Interventional Radiology: A Half Century of Innovation

Richard A. Baum, MD, MPA, MBA
Stanley Baum, MD

The evolution of modern interventional radiology began over half century ago with a simple question. Was it possible to use the same diagnostic imaging tools that had revolutionized the practice of medicine to guide the real-time treatment of disease? This disruptive concept led to rapid treatment advances in every organ system of the body. It became clear that by utilizing imaging some patients could undergo targeted procedures, eliminating the need for major surgery, while others could undergo procedures for previously unsolvable problems. The breadth of these changes now encompasses all of medicine and has forever changed the way we think about disease. In this brief review article, major advances in the field, as chronicled in the pages of Radiology, will be described.

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The evolution of modern interventional radiology began over half century ago. Use of the same diagnostic imaging tools that had revolutionized the practice of medicine became a possibility in guiding real-time treatment of disease. This concept led to rapid treatment advances in every organ system of the body. It became clear that by utilizing imaging some patients could undergo targeted minimally invasive procedures, thus avoiding major surgery, while others could undergo procedures for previously unsolvable problems. The breadth of these changes now encompasses all of medicine and has forever changed the way we think about disease. In this brief review article, we will describe the major technologic advances in the field, as chronicled in the pages of Radiology. We will also explore the 50-year journey of interventional radiologists, from diagnostic imagers to practicing clinicians.

**Patterns of Innovation**

When tracing the advances in the field over the past 50 years, a discrete pattern of creativity and innovation becomes apparent. There is a regular progression from when a novel idea emerges to when that idea becomes accepted clinical practice, regardless of the disease process or new procedure.

Innovation in interventional radiology typically occurs when someone either takes existing tools or develops new ones to solve a clinical problem. Either way, creativity is the common thread. From gastrointestinal bleeding to angioplasty to embolotherapy, interventional radiology innovators have created better and safer ways to treat disease. After initial discovery, superior tools are then developed that allow procedures to become safer and more durable. These advances may be along the imaging chain, improved contrast agents to medical device design. Finally the new procedure is compared with existing techniques by using clinical, financial, and safety metrics, allowing its role in patient care to become clearly defined. The cycle then repeats and new discoveries are made based on prior accepted procedures. This natural ebb and flow form discovery to enhancement and then back to discovery provides the foundation for all image-guided medicine today. This is a clear distinction from other proceduralists who typically innovate in a much narrower window. The end result is the enormous scope of practice that interventional radiologists have crafted over the past 50 years.

**The Early Years**

The specialty of interventional radiology evolved as an outgrowth of diagnostic catheter angiography. The seminal breakthrough that made catheter angiography possible was the description in 1953 (1) by a Swedish radiologist, Sven Ivar Seldinger, of a simple technique (since called the Seldinger technique) that allowed for the percutaneous catheter replacement of a needle or trocar (Fig 1). Prior to Seldinger, large bore needles or trocars were used to gain access to the vascular system, and this was frequently associated with major complications. After the introduction of the percutaneous method, aortography and selective arteriography became relatively risk-free procedures (2–4) (Figs 2, 3). Because of the popularity of these procedures, new “tools of the trade” were developed that included automatic power injectors (5), rapid film changers (6), image intensifiers, video systems, and cineangiography.

In the early 1960s, selective angiography was used to diagnose pathologic conditions in virtually all organs of the body (7–10). With the advent of lymphangiography, the lymphatic system also fell under the preview of the angiographer (11,12) (Figs 4, 5).

The placement of a preshaped catheter into the feeding artery of an organ also made pharmaco-angiography possible (13) (Fig 6). Also, for the first time, Abrams showed that one could distinguish, in vivo, between malignant and normal vessels (14) (Fig 7).

The preoperative identification of the site of active gastrointestinal bleeding (15,16) was made possible by selective mesenteric arteriography. To put this exciting development in perspective, one must remember that flexible procedures (2–4) (Figs 2, 3). Because of the popularity of these procedures, new “tools of the trade” were developed that included automatic power injectors (5), rapid film changers (6), image intensifiers, video systems, and cineangiography.

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endoscopic techniques were not available in the 1960s. Even at laparotomy, the surgeon often could not identify the site of bleeding because of the large amount of blood throughout the gastrointestinal tract. Blind resections were frequently performed in the hope that the resected portion of the stomach or bowel contained the bleeding site. Gastroenterologists and surgeons welcomed preoperative angiography, but the performance of emergency studies required that the angiographer be available all hours of the day and night. This caused a major paradigm shift in the specialty of radiology. In addition to having to take emergency call, radiologists were now making hospital rounds and writing orders in the patient’s chart.

The use of the vascular catheter for the performance of endovascular treatment quickly followed. It was logical to attempt to treat the vascular abnormality identified on an angiogram by either narrowing or blocking the vessel in cases of bleeding or dilating the vessel by means of percutaneous transluminal angioplasty in cases of vascular narrowing or occlusion. The introduction of these two procedures in the 1960s heralded the beginning of interventional radiology.

Figure 2: Selective coronary arteriography technique shows contrast material injection in, A, left coronary artery in right anterior oblique projection, B, left coronary artery in left anterior oblique projection, C, left coronary artery in lateral projection, and, D, right coronary artery in right anterior oblique projection (fig 6 from reference 3).
Figure 3: Renal arteriography during arterial and parenchymal opacification (fig 10A and 10B from reference 2).

Figure 4: Anteroposterior lymphangiogram of the pelvis (fig 5A from reference 11).

Figure 5: Lymphangiogram. Intravenous urogram and inferior vena cavaogram depicts an 8-cm mass proven to be choriocarcinoma (fig 14 from reference 12).

Treatment of Gastrointestinal Bleeding

The angiographic criteria used to make the diagnosis of gastrointestinal bleeding are straightforward and independent of the presence of large amounts of blood in the gastrointestinal tract. Since successful visualization requires that the bleeding be active and occurring at a rate of at least 0.5 mL/min, the patients being sent for angiography were quite ill and required very careful monitoring. The angiographic suite was converted into a mini-intensive care unit, with patients frequently on respirators, receiving blood transfusions, and undergoing gastric lavage. Gastroenterologists and surgeons were usually present and together with the radiologists participated in the inter-disciplinary care of these acutely ill patients. The radiologist was no longer
Figure 6: Renal angiograms in a dog before administration of epinephrine (left) and at 11 seconds after administration of epinephrine directly into the left renal artery (right). The main left renal artery remains filled but none of the peripheral branches fill (figs 1 [top left] and 2 [fourth image] from reference 13).

Figure 7: Selective renal arteriograms in a patient suspected of having carcinoma of the kidney, A, before and, B, after injection of epinephrine. In B, there is further filling of tumor vessels but there is cessation of flow through the vessels supplying normal renal parenchyma (Figs 1B and 2C from reference 14).
of coaxial or dilating catheters was described by Dotter and Judkins in 1964 (22,23) (Fig 10). However, since the diameters of these catheters were large, there was a limitation in the size of the vessels that could be treated. If a large vessel was being dilated, there was increased risk of puncture site complications such as a large hematoma and pseudoaneurysms. Because of these limitations, the technique never gained a great deal of popularity in the United States. However, it continued to be performed in Europe, and multiple reports described the technique being used for the successful treatment of peripheral vascular claudication (24,25).

In the early 1970s, polyvinyl chloride balloon catheters were introduced primarily for the performance of coronary transluminal angioplasty (26–28). The small diameter, balloon compliance, and dilating force of these catheters addressed almost all of the limitations of the previous techniques. Because restenosis, either immediate or delayed, after angioplasty remained a problem, intravascular stent placement (29–31)
**Figure 9:** Selective mesenteric arterial infusion of vasopressin for a bleeding Mallory-Weiss tear. *A, B,* Selective left gastric arteriograms show extravasation of contrast material (arrows). *C,* Cessation of bleeding during intra-arterial administration of vasopressin (fig 7 from reference 19).

**Figure 10:** Arteriograms depict the stages of percutaneous transluminal treatment of arteriosclerotic obstruction (fig 7 from reference 23).
(Fig 11) was introduced as a major strategy to address the major shortcomings of percutaneous transluminal angioplasty. In more recent years, drug-eluting stents (32) have been introduced to prevent in-stent restenosis.

Although selective percutaneous coronary arteriography was developed and popularized by angiographers (33–36), most radiologists had little interest in performing cardiac catheterizations, and in most institutions these studies, as well as coronary angioplasty, are performed by cardiologists (37). Almost all of the other vascular interventional procedures remained within radiology.

Balloon angioplasty, either with or without stent placement, has become such an important part of modern medicine that it is hard to remember when these techniques were not available. What started as an attempt to nonsurgically treat claudication in the legs has evolved into a technique that has had a major impact in all forms of vascular disease, whether it is in the heart, brain, or solid organs like the kidney or liver. It represents and is recognized as a major innovation in the treatment of disease.

Nonvascular Interventions

There was very rapid growth of interventional radiology in the 1970s and
1980s, and angiographers started performing image-guided procedures that were outside of the vascular system and involving almost all organ systems of the body. The interventional radiologist became very important in the management of both benign and malignant obstruction of the biliary system. Techniques were developed for the diagnosis and drainage of the bile ducts (38–41) (Fig 12), and the radiologist also monitored tubes placed either percutaneously or surgically (42,43).

Percutaneous nephrostomy was initially described as a technique to drain acute or chronic urinary obstruction (44); however, it rapidly evolved into a way to gain access to the entire urinary tract (45–47). The clinical treatment of patients with intrathoracic, abdominal, and pelvic abscesses has changed dramatically since the introduction of percutaneous image-guided catheter placement (48). Few procedures performed by the interventional radiologist have had as dramatic impact in the survival of patients (49). Primary intrathoracic lung abscesses are usually caused by aspiration (50) (Fig 13), and in abdominal abscesses, approximately two-thirds are a result of an abdominal operation and one-third result from a perforated viscus (51,52) (Fig 14).

**Figure 14:** Drainage of abscesses and fluid collections. (a) CT scan shows large fluid collection (arrows). (b) CT scan demonstrates needle insertion into the more caudal portion of the abscess (arrow). (c) Transhepatic insertion of the catheter. (d) Fluoroscopic image of contrast material injection into the catheter (fig 2 from reference 52).
Perfecting Tools

In the past 2 decades of the 20th century, technologic advances in computing power and medical device manufacturing led to rapid improvements in the field. Stents, microcatheters, and embolic material became widely available and provided the interventionalist with new sets of tools to treat disease. Digital subtraction angiography quickly replaced traditional screen-film imaging, making procedures quicker and safer (53–55). In addition, noninvasive imaging emerged as an alternative to contrast material–enhanced angiography in the diagnosis of vascular disease. In 1986, Dumoulin and Hart (56) published images of flowing blood obtained by using magnetic resonance (MR) imaging (Fig 15). Twenty years later, MR angiography and CT angiography have become the mainstays of vascular diagnosis (57–60) (Fig 16).

The positive reinforcing loops leading to this explosive growth in the specialty were not fortuitous accidents. Instead they were strategically crafted by the first wave of modern interventionalists (61) (Fig 17). This forward-thinking group realized that politics, economics, research, and longitudinal patient care were critical for the survival of the field. Much of the way we practice today is a result of seeds planted 20 years ago by Ring, Katzen, van Breda, Martin, Dorffman, Pentecost, Keller, Vogelzang, Roberts, Becker, Mauro, and others (62–67).

Transjugular Intrahepatic Portosystemic Shunts

Percutaneous portal decompression was described by Rösch et al in the pages of Radiology in 1969 (68). The procedure became a clinical reality with the introduction of the flexible stent 2 decades later. This enabled interventional radiologists to create durable connections from high-pressure portal veins to lower pressure hepatic veins in patients with portal hypertension. LaBerge and colleagues in 1993 published their experience in creating transjugular intrahepatic portosystemic shunts in 100 patients. They demonstrated a high degree of technical success, with control of variceal hemorrhage in 29 of 30 patients (69) (Fig 18).
As interventional radiologists gained more experience with the procedure there were advances in technique, equipment, and imaging. This made placement of the shunts safer and more durable (70–73) and led to the expansion of indications for the procedure (70,73–77).

**Uterine Artery Embolization**

In May of 2000, Pelage et al reported in the pages of *Radiology* their midterm results with uterine artery embolization in patients with fibroid-related menorrhagia (78) (Fig 19). They showed that superselective embolization was an effective technique in controlling symptomatic uterine leiomyoma. The procedure has since been refined with better imaging techniques and a better understanding of various failure modes. Good science paired with good clinical outcomes has resulted in uterine artery embolization becoming a mainstay in the treatment of symptomatic uterine fibroids (79–87).

**Stent Grafts**

Stent grafts became possible because of advances in metallurgy and textile manufacturing. Stents with outstanding radial force were combined with...
thin, durable, nonthrombogenic material. This allowed the creation of neovessels through diseased vascular segments by using an intravascular approach (88–100) (Fig 20). As devices became smaller and more flexible, the indications for stent grafts increased. Today they are utilized to solve a wide range of clinical problems, from abdominal aortic aneurysms to transcatheter liver-directed therapies. The ability to deliver drug-eluting stents and other biodegradable scaffolds has expanded the options for treating a variety of vascular conditions. Postoperative imaging surveillance and management are critical for the long-term success of these devices (72,75,93,101–105) (Fig 21).

Regional Cancer Therapies

Targeted therapies of primary and metastatic disease have revolutionized cancer treatment and provided options for patients who had previously been considered inoperable. Once again innovation in imaging and medical device design has led to focused therapies in almost every organ system of the body. In some patients these minimally invasive procedures are a curative first-line treatment, while in others they are performed to prolong life in nonoperative disease (106–109).

Percutaneous ablative techniques are capable of delivering targeted cytotoxic therapy directly to tumors while leaving neighboring normal tissue unaffected (110–114) (Fig 22). Some of these procedures are performed by using real-time imaging, while others are done by using a hybrid imaging approach (115) (Fig 23). Ablative techniques using energy or thermal deposition, as well as cytotoxic chemical injections, have been refined to best fit a particular organ and neoplastic process (116–119).

Dual hepatic blood supply provided an opportunity for interventional radiologists to create ways to selectively treat primary and metastatic disease of the liver through an intravascular approach. By mixing chemotherapeutic and embolic agents, high-dose chemotherapy can be delivered while minimizing systemic toxicity (120–124) (Fig 24). Chemoembolization continues to undergo constant refinements of materials and mixtures to develop the optimal regimen for the specific disease process. This treatment method also provides an optimal route for the delivery of new chemotherapeutic agents directly into the tumor.

Summary

To fully appreciate the impact and scope of interventional radiology on modern medicine it is useful to compare it to other procedural specialties. Whatever the field, most other specialists perform at most a dozen or so procedures, and their scope of practice is relatively narrow and well defined. Improvements in these disciplines are also confined to a rather limited spectrum. We hope we have demonstrated in this brief review that given a pallet of imaging and technology, interventional radiologists have been able to craft literally hundreds of original procedures in all organs.
Figure 21:  A, B, Four-dimensional volume-rendered images and, C, D, corresponding CT images in a patient with type II and III endoleaks (fig 5 from reference 105). * = contrast-enhanced aorta in A and unenhanced aorta in B. While arrow = early enhancement of small type III endoleak in A and C and unenhanced small type III endoleak in B and D. Red arrows = lower lumbar artery feeding a type II endoleak in A and upper lumbar artery communicating with type II endoleak in B. Blue arrows = type II endoleak in A and type II endoleak with increased enhancement in upper part in B and D.

Figure 22:  (a) Portal phase CT scan prior to radiofrequency (RF) ablation shows a single noninfiltrating hepatocellular carcinoma (arrows).  (b) Intercostal US scan obtained 1 month after RF ablation shows two hyperechoic lines (arrowheads) traversing the lesion, which correspond to two of the electrodes.  (c) Portal phase CT scan obtained 5 months after RF ablation shows complete absence of enhancement within the tumor (arrows), indicating complete necrosis (fig 1 from reference 110).

and body systems. The scope of this relatively new subspecialty facilitates creativity and innovation and enables interventional radiologists to improve patients’ lives.

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References

Figure 23: Focused ultrasound treatment of breast fibroadenoma. (a) T1-weighted spin-echo image before focused US treatment shows the enhancing fibroadenoma. (b) Fast spoiled gradient-recalled acquisition in the steady state (SPGR) image, obtained 1 week after repeated 60-W power depositions were applied to the entire tumor volume, shows no enhancement at the site of the tumor (arrows). (c) Fast SPGR temperature-sensitive phase-difference image of breast tumor during 10-second sonication obtained at the point of peak increase in temperature. Red to blue colors represent temperature differences, with red being the hottest temperature (Fig 8 from reference 115).

Figure 24: Chemoembolization of a hepatic tumor. A, Conventional baseline contrast-enhanced T1-weighted MR image of homogeneously enhancing lesion (arrow). B, Transcatheter intraarterial perfusion (TRIP) MR images obtained before and after transcatheter arterial chemoembolization (TACE) and perfusion maps show significant perfusion reduction in the target lesion. C, Unenhanced CT image obtained immediately after TACE enabled verification of the contrast agent distribution in the targeted segment (black arrows) and tumor (white arrow). D, Follow-up contrast-enhanced T1-weighted MR image 1 month after TACE shows no residual tumor enhancement, indicating complete necrosis (arrow). E, Gross pathologic specimen shows treated right-lobe tumor (arrow). F, Magnified view of the treated tumor within the pathologic specimen. G, Specimen stained with hematoxylin-eosin (H & E) enabled confirmation of complete tumor necrosis. (Fig 5 from reference 123).


