediate risk or even low risk group patients should ongoing trials prove non-inferiority.

Amat-Santos IJ, Rodés-Cabau J, Urena M et al (2012) Incidence, predictive factors, and prognostic value of new-onset atrial fibrillation following transcatheter aortic valve implantation. *J Am Coll Cardiol* **59**: 178–88 (doi: 10.1016/j.jacc.2011.09.061)
Awad W, Mathur A, Baldock L, Oliver S, Kennon S (2014) Comparing post-operative resource consumption following transcatheter aortic valve implantation (TAVI) and conventional aortic valve replacement in the UK. *J Med Econ* **17**(5): 357–64 (doi: 10.3111/13696998.2014.904322)
Barker CM, Reardon MJ (2014) The Core Valve US pivotal trial. *Thorac Cardiovasc Surg* **26**(3): 179–86 (doi: 10.1053/j.semtcvs.2014.10.001)
Bax JJ, Delgado V, Bapat V et al (2014) Open issues in transcatheter aortic valve implantation. Part 2: procedural issues and outcomes after transcatheter aortic valve implantation. *Eur Heart J* **257**: 2639–54 (doi: 10.1093/eurheartj/ehu257)
Ben-Dor I, Pichard AD, Satler LF et al (2010) Complications and outcome of balloon aortic valvuloplasty in high-risk or inoperable patients. *JACC Cardiovasc Interv* **3**(11): 1150–6 (doi: 10.1016/j.jcin.2010.08.014)
Ben-Dor I, Maluenda G, Dvir D et al (2013) Balloon aortic valvuloplasty for severe aortic stenosis as a bridge to transcatheter/surgical aortic valve replacement. *Catheter Cardiovasc Interv* **82**(4): 632–7 (doi: 10.2478/raon-2013-0078)
Bleiziffer S, Ruge H, Hörer J et al (2010) Predictors for new-onset complete heart block after transcatheter aortic valve implantation. *JACC Cardiovasc Interv* **3**: 524–30 (doi: 10.1016/j.jcin.2010.01.017)
Buchanan GL, Chieffo A, Montorfano M et al (2013) A "modified crossover technique" for vascular access management in high-risk patients undergoing transfemoral transcatheter aortic valve implantation. *Catheter Cardiovasc Interv* **81**(4): 579–83 (doi: 10.1002/ccd.24380)
Cribier A, Eltchaninoff H, Bash A et al (2002) Percutaneous transcatheter implantation of an aortic valve prosthesis for calcific aortic stenosis: first human case description. *Circulation* **106**: 3006–8 (doi: 10.1161/01.CIR.0000047200.36165.B8)
Delgado V, Ng AC, van de Veire NR et al (2010) Transcatheter aortic valve implantation: role of multi-detector row computed tomography to evaluate prosthesis positioning and deployment in relation to valve function. *Eur Heart J* **31**(9): 1114–23 (doi:10.1016/j.jcmg.2011.01.014)
Dworakowski R, Wendler O, Bhan AM et al (2011) Role of inflammation and reactive oxygen species in Acute Kidney Injury (AKI) after Transcatheter Aortic Valve Implantation (TAVI). *Eur Heart J* **32**(Abstract Supplement): 895
Dworakowski R, Wendler O, Halliday B et al (2014) Device-dependent association between paravalvar aortic regurgitation and outcome after TAVI. *Heart* **100**(24): 1939–45 (doi: 10.1136/heartjnl-2013-305390)
Elhmidi Y, Bleiziffer S, Piazza N et al (2011) Incidence and predictors of acute kidney injury in patients undergoing transcatheter aortic valve implantation. *Am Heart J* **161**(4): 735–9 (doi: 10.1016/j.acvd.2014.01.002)
Ferreira ND, Caeiro D, Adão L et al (2010) Incidence and predictors of permanent pacemaker requirement after transcatheter aortic valve implantation with a self-expanding bioprosthesis. *Pacing Clin Electrophysiol* **33**: 1364–72 (doi: 10.1111/j.1540-8159.2010.02870.x)
Joint Task Force on the Management of Valvular Heart Disease of the European Society of Cardiology (ESC); European Association for Cardio-Thoracic Surgery (EACTS), Vahanian A, Alfieri O, Andreotti F et al (2012) Guidelines on the management of valvular heart disease (version 2012). *Eur Heart J* **33**(19): 2451–96 (doi: 10.1093/eurheartj/ehs109)
Kapadia SR, Leon M, Makkar RR et al; PARTNER trial investigators (2015) 5-year outcomes of transcatheter aortic valve replacement compared with standard treatment for patients with inoperable

aortic stenosis (PARTNER 1): a randomised controlled trial. *Lancet* **385**(9986): 2485–91 (doi: 10.1016/S0140-6736(15)60290-2)

Leon MB, Smith CR, Mack M et al; PARTNER Trial Investigators (2010) Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. *N Engl J Med* **363**: 1597–607 (doi: 10.1056/NEJMoa1008232

Lerakis S, Hayek SS, Douglas PS (2013) Paravalvular aortic leak after transcatheter aortic valve replacement. *Circulation* **127**: 397–407 (doi: 10.1161/CirculationAHA.112.142000)

Lindroos M, Kupari M, Heikkilä J, Tilvis R (1993) Prevalence of aortic valve abnormalities in the elderly: an echocardiographic study of a random population sample. *J Am Coll Cardiol* **21**(5): 1220–5 (doi: 10.1016/0735-1097(93)90249-Z)

Ludman PF; UK TAVI Steering Group and the National Institute for Cardiovascular Outcomes Research (2012) The UK transcatheter aortic valve implantation registry; one of the suite of registries hosted by the National Institute for Cardiovascular Outcomes Research (NICOR). *Heart* **98**(24): 1787–9 (doi: 10.1136/heartjnl-2012-302534)

Ludman PF, Moat N, de Belder MA et al (2015) Transcatheter aortic valve implantation in the United Kingdom: temporal trends, predictors of outcome, and 6-year follow-up: a report from the UK Transcatheter Aortic Valve Implantation (TAVI) Registry, 2007 to 2012. *Circulation* **131**(13): 1181–90 (doi: 10.1161/CirculationAHA.114.013947)

Malhotra A (2012) The Changing Burden of Valvular Heart Disease. www.bcs.com/pages/news_full.asp?NewsID=19792059 (accessed 22 February 2016)

Oguri A, Yamamoto M, Mouillet G et al; FRANCE 2 Registry investigators (2015) Impact of chronic kidney disease on the outcomes of transcatheter aortic valve implantation: results from the FRANCE 2 registry. *EuroIntervention* **10**(9): e1–9 (doi: 10.4244/EIJV10I9A183)

Reardon MJ, Adams DH, Kleiman NS et al (2015) 2-Year outcomes in patients undergoing surgical or self-expanding transcatheter aortic valve replacement. *J Am Coll Cardiol* **66**(2): 113–21 (doi: 10.1016/j.jacc.2015.05.017)

Saia F, Marrozzini C, Ciuca C et al (2013) Emerging indications, in-hospital and long-term outcome of balloon aortic valvuloplasty in the transcatheter aortic valve implantation era. *EuroIntervention* **8**(12): 1388–97 (doi: 10.4244/EIJV8I12A212)

Sehatzadeh S, Doble B, Xie F et al (2013) Transcatheter aortic valve implantation (TAVI) for treatment of aortic valve stenosis: an evidence update. *Ont Health Technol Assess Ser* **13**(1): 1–40

Selle A, Figulla HR, Ferrari M et al (2014) Impact of rapid ventricular pacing during TAVI on microvascular tissue perfusion. *Clin Res Cardiol* **103**(11): 902–11 (doi: 10.1007/s00392-014-0728-9)

Smith CR, Leon MB, Mack MJ et al; PARTNER Trial Investigators (2011) Transcatheter versus surgical aortic-valve replacement in high-risk patients. *N Engl J Med* **364**: 2187–98 (doi: 10.1056/NEJMoa1103510)

Thyregod HG, Steinbrüchel DA, Ihlemann N et al (2015) Transcatheter versus surgical aortic valve replacement in patients with severe aortic valve stenosis: one-year results from the All-comers Nordic Aortic Valve Intervention (NOTION) Randomized Clinical Trial. *J Am Coll Cardiol* **65**(20): 2184–94 (doi: 10.1016/j.jacc.2015.03.014)

Wendler O, MacCarthy P (2013) Renal failure after transcatheter aortic valve implantation. Do we know the full story? *J Am Coll Cardiol* **62**(10): 878–80 (doi: 10.1016/j.jacc.2013.04.058)