

Original Studies

The Catheterization Laboratory and Interventional Vascular Suite of the Future: Anticipating Innovations in Design and Function

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INTRODUCTION

Any attempt to forecast the function and design of the interventional catheterization laboratory and vascular suite presumes that current trends are an accurate window into the future. This must be recognized as a fallacious assumption; indeed, it can be quite amusing years later to review predictions of the future based on then-current proclivities. In fact, cardiovascular practice over the past 25 years suggests that one cannot predict accurately which innovations will succeed and which will fail based either on theoretical considerations or on initial clinical experience. Moreover, the “future” is a nebulous time and place; certainly, it anticipates progress that renders obsolete the current state of the art laboratory. It may be most practical to characterize the “medium” future, perhaps 5–10 years, rather than the “longer term” future, which grows increasingly indistinct. By beginning with certain economic and scientific realities, it may be possible to generate reasonable, educated guesses regarding the design and use of the catheterization laboratory and interventional vascular suite of the future.

Despite these inherent pitfalls, the MultiSpecialty Occupational Health Group (MSOHG), a committee composed of practicing physicians representing all of the major cardiac, radiologic, and electrophysiological societies, has prepared this study and is making this document public for two reasons. First, in an effort to represent the needs of each society’s members in influencing industry to improve and alter current laboratory designs [1], the committee determined that an attempt to develop a blueprint of the possible future laboratory

would assist in such discussions. Second, MSOHG seeks to reach out beyond medical personnel to engineering and industrial interests in an effort to inspire thought, and perhaps invention, to bring a positive future much closer. By gathering together our current thoughts regarding trajectory, the consequent stimulus may lead to even better ideas than those currently conceived.

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MSOHG believes that a shared vision of the future could synchronize perspectives, whether optimistic or simply pragmatic, and could also encourage a sense of excitement where the potential for positive developments is concerned. The collaborative energy generated from such a dialogue can align physicians, paramedical personnel, and manufacturers in raising their expectations for the future and to actively participate in innovation, development, and positive change, rather than leaving all such constituents to passively react to their environment and wait for others to construct the pathway to an indistinct and nebulous future. Considering a shared vision may result in an energized sense of optimism and proactivity, which could help us move faster and farther than otherwise possible. An intentional conversation regarding the future may cultivate reasonable imagination rather than breed acceptance of relative technological stasis. We therefore consider a proactive open dialogue regarding the future as a constructive, and hopefully catalytic, effort.

FOUNDATIONS AND ASSUMPTIONS

Naturally, the precepts on which one builds a conception of the future should be coherent and realistic, or the consequent predictions will be flawed. Although inevitably predictions are bright with the vision of limitless innovation and industry, and an ideal economic climate, reality typically is less utopian. A more balanced view, grounded in realistic prospects recognizing that tomorrow's opportunities are today's problems, is therefore more apt to lead to an accurate forecast. In this regard, the committee selected several observations as plausible starting points.

Economics will play an ever-increasing role in the speed and nature of which emerging technologies ultimately are incorporated into clinical use. The pressure on physicians and the healthcare delivery system for economic responsibility is only gaining momentum. Few areas of the hospital have seen technology evolve as rapidly as the catheterization laboratory, and new imaging and diagnostic adjuncts have the potential to dramatically impact the financial landscape of profitability. Economic and technical dependencies will determine which of today's brainstorms will become tomorrow's standard therapy. Hence, it is mandatory that expenditures for new technology are justified by proven benefit and clinical importance, and that cost expenditures are minimized to sustain profits.

Cardiovascular programs increasingly rely on diagnostic and therapeutic procedures, particularly the ones performed in the interventional laboratory, to maintain a large revenue stream, which frequently is expected to be sufficient to offset other revenue defi-

cient areas and services. Despite all of the predictions and efforts to stabilize and even reduce the costs of medical testing and treatment over the past 25 years [2], total expenditures continued to rise at a dizzying pace. This is not a sustainable trend. Therefore, new techniques cannot be conceived as "add-ons" to the cost burden, but must be proposed as replacements or alternatives for already existing diagnostic and therapeutic procedures.

Competition between hospitals and institutions for the latest technique or equipment, particularly in densely populated urban markets, is a significant cause of accelerated implementation of technology. The medical institution or practice that gains local prestige for pioneering the latest technique is widely perceived to gain a substantial marketing advantage, even if the actual benefit in terms of outcomes and healthcare delivery is marginally, or only fleetingly, realized. Further, the pressure to spend large sums of money to acquire the technique spurs high costs and reduces the profit margin, particularly in an era of diminishing clinical reimbursement.

The most likely sustainable trends in coronary heart disease include: (1) increased technology utilization with more frequent noninvasive imaging technology utilization as well as invasive direct vascular imaging tools, (2) shifted case mix with fewer diagnostic catheterizations other than those likely to lead to coronary interventions and fewer acute interventions, and more elective interventions, as a consequence of increased screening and improved medical therapy, (3) earlier diagnosis and improved pathophysiologic understanding such as diagnosing vulnerable plaque before presentation as an acute coronary syndrome with newer diagnostic information integrated into the traditional angiogram in borderline and equivocal cases, and (4) novel technical developments such as more combined or hybrid procedures. Improvements in catheter-based therapies could be expected to lead to increased case-loads, but these improvements may be offset in the longer term future by the development of better medical therapies and preventive agents.

Structural heart disease will almost certainly become a larger percentage of catheter-based treatment. Valvular heart disease treatment is likely to undergo dramatic changes as aortic and mitral valve replacement will increasingly be catheterization based. Closure of patent foramen ovale and atrial septal defect, already a part of the interventional laboratory armamentarium, will probably become more frequently performed with earlier diagnosis. Shifting expenditures, resources, and manpower from traditional surgical operations to catheter-based procedures is a critical trend for the future.

Vascular medicine has evolved to a crossover specialty connecting interventional radiology, cardiovascular medicine, and cardiovascular surgery; with further improvements, these procedures will be performed more frequently and will involve more complex cases. A team approach, involving specialists working together rather than in competition, is most likely to lead to better outcomes for patients. At many sites, increasing peripheral vascular volume currently outpaces growth in coronary procedures, and this case mix evolution will continue and directly affect the design of tomorrow's catheterization laboratory. Treatment of abdominal aortic aneurysms and other diagnoses traditionally within the surgical realm will increasingly be performed percutaneously, and hybrid laboratories designed for these procedures may well incorporate multiple imaging or robotic modalities. Similarly, carotid disease and stroke treatment will be treated by a wider variety of practitioners in an ever-increasing number of centers.

Electrophysiologic techniques have become more complex, and there are significant technical aspects to placement of newer pacemakers and AICDs that mandate high image quality. Cardiologists performing electrophysiology studies no longer work in archaic catheterization laboratories or with inadequate fluoroscopic C-arms. Electrophysiologists with new, sophisticated catheterization and ablation techniques rely on visualization of fine details of cardiac structure and require high-quality fluoroscopy. The electrophysiologic laboratory will most likely develop broadly applied complex three-dimensional spatial electrophysiologic mapping and visualization tools. Most importantly, case volume may be anticipated to skyrocket as electromechanical devices are introduced both to prevent stroke in atrial fibrillation [3] and for the treatment of congestive heart failure.

CONTINUED PROGRESS IN MINIATURIZATION AND MINIMAL INVASIVENESS

Over the past 3 decades, innovations in biomedical technology have facilitated progressively more minimally invasive therapeutic procedures, and percutaneous vascular interventions are one profound example of this revolution. Although 30 years ago, 8–10 French guides were used to perform simple balloon angioplasty, the evolution of technology now facilitates delivery of sophisticated drug-eluting stent systems using miniaturized (most recently 3 French!) systems [4]. Although at the current time it has not been demonstrated that smaller catheter sizes will provide a technical advantage, future improvements may be anticipated.

These improvements in equipment and technique have resulted in routinely high procedural success and are safer and more effective for patients while also rendering the procedure itself technically easier and quicker for the operator. What will the “state-of-the-art” look like in the future? Developments in robotic catheter manipulation guided by ever more sophisticated indirect and direct imaging systems give promise of a future of greater miniaturization and precision. Therapeutic devices promise to make present interventions even more efficacious: bioabsorbable stents and innovative drug delivery platforms are already being tested [5], and stents based on a guide wire platform may be in our armamentarium [6]. Catheter-based valve replacement and repair are already in intensive clinical trials and will undoubtedly become standard therapeutic techniques. For all such applications, percutaneous miniaturization can be anticipated. One may foresee an era of access sites the size of small wires with guidance performed based on imaging from miniature devices controlled remotely by computer-based navigation and manipulation systems.

INTEGRATION OF IMAGING MODALITIES

As a result of technology and reimbursement trends, the primary focus in the interventional laboratory of the future will be the integration of imaging modalities in a seamless manner in which the information gained by one technique enhances and is incorporated in an additive manner to the information acquired by other techniques. The composition of the plaque, the presence of vulnerable plaque, its three-dimensional geometric character, its physiologic consequence, and the simulated effect of the planned therapy will all be considered in the context of natural history and procedural morbidity, contributing to therapeutic decision making. There are currently multiple modalities that permit assessment and visualization of blood vessels and vascular structures, each interpreted independently of the others; the opportunity to fuse these data sets to interact with all the necessary information to provide an optimized pre- or intraprocedural perspective is the future of integrated imaging. Currently, imaging workstations include cumbersome packages that attempt to facilitate such multimodality fusion [7]. Similarly, importing physiological information such as blood flow, electrical activity, or metabolic and cellular imaging could dramatically enhance and expand intraprocedural therapeutic latitude, specificity, scope, and scale. As a representative example, importing functional MRI information into a neuroembolization procedure would be beneficial to determine that a particular branch being embolized will not result in injury to the eloquent cortex.

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The standard coronary or vascular angiogram, a silhouette X-ray image of the lumen of the vessel created with contrast media, will continue to play a central role for the medium-term future. However, advanced digital imaging and detailed three-dimensional reconstructions will enable more accurate diagnosis and effective treatment. Very likely, integration of CT and MRI data into vascular reconstructions based on angiographic techniques will result in a new fused “standard” imaging modality. These advanced and integrated analyses will be available online with immediate post-acquisition processing to allow for reproducible decision pathways in real time. Angiographically equivocal lesions will be routinely evaluated in the laboratory using fractional flow reserve or intravascular ultrasound, and potential clinical decisions evaluated real time using validated predictions of procedural and clinical outcomes.

As simulation technology is advanced and incorporated into the teaching process, one possible outcome may be increased utilization of virtual interfaces with haptic feedback [8]. To call such systems “robotic” is an over-simplification, although current, initial implementation versions of robotic angiography exist where the operator is separated from the procedural bedside in order to protect the operator from the radiation environment [9]. The possibility of transforming virtual reality into procedural reality is just one aspect of a general movement away from the direct and inconsistent manual twisting, pushing, and pulling of catheters and wires as operators move toward interacting with graphic user interfaces connected to electromechanical intermediaries. These techniques will ultimately result in the use of intelligent navigation, perhaps by pointing and clicking on an image of an artery as physician-operators “supervise” the semiautomated process and watch the catheter and wire automatically engage and enter the selected vessel. The technique may well incorporate MEMS technologies with microfabrication and piggybacking of various ablative and in vitro diagnostic tools on a multicable catheter package. Additional benefits of this technology will be the development of simulations built on graphic user interfaces as a practical training tool and testing instrument [10]. By developing simulations of “nightmare” scenarios, future physicians will learn how best to respond before actually encountering critical situations in “real-life” patients.

Techniques to analyze the wall and physiology of the vessel rather than just the lumen are currently in development and will be critically important. The components will include an assessment of arterial remodeling, plaque composition, and lesion morphology. These characteristics may determine which therapies are most

likely to be successful [11,12]. Specifically, intraplaque hemorrhage, vulnerable or free lipid-pool components, ulcerations, and other morphologies likely to lead to accelerated plaque progression and impending vascular compromise in asymptomatic patients will be more fully and routinely characterized [13]. Intravascular tools such as ultrasound, dual photon spectroscopy, near-infrared spectroscopy, and optical coherence tomography undoubtedly will gain even further in utility, and defining fractional flow reserve in borderline lesions will become standard [14–17].

Molecular imaging is also on the horizon [18], promising insights into pathophysiologic processes that may be clinically important (e.g., plaque inflammation and its implications for plaque vulnerability). Furthermore, these imaging modalities are now being developed as single multimodality catheters that promise to provide these important data efficiently. Given the wealth of data provided by such direct vascular imaging systems, and the undesirable effects of radiation and contrast dye, it may be foreseen that in the future patients might undergo the bulk of imaging by direct techniques. For example, a patient undergoing coronary intervention might have a single injection each of the left and right coronary arteries to serve as a “roadmap,” with the remainder of the diagnostic and therapeutic aspects of the procedure facilitated by direct imaging using a multimodality catheter. This approach would minimize radiation to patient and operators, minimize contrast dye burden, and provide more information on the vessel wall pathology.

Integration of different imaging modalities (fluoroscopy, ultrasound, CT, and MRI) has already been implemented in limited ways in the interventional laboratory. Multimodality-guided treatment of tumors has proven to be more effective than treatment guided only by fluoroscopy and will probably become the norm for many interventional oncology therapies [19,20].

Not only will the capability to perform these procedures be present in all laboratories, but the findings will also be integrated in real time. A comprehensive psychological and cognitive understanding of how operators process information has not yet developed into a refined field, but advances in this area will be required to produce the next generation of imaging. The rapid assimilation of morphologic and physiological information will be required to compose a coherent understanding of how the interventionist can best interact with a particular patient. As an example, a neurointerventionalist may be interested in information displayed simultaneously on eight monitors suspended from the ceiling: lateral and frontal reference angiograms, lateral and frontal live fluoroscopy, lateral and frontal road maps, a hemodynamic monitor, and a

three-dimensional image of the vasculature tree or structure. This is too much information displayed across too much spatial real estate to access by turning one's head to survey a wide geographic span of monitor screens. A better way of integrating this information into a single set of images that can be viewed interactively is needed. A similar evolution in the psychological ergonomics of multiple visual information streams has led to dramatic advances in information visualization and processing in such environments as jet-fighter cockpits. This discipline of ergonomic multi-stream visualization could be described as "psychovisualization" or an understanding of the needs of the operator for processing multiple converging streams of information to optimally "visualize" the therapeutic intentions and target while performing a complex procedure.

Industry will be asked to find ways to implement these technologies in the interventional laboratory, to aid the interventionalist in integrating visual and other data from multiple sources. Archival solutions must also be easily available and transferable to other laboratories and environments when consultation and long- or short-distance partnering is sought. It is easy to imagine geographically dispersed individuals serving simultaneously in a consulting capacity during a procedure, participating through virtual environments. The challenge of providing up-to-date medical care in rural communities might be addressed with such techniques. However, the demand for on-site responsibility is unlikely to permit large-scale fully centralized telesurgery or teleprocedures.

THE FUTURE OF DIGITAL IMAGING

Digital imaging is the cornerstone of today's catheterization laboratory and will continue to be the basis of future developments. The technical advances of the last few years, especially flat-panel digital detector imaging systems [21], have made it possible to build functional, high-quality combination coronary and peripheral interventional rooms. The essential ingredients for a multipurpose system that supports both vascular and other interventions are already features of modern laboratories, including a wide field of view, digital subtraction, three-dimensional angiography, road mapping features, and even multimodality fusion. Digital imaging improves image quality and not only enables catheterization laboratories to produce high-quality postprocessed images but also facilitates integration of other imaging modalities. Digital archiving, monitoring, and reporting systems markedly decrease wasted physician time by storing images and information instantly and providing immediate access to patient information.

The key to advancement rests in enhancing the digital environment to measure and demonstrably improve patient care and workflow. The drive to create this new environment will, of necessity, affect the equipment architecture and manpower models the laboratory uses. Each hospital needs a comprehensive understanding of the expected procedures and volumes it performs with trending and quality measures. This information will impact the selection of the equipment and workflow that best supports these efforts, as framed by the institution's strategic and investment plans. For example, anticipated growth in peripheral vascular and structural cardiac procedures will guide decisions about which X-ray systems, adjunctive robotic systems, and visualization tools best meet the hospital's needs. Further advancements in digital imaging will bring improvements in both image quality and workflow. Integrated systems to support digital workflow, such as structured reporting tools and electronic image and report distribution systems, will define the manpower needs of the next-generation interventional laboratory.

INFORMATION TECHNOLOGY AND CATHETERIZATION LABORATORY DESIGN

Information technology (IT) services involvement in the daily activities of the laboratory will become a critical component of staffing. Centralization of such services in the laboratory will be necessary, including dedicated IT staff to facilitate implementation, maintenance, and integration of functionality and ever-changing applications with archival, hemodynamic monitoring, and hospital information systems. Significant effort will be required to manage the obsolescence of provincial RIS, HIS, IT, and PACS hardware; retirement and archival of these functions will necessitate intensive IT involvement, as they are replaced by universalized medical application sets with robust interoperability and rapidly updated application changes. Such evolution implies that updates are progressively thinner with concentration on applications, and the dependent hardware is progressively outsourced with very different capitalization and rental models from current systems. Procedural data will be immediately sent electronically to insurance companies, Medicare, and specialty quality assurance programs with rapidly expanding quality assurance initiatives and integrated and dependent reimbursement.

Incorporating such disparate needs as hemodynamic monitoring, billing, hospital information, and archival will require a much greater and more rapid level of integration and development of IT to achieve the necessary efficiencies. Demographic data will be entered just once; in addition, all images will be retrievable on

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hospital and network office computers and system PDA's for immediate review. By avoiding errors associated with manual data entry, billing and archiving will be simplified. Efficiency is improved as information resides in one integrated database instead of several disparate locations. This will also make it possible to rapidly retrieve data and images from examinations performed at other hospitals and institutions. Patient satisfaction will increase as there will no longer be a need to answer the same questions multiple times as the patient progresses from admitting, through the procedure, to recovery. Similarly, practitioners will be automatically identified by systems analogous to radio-frequency identification tags, and elements as disparate as their exposure information and practice connectivity will be automated and integrated.

IMPACT ON CATHETERIZATION LABORATORY DESIGN

As noted, one anticipated central trend is that increasing numbers of patients and procedures traditionally treated with open surgical procedures will instead be treated with minimally invasive approaches in the catheterization laboratory in increasingly sterile environments. Such "laboratories" will likely become more similar to surgical/operating rooms in terms of infrastructure, demanding scrub-only access and including multiple air turnovers similar to open surgical rooms. These needs will be as important as the need for enhanced imaging and diagnosis. In contradistinction, increased outpatient utilization and throughput will be a direct result of more frequent and accurate screening and will increase the need for greater safety, sterility, and procedural consistency.

Likely, these trends may well result in two different interventional laboratory types. One, the diagnostic/traditional interventional type room, will be much like today's laboratory but with greater diagnostic capability. Possibly, these will be designed with a view to greater patient comfort, perhaps with soothing and calming decorations and lighting conducive to an awake, alert patient akin to a contemporary birthing room. Potentially, such awake-patient rooms may include distracting electronic or multimodality features to fully relax and distract the patient with visual or acoustic enhancements. The second type of laboratory may be an alternative surgical suite with fluoroscopy integrated with other large and complex imaging modalities and will be used for sterile procedures that are extensive and more complex. Currently, many institutions are working on ambitious projects and imaginatively configuring "operating rooms of the future," which incorporate a variety of imaging tools, including

but not limited to CT, MRI, and PET [22]. As the advantages and drawbacks of incorporating such a variety of imaging equipment are better understood, the pragmatic pairing of selected large imaging tools will be beneficial in the percutaneous, minimally invasive environment. If emergency open surgery is required, these alternative surgical suites will already be equipped and staffed appropriately without needing to move the patient. These alternative surgical suites may be fully perfusion cardiopulmonary bypass capable or configured and optimized for other procedures with an endovascular component such as craniotomies for aneurysm or arteriovenous malformations and will be equipped to meet the necessary open-surgical specifications, such as frequent air exchanges [23]. Rooms of this type are ideally equipped for percutaneous valve procedures, septal occluder placement, and aortic stent graft placement. They are also capable of immediate intra- or post-CABG angiography.

These laboratory designs are intended to enhance patient satisfaction, further increasing their competitive advantage and enhancing perceived customer value. Of course, proper utilization would require a change in medical culture, requiring a more complete team approach in which surgeons, cardiologists, and radiologists coordinate their schedules and collaborate in a truly integrated manner. More than merely a cultural shift, it reflects the reality of the fields and interests merging, and traditional distinctions between the various specialties blurring.

The cost of such laboratories will likely be significantly higher than current laboratories, as they will be equipped and stocked with novel devices and equipment that is traditionally contained in several separate rooms. Space considerations will be critical, as these laboratories will need to be larger. Storage issues will become more significant. This additional cost will not be transferable to the consumer, or third-party payors, as easily as in the past 2 decades. Scientific evidence will be required to show that the increased expense is justified by improved patient outcomes; moreover, various medical societies will have to work together on behalf of patients to convince the federal government and insurance companies that this is money well spent. Recognition that the "enemy" is not each other but those political forces less interested in providing optimal care than in cutting medical expenditures will have to be the rallying point for organizations of physicians who have not traditionally been politically savvy or economically astute.

Radiation shielding design will have to be completely reconsidered, and new approaches developed [24]. Societal expectations include worker safety as well as patient safety. The current paradigm of physicians and staff wearing ergonomically inefficient lead

makes their musculoskeletal systems and spinal axes vulnerable to injury, leading to occupational hazards (including time inefficiencies and even early curtailment of careers due to spinal disabilities). This is not an economically feasible employment strategy in a future where even more highly trained operators and technicians are required and difficult to replace.

Advances in minimizing the risks of nephrotoxicity, transdermal injury, and infectious transmission to healthcare workers and patients in the endovascular environment will affect the design of such suites. Radiation dosage to operators will be reduced by selecting gantry angles and frame rates that decrease scatter, and shielding will likely be supported by alternative suspension systems. Low-dose fluoroscopy will often be recorded instead of high-dose digital cine runs (fluoroscopy loops), and it is likely that nonionizing imaging techniques will be used to coregister images and to perform desired complementary imaging. As an example, it may not be necessary to use continuous fluoroscopy if a three-dimensional angiogram is stored. Navigation of the vascular tree can be performed through coregistered endovascular ultrasound or radiofrequency tool localization if the necessary coregistration technologies are incorporated in the catheter and wire.

Patient radiation dose is already becoming a critical issue as more and more radiologic procedures with high exposures are performed [25]. It is ironic that in spite of advances in multiple technologies in various areas of nonionizing imaging, ionizing radiation is still the core of sophisticated interventional work. Clearly, as multimodal therapies develop and gain increased utilization and as intermittent coregistration with nonionizing or stereotactic methods become a possibility, better understanding will emerge how patients and healthcare workers can be protected from the side effects of visualization and therapeutic technologies. Early work with MR guidance for interventions can be expected to advance. Interventional MRI will prove useful for many procedures and patients.

DATABASE CONSOLIDATION/POOLED LEARNING

Most interventional laboratories and their physicians currently operate in isolation. Aggregation of information systems and the mandatory consolidation of information into national databases will provide a number of advantages. Quality assurance will demand benchmarking on a national scale. This will be possible with refined IT backbones. It must be accompanied by a clear understanding of how pooled learning and communication should be structured pragmatically. This is a necessary ingredient in the development of compara-

tive effectiveness pathways, and robust, societal-driven outcomes analysis. The National Cardiovascular Data Registry and Society of Thoracic Surgery have pioneered the development of clinical and procedural databases; currently, participation is voluntary in most states. In the future, both government and private insurance will require all laboratories to submit procedural data for quality and outcomes analysis. Reimbursement level may be set accordingly. A mandatory response to suboptimal results will ensure better patient outcomes and appropriate case selection and will be part of dynamic and real-time public reporting. Questions abound regarding the value proposition for many of the procedures that are performed, as physicians explore which metrics need to be used to define quality and to develop accurate appropriateness criteria [26].

In anticipating how the next generation interventional laboratory will function and look, the context within the larger trends facing medicine generally is crucial. Outside agencies will continue to seek to reduce medical expenditures, at times below that requisite to maintain optimal medical care. The best defense against draconian and inappropriate cost cutting is to define what constitutes high quality. It cannot be over emphasized that those who decide what quality is will control the future of medicine. Physicians have in their hands the antidote to the bean counter: the procedural and clinical outcomes of their patients. We cannot allow the next generation to suffer from our inability to collaborate with one another. Only by working together to produce national databases, develop benchmarks, determine the outcome measures of real importance, and create consensus on appropriate utilization of resources, can we control our destiny and the provision of medical care. Therefore, the directors and administrators of the interventional laboratory of the future and its programs must be enthusiastic and fully capable of participating in quality improvement, both locally and nationally.

STORAGE AND INVENTORY

Inventory management is yet another challenge for the multifunctional interventional laboratory of the future. As the laboratory procedure list expands to the full range of peripheral vascular, cardiac structural, complex coronary, interventional neurosurgery, interventional radiology, and interventional oncology cases, the inventory required becomes progressively more costly and requires more storage space. Storage that is bar coded or radiofrequency identification tagged and within easy reach is neither simple nor inexpensive. The laboratory manager and administration will be confronted with conflicting tasks, as the pressures to

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limit costs increase simultaneously with the need for competitive investments. Well-organized storage space and a sophisticated system for inventory management are necessary to locate equipment when needed and to minimize expiration date-related inventory losses. An integrated inventory management, billing and scheduling system is not only a fundamental operational requirement but may become the central requirement to minimize costs in the efficiency-maximized laboratory of tomorrow.

As the laboratory must be prepared to perform many more procedures, its investment in inventory will be substantial. At a time of diminishing reimbursement, it is difficult to conceive how an institution can afford to sink significant capital into equipment with limited shelf life. Flexible purchasing arrangements with industry, including contingency, will be necessary to prevent the expiration of infrequently used disposables from becoming a substantial cost.

CATHETER NAVIGATION AND DEVICE PLACEMENT

Several techniques have been proposed to manipulate catheter movement using magnetic or electromagnetic guidance. These capabilities promise to enhance patient safety through improved control, precision and reduced procedure time and improve operator safety by diminishing X-ray exposure. Magnetic systems appear to offer safe and effective navigation but are limited by requiring significant space around the patient, limiting direct access. Moreover, they require substantial additional shielding and specifically designed catheters with a magnet near their tip. Electromechanical guidance is a simpler design, using cables within the catheter to manage tip deflection and position. Such systems promise rapid and direct hand control [27]. A transition to three-dimensional imaging would be a key enabling step in the use of robotic systems [28]. The development of patient-specific organ models may be the first step in the process [29]. However, the incremental costs of development and changes to the procedure room must be justified with significantly better clinical outcomes, and this will be a substantial barrier to their introduction and clinical acceptance.

CONCLUSION

One prediction about the interventional laboratory of the future that is certain is that neither its function nor its design will remain what it is today. Improvements and innovations produced by industry and pioneered by physicians will be stimulated by the needs of our patients. The efficiency and speed of our response will

be determined by how well we cooperate in moving forward and how creatively we imagine and construct the future. Have we fully engaged the opportunities for novel growth where our technologies are concerned? Have we forcefully and expediently affirmed or refuted the value of such novel tools and technologies as MRI-based catheter interventions, robotic catheterizations, and evidence-based universal order-entry systems? Certainly, the future will be dynamic, exciting, and multifarious. With the charge for transparency, quality, and safety which faces all of medicine, considerable and necessarily revolutionary change in the future of minimally invasive catheter-based therapies is inevitable. If the thoughtful and methodical quest for improved patient care is accompanied by a quest to create a safe environment for practitioners, then the future indeed is promising. This will require teams of physicians, scientists, regulators, and manufacturers working together with the best interests of patients and staff in mind.

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