



TECHNOLOGICAL APPLICATIONS IN ENDOVASCULAR INTERVENTIONS

ENDOVASKÜLER GİRİŞİMLERDE TEKNOLOJİK UYGULAMALAR

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Abstract

Through catheter-based techniques, endovascular interventions are minimally invasive medical procedures used in the treatment of vascular diseases. They minimize recovery time, complication risk and operational difficulties relative to standard open surgery. New technologies have refined endovascular procedures, improved their safety and efficacy, and enabled targeted therapies to produce better outcomes. This article is used to review the face of these technologies in modern medicine and future innovation potential.

Keywords: Endovascular Interventions, Minimally Invasive Procedures, Technological Innovations.

Özet

Kateter bazlı teknikler aracılığıyla gerçekleştirilen endovasküler girişimler, damar hastalıklarının tedavisinde kullanılan minimal invaziv tıbbi prosedürlerdir. Bu yöntemler, geleneksel açık cerrahiye kıyasla iyileşme süresini kısaltır, komplikasyon riskini azaltır ve operasyonel zorlukları en aza indirir. Yeni teknolojiler, endovasküler prosedürleri geliştirerek güvenliğini ve etkinliğini artırmış ve hedefe yönelik tedavilerin daha iyi sonuçlar üretmesini sağlamıştır. Bu makale, modern tıpta bu teknolojilerin mevcut durumunu ve gelecekteki yenilik potansiyelini incelemek amacıyla hazırlanmıştır.

Anahtar Kelimeler: Endovasküler Girişimler, Minimal Invaziv Prosedürler, Teknolojik Yenilikler.

OVERVIEW / GENEL BAKIŞ

In vascular surgery, endovascular interventions are a minimally invasive technique with several advantages, including lower mortality and morbidity rates than open surgical approaches. These help achieve prompt vascular recovery thereby reducing hospital stay, helping attain faster recovery along with lesser complication risk. Endovascular methods, however, are gaining importance in treating a wider spectrum of vascular diseases and for some thoracic aortic pathologies where the complexity of the disease and the relative risk of operation serve as counterinfluences on the commonly high-risk surgical interventions. For this reason, these interventions are performed using catheter-based techniques, which avoid the risks of conventional surgeries, shorten recovery times, and improve the prognosis of the patients. Long story short, endovascular treatments have nobly remained an important part of reducing vascular diseases at risk, providing safer and less invasive alternatives to traditional methods (1-3). This approach is advantageous for its low mortality and morbidity rates,

including in high-risk patients. Usually, they are indicated for conditions that have associated high-perioperative risk with conventional surgery (eg, type 3 aortic dissection, thoracic aortic aneurysm). However, limited use is made of these methods owing to the absence of hybrid operating rooms and cardiologists being unfamiliar with endovascular methods. With hybrid room establishment in cardiovascular surgery clinics, alternative treatment modalities for big vascular lesions might considerably be improved (4). This review focuses on innovations in endovascular surgery and the promise of future technologies.

1. The Development of Technology in Endovascular Interventions

In 1964, Charles Dotter, a radiologist at the University of Oregon, pioneered endovascular technology with the transluminal angioplasty procedure. These techniques were employed to treat vascular diseases through the use of small puncturations without the need for a large incision. Dotter's creation, dubbed "Crazy Charlie," transformed the practice of vascular surgery. Then, effective catheter-based therapies were established (balloon angioplasty and metal endoluminal stents), however, the resistance to adopt these technologies were considerable. His contribution to the field of vascular surgery is significant (5).

During the 2000s, cardiology and radiology have paid attention to endovascular treatment of cardiovascular diseases. The Endovascular Revolution: Juan Parodi's Early 1990s Experiences Make Endovenous Treatment Possible for Vascular Surgery. Aortic treatment utilizing Computed Tomography (CT) and Magnetic Resonance (MR) imaging technologies. The 1970s research of Eugene Strandness on the combination of noninvasive B-mode vascular imaging and Doppler flow detection established the basis of contemporary noninvasive monitoring and treatment of vascular diseases and revolutionized the approaching to comprehensive vascular surgery. In the absence of these advances, aortic treatment would have been inconceivable (5,6).

By late 20th century, minimally invasive, catheter interventions had largely outnumbered open surgical cases in vascular surgeries. Endovascular surgery started in the mid-20th century and successful procedures were performed in the 1960s. Diagnostic imaging technologies such as angiography ultimately identified vascular abnormalities. But, these procedures were restricted by technology and intervention procedures. The 1970s also saw Dr. Andreas Grüntzig develop a pioneering balloon angioplasty technique that enabled non-surgical dilation of obstructed arteries, specifically targeting coronary arteries using endovascular techniques. This was a significant breakthrough that paved the way for an expansion of endovascular techniques and the prelude to modern surgery (7-9).

The industry and physicians worked together to create these advancements, which were first tried in the field of general surgery with laparoscopy. That collaborative model has since spread into



vascular surgery. Although there were no major technological advances in open vascular surgical techniques by the turn of 21th century, several endovascular advances emerged through (9).

1. Imaging Technologies

1.1. Intraoperative fluorescence imaging (IFI), Angiography and Digital Subtraction Angiography (DSA)

Intraoperative fluorescence imaging (IFI) has proven to be an invaluable tool to intra-operatively assess the patency of the graft in coronary artery bypass grafts (CABG), which is essential for both long term survival and need for reintervention (10,11). 26% of grafts fail within a year, with early graft failure being common. Despite low mortality rates, graft failure patients have been shown to be at higher risk of MI, death and re-vascularization (12). This provides reliable graft quality assessment during CABG procedures (10,11), thus IFI assists to solve this problem because it is real-time functional assessment of graft patency and myocardial blood flow.

Introduction: Despite being the reference standard for coronary artery disease (CAD) assessment and diagnosis, invasive coronary angiography has several drawbacks, including invasiveness and complications; thus, the need has become crucial for the development of non-invasive diagnostic tools. Multidetector-row computed tomography (CT) systems have gained popularity for analysis of the heart. Although conventional angiography provides unrivalled temporal and spatial resolution compared to CT techniques, significant improvements in both the CT modality and contrast agents now allow rapid diagnostic testing for many coronary artery diseases (13). Importance of CTA in the evaluation of patients with MICS Computed tomography angiography (CTA) in minimally invasive cardiac surgery (MICS) remarked by a research by Dr. Aencino et al. [22] mentioned about a clinical examination of MICS in patients with abnormal arteries where of the 1325 patients, 32% did not have MICS because of arterial deformities and underwent sternotomy while 68% underwent MICS as CT prevails accurate hindrance and recognized mapping 2D point of account [22] Accuracy in patient selection can lead to early abolition of potentially dangerous complication —such as calcified areas and arterial changes — eliminating the need to perform coronary surgery (14). Development of multidetector CT systems is advancing rapidly. The spatial and temporal resolution of conventional angiography has not yet been attained, but much advancement has been achieved in an extremely short time (14). As of the development of sixty-four-slice CT systems, the diagnostic effectiveness of CT coronary angiography has markedly increased in relation to 4-slice and 16-slice systems; thus, the clinical usage of the method is rapidly growing (16-18). A new dual-tube CT system may specifically address many of the shortcomings of 64-slice CT at a temporal resolution of 19 to 21.

Digital subtraction angiography (DSA) is a fluoroscopy technique used in interventional radiology to obtain an image of blood vessels in a soft tissue background. This is the process of taking a pre-contrast image or mask and subtracting it from subsequent images. DSA was first described in 1935 and described in detail in 1962, but digital technology made the practical development of the



technique possible in the 1970s (22-24). DSA remains the gold standard for the confirmation of aneurysmal obliteration, but it requires invasive arterial access (25,26). Endovascular aneurysm repair (EVAR) is extremely reliant on intraoperative fluoroscopic imaging, and in the last decade, innovation in exploratory technology has transformed conventional mobile fluoroscopic C-arms into cutting-edge hybrid operating rooms. In these rooms, high amounts of fluoroscopy and DSA images are obtained during and after EVAR procedures. Nevertheless, decisions taken at the time of operation are dependent on visual inspection of these images, apart from computed tomography-fluoroscopy image fusion for navigational guidance (27,28).

1.2. Intravascular Ultrasonography (IVUS), 2 D and 3D Imaging and Interventional Imaging

Intravascular ultrasound (IVUS) imaging offers real-time, two-dimensional (2D) images of intravascular vessels, providing detailed pathological information. However, it lacks spatial pose information, making it challenging to construct three-dimensional (3D) intravascular visualizations. IVUS imaging-driven 3D reconstruction techniques have been developed to address this limitation, enabling accurate diagnosis and quantitative measurements of intravascular diseases, extending the imaging modality to intraoperative navigation and guidance, supporting both therapeutic options and interventional operations (29).

Torres and De Luccia (30) evaluated the effectiveness of a simulator developed with 3D printers for EVAR. In a prospective controlled study conducted at a university hospital in Brazil, aneurysms produced with patient-specific 3D printers in 2015 were used for training vascular surgery residency students. Students in the training group practiced on the simulator and underwent the surgical procedure, while students in the control group underwent the surgical procedure with the routine procedure. The results showed that the patient-specific training group reduced fluoroscopy time by 30%, surgical time by 29% and contrast volume used by 25%. Students reported that the training was useful and realistic and that their confidence increased. The study revealed that training simulations using 3D printers can improve the performance of surgeons in EVAR surgery and improve the effectiveness of the surgical procedure (30).

A recent meta-analysis by Tam et al. (31) analyzed the use of 3D printer technology in vascular surgery, focusing on abdominal aortic aneurysm and thoracic aorta pathology. The study found that 3D printers significantly contribute to anatomic understanding, procedure planning, intraoperative navigation, education, and patient communication. However, the cost-effectiveness of this technology needs further analysis. The study highlights the growing recognition of 3D printers as a useful tool in vascular and endovascular surgery (31). A case report reveals that 3D printing technology was utilized for EVAR of complex neck anatomy aortic aneurysms in a 75-year-old patient. This method aided in selecting the appropriate stent-graft device, but further research is needed to assess its impact on procedure time, radiation dose, and cost (32). A study examined the use of 3D printer technology in



treating complex aortic diseases. Life-size 3D models were printed preoperatively for each patient, and postoperative CT angiography data was used to evaluate treatment results. All cases were successfully treated without major complications or operative mortality. 3D printing is a valuable tool for understanding technical aspects by presenting high-resolution anatomical details (33). Van den Berg's study (34) reveals that 3D rotational angiography is an effective tool for sizing covered stents for peripheral arterial aneurysms. The study shows that this technology is valid and useful in the preoperative and intra-procedural assessment of patients (34).

Interventional radiology uses image-guided methods to diagnose and treat patients with minimally invasive therapies. Central venous catheters and subcutaneous ports are frequently placed via interventional radiology, which has certain advantages over surgical installation. Procedures for arterial embolization are used to treat a variety of hemorrhages, and they work very well for severe postpartum hemorrhage. Surgery is not as effective as vascular interventions, such as endovascular treatment of varicosities, acute limb ischemia, and pulmonary embolism. For chronic limb ischemia and deep venous thrombosis, the choice of therapy is not as clear. Inferior vena cava filters can be placed and removed endovascularly, but there is a significant risk of complications that increases over time (35). After Fogarty's invention of the balloon catheter in 1963, surgical thromboembolectomy was the gold standard treatment for patients with acute lower limb ischemia (ALLI). However, endovascular technologies have evolved, leading to various therapeutic options. In the 1970s, Dotter introduced clot lysis, which was later modified to catheter-directed thrombolysis and clot aspiration techniques. About 70% of ALLI is arterial thrombosis, often in patients with diabetes. Treatment is more challenging due to embolism, device trackability, potential vessel injury, incomplete revascularization, and correction of underlying vascular lesions. Endovascular interventions have become a prominent role in restoring limb perfusion (36). Endovascular revascularization for acute limb ischemia has been demonstrated in recent series to be safe and successful, with success rates that are comparable to or even lower than surgical series and perioperative morbidity and mortality (37).

2. Robotic Systems

Cardiovascular medicine has been using robotics since the late 1990s. Applications include electrophysiology, interventional cardiology, endovascular surgery, minimally invasive heart surgery, and laparoscopic vascular surgery. Robotic technologies allow for quick and extremely accurate catheter and device placement in catheter-based procedures as well as endoscopic reconstructive surgery in confined places (38). The first clinical use of the Sensei™ robotic system in the peripheral vascular field was in 2009 for contralateral gate cannulation during infra-renal EVAR. Prior to this, preclinical studies involving more than 30 interventionalists demonstrated improved capabilities and economy of motion in catheter manipulation (39-42). Endovascular robotic technology has received increased attention with the Magellan™ system in use in more than 15 centers worldwide. Magellan™



includes a 6-F lead catheter with 180-degree rotation and a 9.5-F outer sheath with 90-degree rotation. This system utilizes remotely controlled orthogonal pull wires and automated insertion, retraction and rotation of conventional wires for catheter shaping and manipulation (43).

A control station or console is used by the operator to control the robotic arms in all robotic systems. In the field of cardiac surgery, robotic technology can be used to repair myxomas, repair mitral valves, perform CABG surgery, and repair atrial septal defects (38). According to a recent review, robotic-assisted cardiac surgery has advanced in recent years and has been effectively applied in procedures like the removal of left atrial myxomas, the repair of atrial septal defects, the MAZE procedure, and the implantation of left ventricular leads. However, the most common uses of this technique are still coronary artery bypass and mitral valve repair. Additionally, the fact that robotic endovascular surgery gives more flexible and precise minimally invasive treatment alternatives means that a greater number of patients can receive suitable treatment (44). Vascular surgeons can also treat peripheral, visceral, and aortic artery disease with a range of robotically assisted procedures. Atrial fibrillation ablation techniques in electrophysiology can be performed with robotic assistance. Techniques for abdominal aortic endovascular surgery and robotically aided percutaneous coronary intervention have been developed in recent years. Although robotic techniques in cardiovascular therapy have been shown to be fundamentally feasible and safe, their wider application has been constrained by learning curves and expensive prices. However, promising advancements in the field include reduced surgical trauma and shortened recovery times for patients following robotic cardiovascular surgery, as well as improved procedural speed, accuracy, and decreased radiation and contrast agent exposure in robotically assisted catheter-based interventions (38).

More sophisticated techniques are still required to assess the advantages of technology. Even though robotic technology is still in its infancy as a clinical tool, it is becoming more and more recognized as useful in situations where conventional methods have failed because of anatomical challenges (45-47). Using the robotic system in a variety of operations, Imperial College has achieved 100% device delivery and 97% technical success. The 30-day mortality rate, which is unrelated to robotic technology, was 1.8%. Additionally, 15% of cases were done robotically because they were high risk, and 16% of cases were switched from manual to robotic techniques (44).

Endovascular interventions for cardiovascular disease treatment have shown success, but precision navigation remains a challenge. Robotics are being explored for their role in robotics, offering radiation-free 3D imaging, task-oriented interfaces, and partial to full autonomy. Challenges include complexity and cost, but integration of MRI-compatible robots and improved human-robot interaction could lead to advances in endovascular surgery. Catheter technology for endovascular interventions has seen expansion and diversification, with recent experimental work suggesting robotic technology can be integrated with advanced localisation and imaging techniques (44,48). Antoniou et al. (49) discovered that there is limited clinical evidence to evaluate the benefits of robotic-assisted vascular



procedures. They suggest that robotic steerable endovascular catheter systems offer potential advantages over conventional catheterization systems and provide precise navigation in challenging anatomical situations. However, their clinical experience is limited, and more evidence is needed to assess the efficacy of these technologies (49).

3. Smart Stents and Biodegradable Devices

3.1. Smart Stents

The 4D printing industry is a relatively new field in additive manufacturing that enables materials to respond to a variety of stimulus, such as heat transitions, humidity, and pH levels. This adaptability has tremendous potential for applications in healthcare, especially in the design of personalized and responsive medical devices (50). Introduction of 4D printing has provided significant potential for developing smart stents and medical devices that can dynamically respond to stimulation from the environment like body temperature, pH or mechanical stresses. Metal alloys or polymers are used for the manufacture of traditional stents; however, by virtue of 4D printing technologies, it is possible to manufacture stents using smart materials, which can respond to environmental stimuli, thus having enhanced functionality and improved patient outcomes. This shape-shifting capability, or dynamic adaptability, in response to environmental changes enhances not only the mechanical properties of the stent but also lowers the risk of complications like inflammation or restenosis (50-52).

Chen et al. (53) and they developed a smart stent with microsensors and a wireless interface to detect in-stent restenosis. The stent monitors local hemodynamic variations in narrowing scenarios and can identify blood clotting as well as pressure on the outside of the stent. However, this study to some extent brings smart stent technology closer to clinical translation (53).

The road ahead for vascular treatment focused on 4D-printed smart stents is very attractive owing to their tunability. When shape memory alloys or hydrogel-based composites that possess heat responsive properties are used in stent design, stents can be customized according to patient-specific vessel geometry, thus tuning mechanical forces. They are also capable of adapting to biological properties like pH levels, reducing the need for further procedures or intervention. In this context, it may guide the way to personalized medicine, decreasing stent failure rates and promoting long-term effectiveness of treatment, especially in cardiovascular and other disorders that need vascular support (54,55)

3.2. Biodegradable Stents

Over the past two decades, biodegradable metallic stents have been developed as an alternative to permanent cardiovascular stents. These degradable materials could replace corrosion-resistant metals used in stent applications, as stenting is temporary and limited to 6-12 months after



implantation. While corrosion is generally considered a failure in metallurgy, certain metals can be advantageous for degradable implants. Candidate materials should have mechanical properties similar to 316L stainless steel, the gold standard material for stent applications, and be non-toxic as they are absorbed by blood and cells. Iron-based and magnesium-based alloys have been investigated as potential candidates for biodegradable stents (56).

Metallic stents are used to maintain artery patency and promote revascularization after balloon angioplasty. To reduce long-term side effects of corrosion-resistant stents, a new generation of bioabsorbable stents is being developed. These stents corrode and are absorbed by the artery after their function as vascular scaffolding. Research has focused on biodegradable polymeric, iron-based, and magnesium-based stent materials, with metals being more attractive due to their inherent mechanical and surface properties. Recently, a zinc-based class of metallic bioabsorbable materials has been introduced, demonstrating the potential for an absorbable metallic stent with optimal performance (57).

Biodegradable stents are in early stages of research, but concerns about device thrombosis and deficiencies in clinical applications persist. New biodegradable stents are being developed, focusing on biodegradable platforms, bioactive coatings, and drug combinations. Technological advancements are expected to address these issues, and biodegradable stents are expected to become the primary treatment option for coronary artery interventions in the near future (58).

4. Artificial Intelligence (AI) and Machine Learning

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5. Future Potential and Innovations

Where we are going, that is, the future Cardiovascular medicine is being revolutionized with the advent of newer endovascular interventions. One promising area is the integration of artificial intelligence (AI) and machine learning, delivering real-time, data-driven insights that inform decision-making throughout a procedure. Surgeons can leverage AI algorithms that can analyze huge volumes of patient data which help in better decision making and enhance the accuracy and outcome of these procedures. Additionally, these technologies may facilitate the creation of individualized treatment pathways for patients to optimize the applicability and effectiveness of approved medications to a person. This includes advanced biotechnology that is used in the endovascular technology which improves patient safety as well as reduces the complications. Biodegradable stents are an example of the steps biotechnological applications are taking to make endovascular interventions more patient-friendly and minimize long-term complications. With the evolution of these technical innovations, the endovascular interventions in the future shall be much safer, effective and efficient. This, in turn, means more minimally invasive procedures with shorter recovery times, lower pain and less need for additional surgeries.

SUMMARY / SONUÇ

Endovascular interventions are imperative in the management of cardiovascular disease and proceedings to be cornerstone of contemporary TREATMENT STRATEGIES. Innovations in imaging modalities, including high-resolution angiography and intravascular ultrasound, have allowed procedures to become more targeted and precise with lower complication rates. Furthermore, more robotic systems have improved precision and worked to improve accuracy, allowing for the correct positioning of the catheter and with better control of forces when interacting with vascular structures. Sensors and smart devices allow for real time monitoring and optimization of situations which leads to quicker recovery and for providing timely treatment for the patients. Holloway, HCTC will enhance the procedural treatment methods into more targeted, specific therapies as technology improves, allowing surgeons to explore, evaluate, and develop treatment plans for individualized patient results.



Conflict of Interest Statement

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