Hybrid cardiovascular interventions, which integrate techniques of interventional cardiology with those of cardiac/vascular surgery, aim to maximize procedural benefits while minimizing invasiveness. Such hybrid procedures include transcatheter aortic valve replacement (TAVR), endovascular thoracic (TEVAR) or abdominal (EVAR) aortic repair, and combined percutaneous coronary intervention (PCI) with structural heart intervention. Some, such as TAVR, TEVAR, and EVAR, have now become the standard of care for selected patient populations. With documented improvements in outcomes, the indications for such hybrid procedures are expanding. Though some of these novel procedures can be done in either a traditional operating suite or interventional suite, neither location is ideally suited to perform many of these hybrid procedures. Proper application of hybrid techniques requires either an operating room (OR) with a high-resolution angiographic capability or an interventional suite with appropriate operating room features—the "hybrid OR." We aim to review the concept of an integrated heart team as well as the design and implementation of the hybrid OR.

Heart Team Concept

Until recently, patients have been managed with a "silo" approach, with each specialty separately evaluating and treating the underlying condition. This has led in some cases to inefficient competing treatment algorithms. The growth of hybrid procedures that cross traditional specialty lines has in turn spawned the development of interdisciplinary teams. Most frequently this has manifested as a heart team to manage complex valvular heart disease as it pertains to TAVR, but the concept has also been applied to other cardiovascular conditions such as acute aortic syndromes or arrhythmias. Although an integrated team approach has long been used in oncology or transplant patients, it is now integral to the care of patients with complex cardiovascular disease. We raise the concept of the team before reviewing the hybrid OR itself because we feel the team approach is more critical to programmatic success.

The team may include a noninterventional cardiologist, cardiac surgeon, interventional cardiologist, echocardiographer, imaging specialist, heart failure and valve disease specialist, cardiac anesthesiologist, nurse practitioner or physician assistant, among others. This creates an environment in which patients can receive information from varying perspectives, providing balanced patient-centered care.1

Expert consensus documents have highlighted that a multidisciplinary heart team approach is the most appropriate form of decision making in patients with aortic stenosis,2 and is a class I recommendation in the management of coronary artery disease.3,4 The multidisciplinary team can make an unbiased assessment about the optimal treatment algorithm and assess whether a hybrid procedure is appropriate for a given patient. The hybrid OR is, in many ways, the physical manifestation of the multidisciplinary patient care approach.

Design of the Hybrid Operating Room

At its core a hybrid OR combines advanced imaging capability with a fully functioning operating suite. Although many hybrid procedures can be performed in a traditional OR with a portable c-arm or in a catheterization suite, optimal imaging and technical functionality are achieved with a dedicated integrated suite. In practice, this includes all the components of a surgical suite with high-quality fluoroscopy (generally with flat-panel imaging), and operating tables that can accommodate both angiography and open operations.5 Other modalities such as biplane system, integrated ultrasound, and electromagnetic navigation systems can be incorporated to the imaging system as appropriate. A control area for radiological technicians is incorporated with direct view of the surgical field either within or outside of the hybrid OR.

The cardiovascular hybrid OR will be used by combined teams of cardiac or vascular surgeons and interventional cardiologists as well as the anesthesia team, nursing team, perfusion, and radiological technicians. This, along with the added room required for imaging equipment, requires substantially more room area than a traditional OR—generally 1000 square feet or more. It also requires careful preparation of equipment positioning. The hybrid OR ought to have flexibility for future procedures, but anticipated common uses should guide the design. To this end, it is useful to create mock-ups of equipment location, including the need for associated gas and power lines, to assure procedural feasibility. Depending on the type of imaging system used, the location of operating lights, equipment booms, and monitors can vary widely. Secondly, ceiling-mounted fluoroscopy systems must take requirements for laminar airflow into account. Once a provisional floor plan is generated, the future users of the space (including all disciplines) need to assure that it is compatible with their workflow. A surgeon and cardiologist may agree on a plan only to find out later that it did not work.
not adequately address requirements for anesthesia, nursing, perfusion, or imaging. Mock cases should be planned before room layout is finalized.

The hybrid OR should ideally have ready access to both surgical OR and interventional suites; in reality, however, it tends to be located in 1 of these and at a distance from the other. Either location is acceptable but, if the areas are separated, there needs to be a plan to rapidly access cardiopulmonary bypass capability, surgical instruments, or interventional equipment in case of an emergency.

The fundamental fixed assets of the hybrid OR include the imaging system, compatible OR table, lighting and monitors, and necessary booms for anesthesia equipment and perfusion (Figure 1). In addition, the space needs to accommodate anesthesia and perfusion equipment as well as echocardiography, power injector systems, and tables for both surgical and endovascular supplies. The need for ceiling-mounted monitors is often underestimated. They should be placed to allow all team members to visualize the images simultaneously. Monitors for the surgeons, anesthesiologists, and interventionalists should show images of angiography, echo images, and hemodynamic monitoring. Moreover, there needs to be flexibility in boom positioning. Unlike a traditional cardiac catheterization laboratory where the operator stands to the right of the patient, hybrid procedures (such as transapical TAVR) may require creative monitor placement.

Although some facilities have the luxury of new construction to implement a hybrid OR, many must convert an existing interventional or OR space into a hybrid OR. For a cath laboratory, this means meeting all the requirements for a sterile operating room. Though these requirements vary by state, it generally includes a system for laminar airflow and positive pressure within the room as well as a substerile imaging system, compatible OR table, lighting and monitors, and necessary booms for anesthesia equipment and perfusion (Figure 1). In addition, the space needs to accommodate anesthesia and perfusion equipment as well as echocardiography, power injector systems, and tables for both surgical and endovascular supplies. The need for ceiling-mounted monitors is often underestimated. They should be placed to allow all team members to visualize the images simultaneously. Monitors for the surgeons, anesthesiologists, and interventionalists should show images of angiography, echo images, and hemodynamic monitoring. Moreover, there needs to be flexibility in boom positioning. Unlike a traditional cardiac catheterization laboratory where the operator stands to the right of the patient, hybrid procedures (such as transapical TAVR) may require creative monitor placement.

Fluoroscopy and Equipment in the Hybrid OR

Although portable fluoroscopy has been used for hybrid procedures, fixed imaging systems provide superior image quality and are requisite for the majority of hybrid cardiovascular procedures, such as TAVR. The fixed c-arm may be either mounted on the ceiling or floor. Ceiling-mounted systems have the benefit of not occupying OR floor space and of being able to be parked away from the surgical field when not in use. However, this comes at the potential cost of lower ceiling height, which affects lighting, monitor and boom placement, and potentially adversely affecting sterility as a result of interference with laminar airflow. Floor-mounted systems avoid these pitfalls but require dedicated floor space and can limit functionality of the room for nonhybrid cases. Both systems have the advantage of both superior image quality and reduced radiation exposure compared with a portable system, but require significant investment of space. In particular, not only does the c-arm itself require dedicated space within the room, the fluoroscopy operating system generates a significant amount of heat and noise and is generally located in an adjacent room.

A hybrid OR table is made of thin nonmetallic carbon-fiber and is radiolucent. It must also be integrated to the imaging system to avoid collisions. A floating tabletop with multidirectional tilt function is optimal for accurate catheter maneuvering. Inevitably, some functionality is lost when creating an operating table that is fluoroscopically compatible. A traditional fluoroscopic table has minimal ability to assume a myriad of positions, whereas a table that retains full OR capability may compromise on some imaging because of the need for metal parts.

Radiation Safety

Whereas interventional suites are built with radiation safety features, this is not typically done in a standard OR and such features will need to be incorporated in the hybrid OR. Lead-lined walls and doors reduce scatter outside the room. Shielding for personnel can be both portable and built-in. Lead aprons are attached to the table to reduce scatter, and a ceiling mounted clear shield should be easily maneuverable to be positioned between the operator and patient. These both achieve a significant dose reduction. For those personnel who don’t need to be immediately adjacent to the patient, rolling shields can be helpful. The planning team should allow for a dedicated space outside the room for lead aprons to be hung. Finally, the most important aspect is education. All team members need to be well versed in techniques to reduce radiation dosage to both patient and personnel.

Benefit of Hybrid OR Compared With Interventional Suite or Traditional OR

In truth, many hybrid procedures such as TAVR or TEVAR are performed without complication in a traditional cath laboratory or OR rather than a dedicated hybrid OR. We believe, however, that this can lead to compromises in patient safety. In a traditional interventional suite, emergent conversion to open surgery will raise multiple issues. Poor lighting, lack of surgical instruments and suction, and
poor access to cardiopulmonary bypass can be disastrous. Anesthesia and perfusion equipment may create space issues in smaller interventional suites. The hybrid OR provides a more suitable environment for open conversion in these cases. Though such conversions are uncommon, we should aim to prevent any complications attributable to suboptimal procedure location. In addition, the application of sterile technique is more rigorous in the OR environment than in the traditional interventional suite, as mandated by law. This has been acceptable for procedures with low infectious risk such as PCI, but implantation of valves or grafts demands proper sterility.

Just as advanced procedures are currently performed in traditional interventional suites, some are using portable c-arms in traditional ORs to perform procedures such as TAVR or TEVAR. As mentioned earlier, the image quality of modern fixed fluoroscopy units with flat-panel detectors far exceeds that of portable units and can thus increase the safety of the procedure. They also offer the potential for lower radiation dose to both patient and staff while providing superior imaging. In addition, many of these units can rotate fully around the patient and provide cross-sectional or 3-dimensional data using volume-rendering techniques. This 3-dimensional c-arm computed tomography can be obtained in few minutes and can assist positioning for transcatheter valve replacement or aortic stent graft placement (Figure 2). These data can be overlaid on to the real-time 2-dimensional image and navigate the anatomy (Figure 3). This has been used to reduce contrast exposure in complex endovascular aneurysm repair with branched grafts. In summary, the principal reason to invest in a proper hybrid OR rather than compromising with a nonhybrid suite is to achieve superior patient safety.

Financial Considerations
Although the procedural benefits of having a hybrid OR can be myriad, it requires a significant investment of both space and money. The typical cost of building a hybrid OR is ≈120% more than that of a traditional surgical OR, and the operating costs for each hybrid OR adds 90% to standard OR costs. The installation costs range from US $1.2 million to $5.0 million depending on the devices that are installed. This capital investment expense is compounded by ongoing equipment maintenance expenditures and an equipment lifecycle that would typically be shorter than that of a traditional OR. Moreover, because the space requirements are substantially greater for the hybrid OR than a standard OR or cath laboratory, this has the potential to parasitize the space of 1 of these locations.

The return on investment depends on the growth of the hybrid program. There has been a reported increase in cases after building a hybrid OR, though this can be unpredictable. In some cases, volume increases are likely a result of marketing effect and, though this may not be sustained, the Cleveland Clinic Foundation showed that the investment was returned in just over 2 years. Smaller hospitals may find it challenging to completely fill the hybrid OR schedule with 1 team’s cases, and effectively dividing the utilization among multiple services will allow more efficient use of the hybrid OR.

Effect on Training
The rise of hybrid procedures and hybrid ORs has implication for training of both surgical and interventional specialists. Vascular surgeons were early adopters of endovascular techniques and training, which has become universal among vascular training programs. In contrast, few cardiac surgeons have performed cross-training by spending extra training in

Figure 2. Four images after abdominal aorta stent graft. A and B are obtained from 3-dimensional c-arm computed tomography (CT). C and D are obtained from multidetector CT. Reprinted from Eide et al with permission of the publisher. Copyright © 2009, Elsevier.
Transcatheter Valve Replacement

Clinical Application in Cardiovascular Medicine

Transcatheter Valve Replacement

The first clinical TAVR was performed in 2002, when a stented pericardial prosthesis was placed within the native valve under fluoroscopic guidance from a percutaneous transfemoral approach. 16,17 Since then, it has grown to be the procedure of choice for patients who are not candidate or extremely high risk for the traditional surgical aortic valve replacement. There have been >100,000 implantations in >50 countries worldwide, and in some countries TAVR is applied to nearly 40% of isolated aortic valve replacement. 18,19 Currently, the Edwards Sapien valve (Edwards Lifesciences, Irvine, CA) and the Medtronic Corevalve (Medtronic, Minneapolis, MN) are the only devices approved by the Food and Drug Administration (FDA) in the United States for clinical use. A number of other designs are in clinical trial in the United States and in clinical use in other countries.

During valve implantation, fluoroscopic imaging is the main tool used to confirm valve positioning and the aortic annular anatomy. Therefore, high-resolution images are required and should not be performed with portable fluoroscopy. Hence this procedure is performed either in the hybrid OR or in the interventional cardiology suite.

The Placement of AoRtic TraNsccatheterER Valves (PARTNER) randomized control trials showed that TAVR was superior to medical treatment in inoperable patients (cohort B) and had similar survival to surgical AVR in high risk patients (cohort A). 20,21 The majority of patients show significant improvements in quality of life after this procedure. 22,23 The European Society of Cardiology and the European Association of Cardiothoracic Surgery (ESC/EACTS) guideline gave class I recommendation for TAVR in patients with severe symptomatic aortic stenosis who are not suitable for surgical AVR. 24 TAVR is currently one of the main forces in the increasing utilization of hybrid OR, and this is only expected to grow with an increasingly elderly population.

Transfemoral TAVR can be performed in either the interventional cardiology suite or hybrid OR, but alternative-access TAVR (transapical and transaortic) is better suited to the hybrid OR because of its surgical component. The transapical approach is typically performed through a left thoracotomy and transaortic through upper hemisternotomy or right anterior thoracotomy. In PARTNER cohort A, 29.9% of patients were treated transapically. 21 Although future devices will be smaller and the percentage of transfemoral cases is expected to increase, the hybrid OR may be beneficial even for high-risk transfemoral TAVR. The hybrid OR has larger space, cardiopulmonary bypass backup, and allows prompt conversion to open surgery for complications such as valve migration, myocardial perforation, and vascular injuries.

Other alternative access for TAVR such as transaxillary, transaorti, and transcarotid are more suited to the hybrid OR. Transcatheter valve implantation for deteriorated bioprostheses can be performed as valve-in-valve procedures. This may be performed through femoral or transaortical/sapical approach, but other strategies such as transatrial approach by small right thoracotomy in the hybrid OR has been described. 25,26 Similarly, in patients with previous mitral annuloplasty ring, valve-in-ring transcatheter mitral valve replacement has been reported, although the noncircular shape of the ring create risk for paravalvular leak. 27

Endovascular Aortic Repair

Endovascular aortic repair is utilized for both the thoracic aorta (TEVAR) and abdominal aorta (EVAR). TEVAR and EVAR are among the most common procedures performed in the hybrid OR. The most common indication for TEVAR/EVAR is aneurysm, though it has been applied for a number of pathologies including acute and chronic aortic dissection, traumatic disruption, and penetrating ulcer. Open repair of aortic aneurysms has been performed for >50 years, and despite all the advances in technique, it still carries significant mortality and morbidity. TEVAR and EVAR has become the procedure of choice for patients with aortic aneurysms with suitable anatomic characteristics (eg, limited tortuosity, good
landing zones, and adequate femoral or iliac artery access). Several randomized, controlled trials have been performed for EVAR, which showed lower 30-day mortality and similar survival rate after the first year compared with open surgery. For TEVAR, a recently published systematic review showed that TEVAR was associated with lower mortality and lower neurological complications with no increase in re-intervention rate compared with open surgical repair. TEVAR is mainly performed in thoracic descending aortic aneurysms distal to the subclavian artery. Hybrid debranching procedures have been reported, in which open vascular bypass is performed to branches to create a landing zone for the endograft in complex cases such as arch aneurysms and thoracoabdominal aneurysms (Figure 4).

Endovascular and hybrid techniques have been applied to aortic dissection. Although several trials have shown that TEVAR did not improve survival compared with standard medical therapy in uncomplicated Type B dissection, it remains a primary treatment for complicated Type B dissection (rupture, malperfusion, increase in growth, persistent hypertension, and persistent pain). Interestingly, there are reports of using TEVAR for Type A aortic dissection in inoperable patients.

TEVAR is also used in the setting of traumatic aortic transection. Large studies have shown lower mortality rate and lower postoperative paraplegia rate compared with open repair. The Society for Vascular Surgery has published guidelines for endovascular repair of traumatic aortic disruption and gave a grade 2 recommendation stating “endovascular repair of thoracic aortic transection is associated with better survival and decreased risk of spinal cord ischemia, renal injury, graft, and systemic infections compared with open repair or nonoperative management.” Moreover, this approach allows for more rapid treatment of associated injuries.

In modern hybrid ORs, 3-dimensional computed tomography (CT) capability has been integrated into fluoroscopy systems and may enable early detection and correction of the endoleak that standard fluoroscopy may not detect. This technology can also facilitate placement of branched or fenestrated endografts with less need for repeated contrast injections.

Hybrid Coronary Artery Revascularization

Hybrid coronary artery revascularization combines coronary artery bypass grafting (CABG) and PCI for multivessel coronary artery disease. Randomized trials such as SYNergy between PCI with TAXUS and Cardiac Surgery (SYNTAX) and Future Revascularization Evaluation in Patients with Diabetes Mellitus: Optimal Management of Multivessel Disease (FREEDOM) demonstrated a benefit of CABG over PCI in high-risk left main, 3-vessel disease, decreased left ventricular ejection fraction, and diabetic patients. The benefit of CABG appears to derive from the left internal mammary artery (LIMA) to left anterior descending artery (LAD) graft. The LIMA to LAD graft is known to have 20-year patency of >95% and has survival benefit over saphenous vein graft to LAD. In contrast, saphenous vein grafts have a patency of only 50% to 60% at 10 to 15 years, and therefore may not provide superiority to PCI with drug eluting stents.

Hence, hybrid coronary artery revascularization maintains the hypothetical benefit of CABG by performing minimally invasive off-pump LIMA to LAD while allowing other target vessels to be treated with PCI. This can be done at the same setting in the hybrid OR as 1-stage procedure or 2-stage procedure at different settings during the same hospitalization. Typically LIMA to LAD is performed first to provide protection to LAD territory during PCI and to avoid the risk of bleeding induced by use of anticoagulants such as clopidogrel.

This technique may be applied to patients with porcelain aorta, which prohibits proximal anastomosis, poor conduit quality, lack of conduit, poor target for CABG but good target for PCI, and LAD not suitable for PCI. Patients with significant comorbidities or previous sternotomy may also benefit from this procedure.

Small retrospective studies have reported low 30-day mortality rate and low stent stenosis rate. However, long-term follow-up data are lacking, and future randomized, controlled study data are anticipated to compare the outcome to traditional CABG.

Hybrid Arrhythmia Procedures

In paroxysmal atrial fibrillation (AF), the culprit lesion is typically around the pulmonary vein confluences with the left atrium. Catheter ablation has success rate of >80%, and has been the first choice when antiarrhythmic drugs fail, but is associated with high recurrence and multiple procedures are often necessary. The surgical Maze procedure proposed by Cox and colleagues shows much greater efficacy but is also more invasive. The development of surgical ablation tools allows application of minimally invasive techniques using video-assisted thoracotomy. These approaches, however, have shortcomings such as difficulty creating linear lesions or lack of transmurality.

The hybrid AF procedure combines the advantages of the transvenous endocardial and the thoracoscopic epicardial approaches. In theory, more complete transmural lesions can be created by approaching from both endocardial and epicardial directions. Intraoperative mapping allows additional

Figure 4. Debranching procedure using thoracic endovascular aortic repair. Type I is good proximal and distal landing zone, type 2 is good distal but poor distal landing zone, and type 3 is poor proximal and distal landing zone. Reprinted from Bavaria et al with permission of the publisher. Copyright © 2010, Elsevier.
endocardial touch-up when incomplete ablation is detected. This approach allows endocardial ablation of mitral isthmus, which can be difficult to approach surgically, and can limit complications from the transvenous approach such as phrenic nerve injury, esophageal injury, and cardiac tamponade. Initially, a 2-stage procedure separating the epicardial and endocardial ablation was used, but more recently the 1-stage procedure has used the hybrid OR to maximize its advantages. The 1-stage procedure has success rate >93% for paroxysmal AF and 90% for persistent AF in 1 year. Although hybrid AF surgery is still in its infancy, this procedure may be able to overcome the disadvantages of the surgical or endovascular approaches done in isolation.

Hybrid Congenital Procedures
Hybrid procedures have also established a role in the field of congenital cardiac surgery. Hybrid stage I procedure for hypoplastic left heart syndrome is the most commonly recognized. This strategy combines bilateral pulmonary artery banding through sternotomy and ductal stenting (Figure 5). However, initial enthusiasm for this procedure has tapered as a result of several problems. The hybrid procedure has lower brain oxygen delivery compared with the traditional Norwood procedure, occurrence of retrograde coarctation, and inferior outcomes than that of the traditional Norwood procedure.

Other congenital cardiac procedures that use a hybrid approach are repair of pulmonary venous baffle obstruction after atrial switch operation for transposition of the great arteries, perventricular closure of ventricular septal defect using occluder device, and pulmonary artery stenting for stenosis or tortuous pulmonary artery during repair. However, these approaches have been reported only in case reports; large series are lacking to validate their use as standard therapy. Nonetheless, it is likely that use of hybrid procedures will grow in congenital cardiac surgery, given the desire to minimize invasiveness in this population.

Other Uses of the Hybrid OR
The hybrid OR can be used to combine surgical procedures with diagnostics. Preoperative coronary angiogram is performed on-table in patients undergoing cardiac surgery. This can eliminate the need for a separate (or longer) hospital stay for isolated preoperative diagnostic angiography. Inversely, patients undergoing CABG can receive completion coronary angiogram to confirm the patency of the surgical graft.

Hybrid valve surgery consists of surgical valve repair/replacement and PCI. In general, this allows the valve surgery to be performed in minimally invasive fashion through a smaller incision and the coronary lesion is treated by PCI using 1-stage in the hybrid OR or in another setting as 2-stage procedure. This procedure can be useful in patients undergoing reoperative mitral surgery with coronary artery disease, who had previous cardiac surgery. Minimally invasive surgery through right mini thoracotomy will give great exposure while eliminating the need for reoperative sternotomy and minimizing risk to previous grafts. New or recurrent coronary disease can be addressed by PCI.

Future Perspectives
The application of hybrid procedures and use of the hybrid OR is expected to grow with evolution of technology. Increase in numbers of TAVR, TEVAR, and EVAR will require more hybrid ORs to accommodate its demand. Improved device technology will enable expansion of these techniques to a broader patient population. In the short term, new image applications that allow 3-dimensional guidance such as syngo DynaCT (Siemens, Munich, Germany) and Heart Navigator (Philips, Eindhoven, Netherland) may be useful tools to guide device placement (Figure 3). Over the longer term, integration with other advanced imaging modalities, rather than purely fluoroscopy, will expand opportunities for image-guided therapies. In addition, future advances in hybrid OR equipment (eg, wireless c-arm, smaller equipment) will create more working space and a more efficient work environment for the team.

Conclusion
The hybrid cardiovascular OR is, at its core, an operating room with image guidance. In current practice, this means a fixed fluoroscopy unit combined with a fully functioning operative suite. Inevitably, the imaging source will evolve but the hybrid OR will retain some defining traits. First, it uses image guidance to minimize the invasiveness of traditional surgical procedures. Second and perhaps most importantly, it has bolstered the concept of an integrated, multidisciplinary heart team. New hybrid strategies in valve disease, coronary artery disease, aortic disease, antiarrhythmic treatment, and congenital disease are evolving, and some have achieved standard-of-care status. Technological advances including newer imaging...
and navigation technology may create a patient-focused arena for the treatment of complex cardiovascular disease.

Disclosures

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Tsuyoshi Kaneko and Michael J. Davidson

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