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The Architecture of Occlusion: Embolization in Interventional Medicine

Vaishnavi Khandare[1], Shreyas Patil[1], Divya Patil[2]

[1]*MIT School of Bioengineering Sciences and Research, Pune, Maharashtra, India.*
[2]*Centre of Excellence-Additive Manufacturing, Andhra Pradesh MedTech Zone (AMTZ), Visakhapatnam, Andhra Pradesh, India*

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ABSTRACT

Embolization is a minimally invasive medical treatment that uses different types of embolic techniques to block specific blood vessels or body cavities. Embolization was initially used as a solution for emergency bleeding situations but is now an accepted treatment method in multiple medical disciplines including trauma medicine, interventional oncology, neurovascular treatment, pulmonary haemorrhaging, and various gynaecological and urological procedures. Embolization procedures can be categorized based on their access method, treatment purpose, targeted body parts, and the duration which their blockage remains active. The most common method for performing the procedure uses endovascular techniques because they provide accurate results and flexible treatment options. The medical field uses various embolic devices including coils, vascular plugs, calibrated microspheres, liquid embolic systems to create specific occlusions based on the size of blood vessels, the speed of blood flow and the desired clinical results. The selection of materials serves as the primary factor which determines how well embolic materials perform because their physical and chemical characteristics and visibility in medical imaging, strength and blood clotting ability affect their performance. Medical specialists still observe multiple complications which include non-target embolization, recanalization, catheter entrapment, hydrophilic polymer embolism despite major improvements in catheter technology and embolic product development. The medical field experts expect that new technologies will improve procedural safety and patient treatment methods and extend patient life through the introduction of smart biomaterials, shape memory polymers, radiopaque drug eluting platforms, computational modelling, artificial intelligence driven planning and 3D printing. This review provides a complete framework which shows all aspects of embolization methods and their medical uses and their embolic materials and their device requirements and their future research paths in this fast-developing industry.

Keywords: Embolization, Interventional Medicine, Medical specialists.

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INTRODUCTION

Embolization describes a medical procedure that involves closing blood vessels, vascular spaces and abnormal body cavities through the use of biological, chemical, and mechanical energy-based treatment methods. Multiple methods exist for embolization, which include endovascular embolization as the most common method and advanced technological method and, percutaneous direct puncture embolization and transvenous embolization and surgical embolization and hybrid techniques that combine open and minimally invasive methods [1–3]. Embolization developed before modern catheter-based methods because early surgeons used surgical and percutaneous methods to stop bleeding and treat vascular malformations. Embolization has developed from basic vessel ligation and injection methods into accurate image-guided procedures that match the individual patient's body structure and medical condition through advancements in imaging technologies, biomaterials and device engineering [1-3]. Endovascular embolization has become the primary treatment method owing to its operational flexibility and capacity for limited invasive procedures, which doctors perform through transarterial or transvenous catheterization. Vascular routes do not allow access to certain lesions, including superficial arteriovenous malformations, venous malformations, and

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**Author for Correspondence:* vgkhandare0310@gmail.com

specific musculoskeletal and pelvic pathologies; therefore, percutaneous embolization is essential for these cases [4,5]. Surgical embolization and hybrid approaches continue to play a role in complex cases requiring direct visualization, immediate control, or combination therapies [6].

The scientific study of healthcare technology and its development shows that both healthcare institutions and research centres use embolization as a treatment method, which requires different approaches to achieve its goal of blocking blood vessels or body cavities. The studies on embolization methods need to include all available treatment options instead of focusing on endovascular procedures only [1,2]. The procedure of endovascular embolization uses imaging technology to guide doctors as they perform blood vessel closure procedures using special catheter-based materials. Medical professionals use embolization procedures to achieve various objectives, which include stopping bleeding through haemostasis and removing blood supply from diseased tissues and redirecting blood flow and changing body functions and permanently blocking access to pathological blood vessels [1-3]. Embolization was originally developed for use during critical bleeding situations, but it has now become a standard treatment method in various fields, including trauma care, oncology, neurovascular disease, pulmonary bleeding, gynaecology and urology [7-9].

The development of catheter-based embolotherapy from open surgical ligation occurred because of progress in angiographic imaging, digital subtraction angiography, microcatheter, guidewire technology and the development of specialized embolic materials [2,3]. Current microcatheter systems enable doctors to perform super selective catheterization of vessels with a diameter below 1 mm, which enables them to precisely treat diseased blood vessels while maintaining the health of nearby tissues and organs [3,10]. These medical advances have resulted in decreased surgical complications, shorter patient hospitalizations and better patient results when compared to traditional surgical methods [7,11]. (Figure 1) illustrates the chronological evolution of embolic agents and techniques from the earliest surgical ligation and percutaneous methods to contemporary image-guided endovascular approaches, highlighting the key milestones that have shaped modern embolization practice

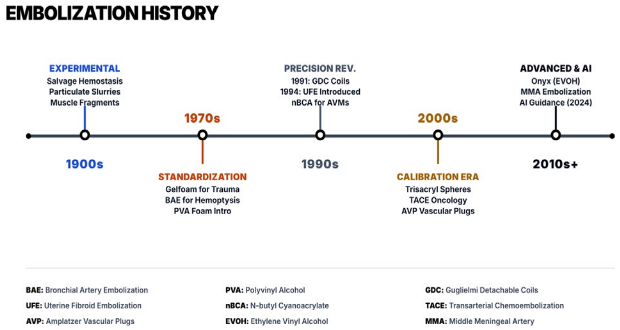


Figure 1: Timeline of the chronological evolution of embolic agents and techniques

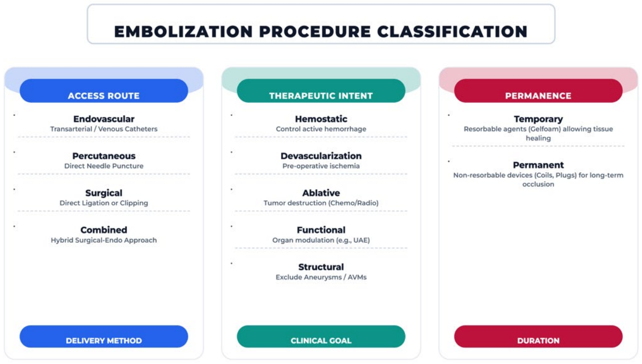


Figure 2: Classification of embolization procedures based on access route, therapeutic intent, and occlusion permanence.

Embolization combines materials science, fluid mechanics, biomechanics, and micro-manufacturing to create a link between engineering and healthcare technology. The performance of embolic agents depends on their physicochemical properties, their interaction with blood flow, their potential to cause thrombosis, their ability to show up on imaging and their capacity to maintain stability in the vascular system over time [3-12]. The process of optimizing device selection, procedural planning and treatment durability requires an understanding of these parameters.

CLASSIFICATION OF EMBOLIZATION PROCEDURES

Embolization procedures can be comprehensively classified based on access route, therapeutic intent, target anatomy, and permanence of occlusion (Figure 2). The classification system needs to include multiple dimensions because embolization should be viewed as an entire treatment method that extends beyond endovascular procedures [1,2]

Classification Based on Access Route

Embolization techniques use different methods to deliver embolic agents, which determine their technical difficulty, imaging needs, risk assessment, and ability to be used in medical treatment.

[A] Endovascular embolization

This process requires medical professionals to use fluoroscopy to guide the delivery of embolic agents through either transarterial or transvenous catheter systems. The method stands out as the most flexible solution because it can precisely access distant body parts, including organs, brain blood vessels, and lung areas. Super selective catheterization using microcatheters enables healthcare professionals to access remote blood vessels while preventing unwanted embolization to non-target areas [2,10]

[B] Percutaneous direct puncture embolization

This procedure requires image-based guidance for performing needle access, which directly targets the lesion instead of using the vascular system. The method shows its greatest effectiveness when treating superficial arteriovenous malformations, venous malformations, pseudoaneurysms, and specific musculoskeletal or pelvic lesions that cannot be treated through endovascular methods. Direct puncture enables medical professionals to achieve high levels of embolic agent concentration in the target area while limiting their distribution throughout the body. The procedure requires precise imaging direction to prevent unintentional leakage of the material outside the targeted area [4,5]

[C] Surgical embolization

This process involves delivering embolic agents or performing vessel ligation through direct surgical observation during the procedure. Surgical embolization still provides essential medical treatment for multiple emergencies, which include complex trauma cases and surgical procedures with uncontrolled bleeding and conditions that demand instant surgical access [6]

[D] Hybrid embolization

The combination of two or more access routes with preoperative endovascular embolization and surgical resection forms the basis of hybrid approaches. Hybrid strategies decrease blood loss during operations, increase surgical visibility, and make procedures safer for patients with hyper vascular tumours and complex neurovascular lesions [13,14]

Classification Based on Therapeutic Intent

The main study of embolization treatment procedures for biomedical research uses therapeutic intent as its basis for determining patient classification. This framework serves to guide both the selection of embolic agents and the planning of medical procedures [1,2]

a. Haemostatic Embolization

Emergency bleeding that threatens a patient's life, which includes stopping bleeding from traumatic injuries, gastrointestinal bleeding, haemoptysis and postpartum vaginal bleeding, and bleeding from tumours [5-8]. The main goal of this procedure is to quickly decrease blood flow and pulse pressure transmission, which delivers blood to the area of bleeding to create conditions that support clotting and patient stabilization [5].

Doctors use gelatine sponges as temporary embolic agents to treat both trauma and obstetric haemorrhage because they create a scaffold that supports clot development while permitting blood vessel reopening, which helps reduce the chance of lasting oxygen deprivation [9]. Medical experts prefer permanent embolic agents, which include metallic coils and vascular plugs for treating focal arterial injuries and pseudoaneurysms and high-flow bleeding situations that require permanent blockage to stop further bleeding [21,22]

b. Devascularization Embolization

Devascularization embolization targets hyper vascular tissues by intentionally shutting down their blood flow. Transarterial embolization (TAE) and transarterial chemoembolization (TACE) represent two common methods used to treat patients with hepatocellular carcinoma and metastatic liver disease [8,15]

Experimental and clinical evidence has demonstrated that ischemia serves as the main mechanism through which tumours are controlled in embolotherapy procedures while chemotherapeutic agents create additional cytotoxic effects [15]. The existence of excessive or inaccurately directed ischemia creates conditions that lead to hypoxia-induced angiogenesis and tumour recurrence, thus creating a requirement for improving embolization techniques together with combination treatment approaches [16].

c. Ablative Embolization

Ablative embolization uses embolic agents as carriers of therapeutic payloads, such as cytotoxic drugs or radioisotopes, to destroy tissues. Radioembolization (transarterial radioembolization, TARE) uses yttrium-90 or holmium-166 microspheres to deliver high-dose localized beta radiation while depending on ischemia to a minimal extent. [15,18]. This method is especially useful for patients with portal vein thrombosis and restricted liver function.

d. Functional Embolization

This procedure uses functional embolization to treat non-cancerous hyperplastic and inflammatory tissues by controlling organ function without causing total tissue death. The procedure uses uterine artery embolization (UAE) to treat fibroids and prostatic artery embolization (PAE) to treat benign prostatic hyperplasia [9,19]. The procedure needs super selective distal embolization, which requires exact particle calibration to prevent non-target ischemia from happening [12]

e. Flow Redistribution Embolization

This procedure uses embolization to reroute blood flow instead of permanently blocking blood flow to tissues. The established preoperative portal vein embolization method creates liver hypertrophy, which decreases the risk of liver failure after major hepatectomy [11]

f. Structural Embolization

The procedure of structural embolization creates a blockage to prevent blood flow through abnormal blood vessels, which include intracranial aneurysms, arteriovenous malformations and dural arteriovenous fistulas. The durability of embolic devices in this category depends on their mechanical strength and ability to maintain stability over extended periods [3,6]

2.3 Classification Based on Permanence

This classification system uses permanent objects as a basis to determine whether vascular obstruction should be treated as a temporary condition or a permanent one. The decision evaluates three factors, which include the organ's ability to withstand ischemia and the potential for disease reversal and the presence of alternative blood vessel pathways [9,21]

Temporary embolization uses materials that can be broken down through natural processes to block blood vessels during a limited period. The medical field uses these agents in trauma cases, obstetrics, and paediatric treatment, where practitioners seek to restore blood vessel function and help patients heal.

Table 1: Comprehensive classification of embolization techniques

Embolization Type	*Primary Objective*	*Typical Indications*	*Agents Used*	*Permanence*
Hemostatic embolization	Rapid hemorrhage control	Trauma, GI bleeding, hemoptysis, postpartum hemorrhage	Gelatin sponge, coils, vascular plugs	Temporary / Permanent [5,8,9,21,22]
Devascularization embolization	Induce ischemia	Tumors, AVMs	PVA particles, microspheres, coils, liquid embolics	Permanent [8,15,21,22]
Ablative embolization	Deliver cytotoxic or radiologic payload	HCC, metastatic liver tumors	Drug-eluting beads, Y-90 microspheres	Permanent [15,18,21,22]
Functional embolization	Modulate organ function	UAE, PAE, GAE	Calibrated microspheres	Permanent [9,12,21,22]
Flow redistribution embolization	Redirect blood flow	Portal vein embolization	NBCA, particles	Permanent [11,21,22]
Structural embolization	Exclude abnormal vasculature	Aneurysms, DAVFs, AVMs	Coils, NBCA, EVOH	Permanent [3,6,21,22]

The medical field does not possess reliable methods to predict degradation rates. This situation requires doctors to observe patients closely throughout their treatment process [9]

Permanent embolization uses non-degradable materials such as metallic coils, vascular plugs, and liquid polymers to achieve durable vessel occlusion. Permanent strategies are preferred in oncologic, neurovascular, and structural embolization, where recurrence poses a significant clinical risk [21,22]. The decision to use temporary or permanent embolization does not result in a strict choice because doctors can use two methods together for treatment. They should start with temporary embolization to manage the patient's current condition, followed by permanent embolization after the patient reaches a stable state. (Table 1) provides a comprehensive classification of embolization techniques, summarizing each approach by access route, therapeutic intent, target anatomy, embolic agent type, and permanence of occlusion to facilitate systematic clinical decision-making.

CLINICAL APPLICATIONS OF EMBOLIZATION

Embolization shows its value through many medical situations where it can be performed through endovascular, percutaneous, surgical, or hybrid techniques. The choice of embolization method depends on the position of the lesion, together with the blood vessel structure, the blood flow patterns, the treatment needs of the patient, their existing medical conditions, and their blood circulation status [14,21]. The development of better imaging techniques together with new embolic materials has transformed embolization from its original role as an emergency rescue treatment into a reliable permanent medical solution for multiple health conditions [1,2].

Trauma and Haemorrhage Control

The practice of embolization serves as a fundamental method for controlling bleeding in non-surgical settings of trauma and emergency medical treatment. Physicians use endovascular embolization to treat patients who experience bleeding from their liver, spleen, kidneys, pelvis and retroperitoneal area, especially when their hemodynamic status remains stable or temporarily improves [5,23]. Temporary embolic devices such as gelatin sponge function to treat diffuse parenchymal bleeding by blocking arterial blood flow until the body can restore normal blood flow and heal damaged tissues [5,9]. Focal vascular injuries, including pseudoaneurysms, arterial transections, and active contrast extravasation, require permanent embolization using coils or vascular plugs to prevent rebleeding [21,22]. The medical field uses percutaneous embolization techniques that include ultrasound-guided thrombin or glue injection for treating iatrogenic pseudoaneurysms and superficial vascular injuries, which do not require catheter access. Surgical embolization or vessel ligation may be required in cases of uncontrolled haemorrhage or when endovascular access is not feasible [6]. Medical professionals frequently use hybrid methods that combine embolization with surgical stabilization to treat patients with complex pelvic injuries [24].

Oncology and Tumour Management

Embolization functions as the core procedure in interventional oncology because it enables tumour blood supply destruction, provides treatment relief, tumour size reduction and surgical and transplantation procedure support [8,15]. Procedure of transarterial embolization (TAE) together with transarterial chemoembolization (TACE) uses the specific blood flow patterns of solid tumours to create targeted tissue death in tumours while keeping their adjacent healthy tissue intact [8,15]. Drug-eluting embolic systems provide localized chemotherapy treatment for an extended period while decreasing toxicity to the entire body [25].

Microspheres that contain radioisotopes serve as the core element of radioembolization TARE, which functions as an ablative embolization method because it delivers high radiation doses to specific areas while producing minimal blockage effects, thus enabling treatment for patients who have portal vein thrombosis or who possess restricted liver function [17,18]. Embolization serves as a treatment method for hyper vascular renal tumours and bone tumours and soft-tissue tumours which exist outside the liver [4,13]. The process of preoperative embolization, which medical professionals perform through either endovascular or percutaneous methods, leads to substantial decreases in blood loss during surgery while enhancing the ability to see hyper vascular tumours during operations [13,14].

Neurovascular Disorders

In neurovascular disease, embolization serves as the main treatment method for both intracranial aneurysms and arteriovenous malformations (AVMs) and dural arteriovenous fistulas. Endovascular coil embolization has become the standard of care for many aneurysms because it produces lower patient complications than surgical clipping does [3,11,10]. Physicians use adjunctive techniques such as balloon- or stent-assisted coiling to treat patients who have wide-neck or complex aneurysms [6,7]

Liquid embolic agents (such as Onyx or NBCA) receive extensive application in AVM embolization because they can penetrate the complex architecture of the nidus [5]. These agents can be delivered through endovascular delivery or direct percutaneous puncture to treat extracranial vascular malformations [4,5]. In complex cases, hybrid surgical–endovascular methods are used, which involve embolization for flow control together with surgical removal or radiosurgery to achieve total patient care [26].

In addition to liquid embolics, flow diverters have emerged as a transformative strategy. It represents a paradigm shift in the treatment of large or giant wide-necked intracranial aneurysms. Unlike conventional coil embolization, which fills the aneurysm sac, flow diverters such as the pipeline embolization device (PED) are deployed across the aneurysm neck within the parent artery, redirecting blood flow away from the aneurysm sac and promoting progressive thrombosis and endothelial remodelling. This approach enables treatment of complex aneurysms that are not amenable to coiling, often without placing any embolic material within the sac itself. Clinical trial data have demonstrated high rates of complete aneurysm occlusion at follow-up, establishing flow diversion as a standard option for uncoilable or previously failed aneurysms [71]

Gynaecologic, Urologic, and Musculoskeletal Applications

Functional embolization has rapidly developed into a minimally invasive alternative to surgery that preserves organ function for gynaecological and urological procedures. Uterine artery embolization functions as a recognized treatment method for both symptomatic fibroids and postpartum haemorrhage because it delivers faster symptom relief and shorter recovery periods than hysterectomy [9,27]. The process of choosing embolic particles demands precise selection because their delivery through super-selective methods needs to stop ovarian or non-targeted embolization from occurring [12]

Prostatic artery embolization has emerged as a minimally invasive option for benign prostatic hyperplasia, offering improvement in lower urinary tract symptoms with reduced risk of sexual dysfunction [19]. Embolization has become a more common treatment method in musculoskeletal medicine, which uses it to manage both chronic pain syndromes and hyper vascular lesions because it stops pathological neovascularization and maintains structural integrity while decreasing inflammation and pain levels [28,29]. The combination of endovascular and percutaneous techniques forms the basis for these applications.

Pulmonary and Peripheral Vascular Applications

The treatment of haemoptysis together with pulmonary arteriovenous malformations forms the foundation of pulmonary embolization. The primary treatment for patients who experience heavy or ongoing haemoptysis combines bronchial artery embolization with its ability to stop bleeding within a short time frame [7,30]. The procedure shows high success rates, but patients often experience bleeding in the future because their body develops new blood vessels, which require additional medical treatment [30,31]. The treatment of pulmonary arteriovenous malformations uses mechanical embolic devices, which include vascular plugs to prevent both paradoxical embolization and systemic complications [22,32]. The procedure of peripheral vascular embolization includes endovascular and percutaneous glue-based systems, which treat varicoceles and venous malformations and varicose veins. The medical procedure delivers quick patient recovery results after it achieves minimally invasive closure of unusual venous pathways.

EMBOLIZATION TECHNIQUES

Mechanical Occlusion Techniques

The process of mechanical occlusion requires the use of permanent devices, which include coils and plugs to create both thrombus formation and physical blockage of blood vessels. The degree of coil packing density establishes the time period during which occlusion will remain effective because low packing densities permit blood vessels to reopen at a later time. [10,33]

Particulate Embolization Techniques

The process of particulate embolization uses flow-directed particles or microspheres to create blockages in distant arterioles and capillary networks. The three characteristics of particles, i.e., size, shape and compressibility, determine how deep particles penetrate materials and how uniformly they create embolization and how much non-target embolization occurs [12,34,35]

Liquid Embolization Techniques

Liquid embolic agents create better access to intricate vascular systems than solid embolics [5]. Adhesive agents such as NBCA polymerize rapidly upon contact with blood, whereas non-adhesive agents such as EVOH precipitate gradually, allowing controlled delivery [5,26,36,37]

EMBOLIZATION DEVICES

Embolization devices exist to provide precise, safe and long-lasting control over vascular or cavity occlusion. (Table 2) summarizes the major categories of embolization devices, detailing their material composition, occlusion mechanism, primary clinical indications, and known limitations. The procedure requires the selection of a device which depends on three factors: (i) the access route, which includes endovascular and percutaneous surgical methods, (ii) the size of target blood vessels, and the flow patterns, and the required time of operation, and (iii) the system's ability to work with both imaging and delivery devices. The ongoing research progress in material science and micro-manufacturing fields has created multiple new types of embolization devices that medical professionals can now use [5,26]

Coils (Detachable, Pushable)

Embolization coils are among the most widely used devices, particularly in endovascular and neurovascular applications. The devices operate through two mechanisms, which create an obstruction and initiate thrombosis within their designated target areas, as shown in Figure 3. Modern coils are typically manufactured from platinum or platinum–tungsten alloys to ensure radiopacity, flexibility and biocompatibility [10,38]The inclusion of tungsten (often 8%) significantly enhances the tensile strength and stiffness of the coil compared to pure platinum, allowing it to maintain its secondary shape (helix or sphere) against arterial pulsations. The manufacturing process involves winding this alloy wire, which has a thickness of 0.001 inches, around a mandrel under precise tension. Many modern coils include hydrogel coatings to prevent the "water hammer" effect, which causes the coil mass to compact over time. These coatings undergo volumetric expansion upon contact with blood, which leads to increased packing density and biological organization of the thrombus [10]. The detachment mechanisms have also evolved from simple mechanical pushing to electrolytic systems, where a low-voltage current dissolves a sacrificial linker, allowing for atraumatic and precise release [6]. Coils may be classified as pushable or detachable. Pushable coils are deployed irreversibly and are primarily used in straightforward vascular anatomy. Detachable coils use mechanical, electrolytic, or thermal detachment mechanisms to enable accurate positioning and repositioning before release, which proves essential for navigating complex high-risk anatomical structures like intracranial aneurysms [11,29].

The design innovations of the system use fibered coils, which improve thrombogenicity and hydrogel-coated coils, which expand through blood contact to achieve higher packing density while decreasing recanalization rates. The system faces two main operational challenges, which include increased deployment time and higher operational costs. The system experiences coil compaction through arterial pulsatile forces, which causes a recognized failure mode that specifically affects large and wide-neck aneurysms [33,39]

Vascular Plugs

Plugs are self-expanding devices, most commonly constructed from nitinol mesh, which provide fast and lasting closure of vessels that have medium to large diameters, as shown in Figure 4. Plugs provide full closure through one device because it works better than coils, which need multiple devices to reach the same result. [22,40]. The pulmonary arteriovenous malformations, splenic artery embolization, and peripheral vessel occlusion procedures derive special benefits from using plugs in their high-flow operational settings. The correct sizing process needs to take place because it serves as the essential method to stop both migration problems and incomplete closure problems. The introduction of microvascular plugs has made it possible to use plugs on smaller vascular systems because plugs need bigger delivery catheters than coils do. [32,38]. Vascular plugs use Nitinol properties, which consist of a nickel-titanium alloy that shows both shape memory and super elasticity. The devices receive a heat-set process during manufacturing, which establishes their final expanded shape. The alloy changes its phase from austenite to martensite when it is compressed into a delivery catheter. The device expands through the austenitic phase return when body temperature activates the device in the bloodstream deployment. The device creates a radial resistive force (RRF), which pushes against the vessel wall. The device uses RRF to establish its position, which stops the device from moving to other locations. The plug's dense mesh structure creates flow disruptions, which form turbulent conditions that lead to faster thrombosis development, resulting in occlusion that happens quicker than multiple coils [40]

Particulate Delivery Devices and Microspheres

The development of particulate agents has progressed from irregular polyvinyl alcohol (PVA) flakes to modern microspheres, which scientists now use for precise production. The components of particulate embolization devices contain both calibrated microspheres and non-spherical particles, which medical professionals administer through microcatheters or needles, as shown in (Figure 5). The medical

Table 2: Embolization devices and their characteristics

Device type	*Material*	*Occlusion mechanism*	*Clinical use*	*Limitations*
Pushable coils	Platinum	Thrombosis	Trauma, GI bleeding	Migration risk [1,7]
Detachable coils	Platinum alloys	Controlled Thrombosis	Neurovascular	Higher cost [10,11]
Hydrogel coils	Platinum+PEG	Expansion + Thrombosis	Aneurysm	Longer deployment [33]
Vascular plugs	Nitinol	Mechanical occlusion	Large vessel, PAVMs	Larger sheath [21,22]
Microspheres	Polymer hydrogels	Distal Occlusion	UAE, TACE	Radiolucent [9,15,25]

Figure 3: Progression of detachable coil embolization defines initial device deployment via microcatheter (left) and the final healed aneurysm (right).

devices enable doctors to block blood flow at both arteriolar and capillary sites, and they serve multiple medical purposes, including tumour embolization, uterine artery embolization and functional embolization procedures, which have a wide range of applications in medical practice [12]. The size distribution of calibrated microspheres remains predictable, while their penetration depth provides scientists with a better understanding of how these particles will behave during experiments because of their regular size pattern, which prevents particles from sticking together through their entire testing period. The compressibility and elasticity properties of microspheres determine the efficacy of their delivery through microcatheters and the consistent distribution of embolization material. The majority of particulate devices show radiolucency, which restricts their real-time visibility until doctors use contrast or radiopaque materials to enhance visibility [12,35]. The manufacturing process of tris-acryl gelatine microspheres produces standardized microspheres that have consistent diameter measurements and high levels of circularity. The mechanical characteristic of the material involves its ability to compression because the spheres reach a maximum deformation limit of 50%, which enables them to move through microcatheters and return to their original form after entering the target area of the vessel. The process of “shape recovery” enables doctors to achieve controlled distal blood vessel blockage at a designated vessel diameter, which avoids the “proximal clumping” effect produced by irregular particles. The drug-eluting beads (DEBs) use anionic functional groups such as sulfonate to build their polymer matrix, which enables the beads to capture cationic chemotherapy drugs through ion-exchange and release them gradually over a period of several days [25,41]

Liquid Embolic Delivery Systems

The components of liquid embolic devices include both the embolic agent and the specialized delivery systems, which enable the safe delivery of agents. This procedure requires DMSO-compatible microcatheters to deliver liquid embolics, such as cyanoacrylates (nBCA) and ethylene–vinyl alcohol copolymers. These specialized catheters prevent material degradation while ensuring a controlled injection [5,26]. Advanced delivery systems use detachable-tip microcatheters, allowing clinicians to disconnect the distal tip from the system when it becomes trapped inside the solidified embolic cast, as shown in (Figure 6). These procedures use balloon-assisted delivery techniques to control blood flow while stopping reflux, thereby enhancing the system’s ability to reach difficult areas

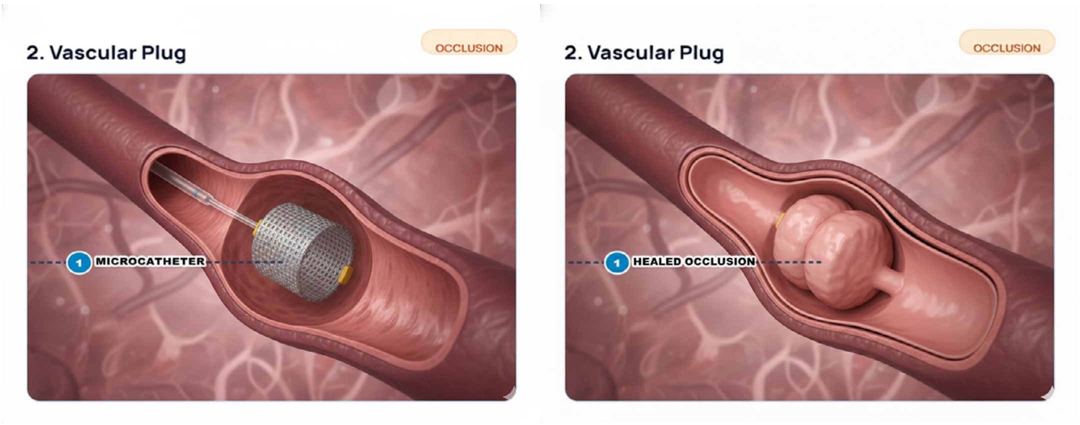


Figure 4: Progression of vascular plug embolization defines initial device deployment via microcatheter (left) and the final healed occlusion (right).

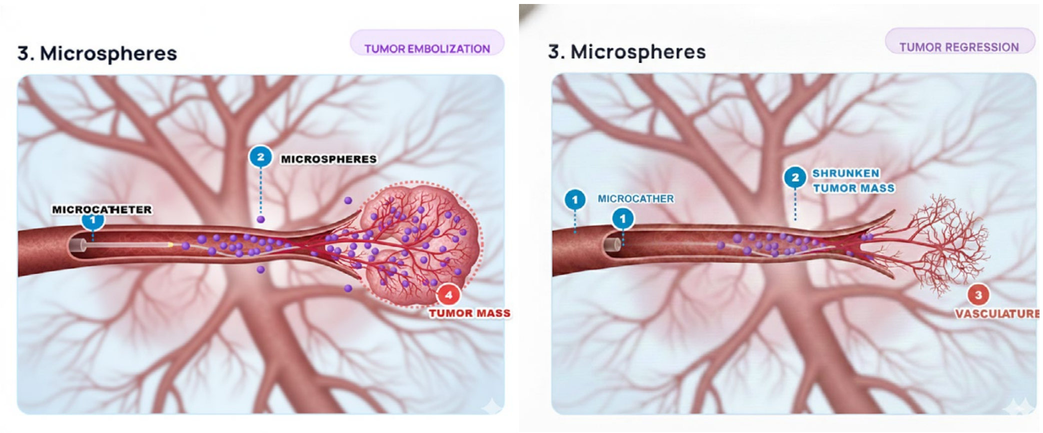


Figure 5: Progression of particulated/microsphere embolization defines initial device deployment via microcatheter (left) and the final shrunken tumour mass (right).

within the body's vascular system [21,42]. Liquid embolic agents are specifically designed to penetrate these difficult-to-reach vascular systems. Cyanoacrylates (nBCA) function as tissue adhesives that create polymerized bonds through an anionic mechanism that blood hydroxyl ions activate. The reaction generates a permanent cast through a process that creates heat, and which takes place within a short time. The Ethylene Vinyl Alcohol (EVOH) copolymers work through precipitation, while Onyx acts as a complete system for the same process. The copolymer stays in a liquid state inside the catheter after it gets dissolved in dimethyl sulfoxide (DMSO). The DMSO solvent leaves the system when it contacts blood, which leads to EVOH precipitation from the external surface towards the internal part of the system. The operator can use the material to enter a nidus because it creates a lava-like flow, which has a high viscosity between 18 and 34 centipoise and this effect enables sustained operation without risking catheter bonding, which typically occurs with cyanoacrylates [5,26].

Percutaneous and Surgical Embolization Devices

The percutaneous embolization devices use needles, cannulas and injection systems to perform direct lesion access under ultrasound, CT and fluoroscopic guidance. These devices serve as standard equipment to treat pseudoaneurysms, superficial vascular malformations and musculoskeletal embolization because their design permits doctors to treat patients with high local embolic concentration while maintaining minimal systemic exposure [4,5]. Research demonstrates that the surgical setting uses embolization devices, which comprise intraoperative catheters, clamps, and direct injection systems that support surgical resection and haemorrhage control, as shown in (Figure 7). The surgical embolization tools function as essential equipment for hybrid procedures and situations that need instant access to surgical facilities, even though they require less technical expertise than endovascular devices [6]

Device Selection Considerations and Failure Modes

Doctors must find the best embolization device by evaluating how well it blocks blood flow against how safe it is to use. The main factors that need to be assessed include vessel diameter, flow velocity, tortuosity, and proximity to critical structures [43,44]. Medical devices create problems through migration, incomplete occlusion, recanalization, and their interaction

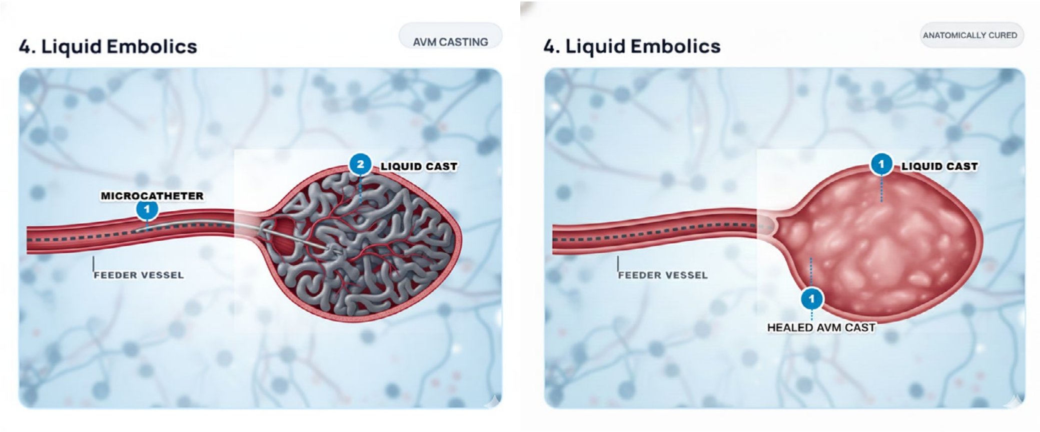


Figure 6: Progression of liquid embolization defines initial device deployment via microcatheter (left) and the formation of liquid cast and healed AVM (right).

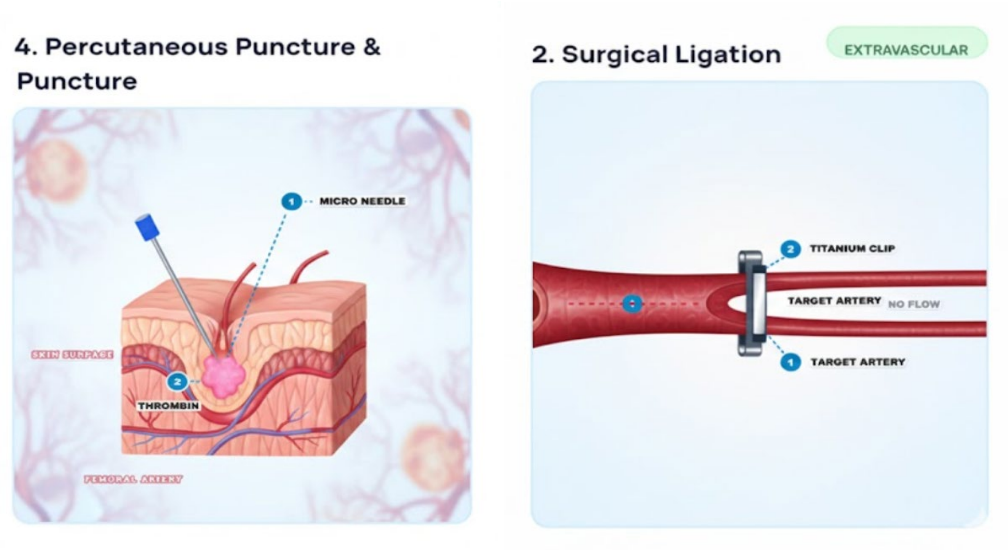


Figure 7: Percutaneous puncture (left) and the surgical ligation (right)

with imaging systems, which produces MRI artifacts caused by metallic components. Understanding how different devices fail has led to design improvements, including better radiopacity and controlled deployment systems, and advanced imaging compatibility. The development of embolization devices demonstrates their ongoing progress as healthcare technologies instead of remaining fixed medical instruments. (Table 3) provides temporal and dimensional specifications for key embolic agents, including degradation timelines, particle size ranges, and viscosity values, with explanatory notes on the clinical rationale for each parameter to support evidence-based procedural planning.

EMBOLIC MATERIALS:

Metallic Materials

Platinum and nitinol dominate mechanical embolics because they show both radiopacity and super elasticity. They maintain their strength for extended periods. Nitinol's shape-memory properties provide essential benefits to vascular plugs and self-expanding devices according to sources [45, 46] (Figure 8).

Polymeric and Particulate Materials

The combination of polyvinyl alcohol particles and Tris acryl gelatine microspheres, together with polymethylmethacrylate and biodegradable polymers, produces materials that display various mechanical characteristics and different degradation rates. [12,35]

Liquid Embolic Materials

The substances NBCA, EVOH, ethanol, and Lipiodol create lasting blockages that extend into body tissues. However, these materials need to be manipulated with great care because improper handling will result in non-target embolization and catheter entrapment incidents [5,43](Figure 8).

COMPLICATIONS AND FAILURE MODES

The procedure of embolization contains risks that exist regardless of technological progress. The main complications of the procedure include non-target embolization, recanalization, catheter entrapment, and hydrophilic polymer embolism from device coatings [43,47,48] as explained in Figure 9. The combination of better device design and imaging technology and operator experience has led to a decrease in complication rates.

Non-Target Embolization (NTE)

NTE happens when embolic material moves into healthy tissue.

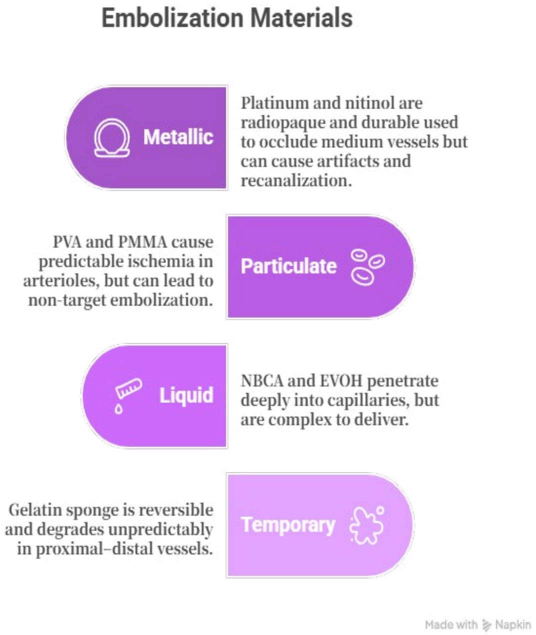


Figure 8: Embolic materials: Composition, mechanism, and limitations

Table 3: Temporal and dimensional specification of embolization strategies

Embolic agent	*Time variable (Duration / Half-life)*	*Dimensional Variable (Size / Viscosity)*	*Explanatory Logic (Why these numbers matter)*	*Refs*
1.Gelatine Sponge (Gel foam)	7-21 Days (Resorption Time)	Macroscopic Slurry (Non-calibrated)	The "Healing Window": 21 days is the ideal duration because it is long enough for an injured artery to heal its wall, but short enough to allow blood flow to eventually return, preventing permanent muscle death in trauma patients.	1,7
2.Radioactive Microspheres (Yittrium-90)	64.1 Hours (Half-life)	2.5mm (Radiation Range)	The "Sniper Effect": Because the radiation only travels 2.5 mm from the bead, it kills tumour cells immediately adjacent to it while sparing healthy liver tissue just a few millimetres away. The short half-life ensures the patient is not radioactive for long.	17, 18
3.Liquid-Embolic (Onyx)	Up to 60 minutes (Injection Time)	18-34cP (Viscosity)	Controlled Lava Flow: Unlike glue (which sets in seconds), Onyx's high viscosity (up to 34 centipoise) allows it to flow like lava. Doctors can inject it slowly for up to an hour to fill complex brain malformations without it washing away.	5,26,36
4.Calibrated Microspheres	Permanent (Occlusion)	300-500 µm (Typical Diameter)	The "Goldilocks" Size: 300–500 µm is the "sweet spot" for tumours. If smaller (<100 µm), they might pass through to the lungs (dangerous). If larger (>700 µm), they block the vessel too early (proximally), missing the tumour bed.	12,35 25
5.Detachable Coils	Immediate (Mechanical Stop)	0.001-0.015 in (Wire Thickness)	Soft Packing: The wire must be extremely thin (0.001 inches, thinner than hair) so that it is soft enough to fold gently inside a fragile aneurysm. If it were thicker/stiffer, it could puncture the aneurysm wall and cause a bleed	10,11, 33

This process can happen in three ways: liquid embolic reflux, undersized coil migration, or particle fragmentation. The results of this situation lead to critical results, which include bladder necrosis in PAE through reflux into the superior vesical artery, ischemic stroke during neuro-interventions, or radiation pneumonitis in Transarterial Radioembolization (TARE) caused by hepatopulmonary shunting [33]

Recanalization

Recanalization represents blood flow restoration through occluded blood vessels, which serves as a major clinical failure mode in embolization procedures. The process of coil embolization in treating intracranial aneurysms operates through looped arterial pressure, which causes coils to compact their mass with each pulse. The coil mass continues to compact until it reaches a state where packing density decreases and the aneurysm neck becomes visible again while the sac experiences new fillings. The risk becomes more severe because large and giant aneurysms with wide necks create an unfavourable condition, which results in high-volume aneurysms compared to their coil surface area [10]. Hydrogel-coated coils were developed specifically to address this failure mode: upon contact with blood, the hydrogel coating expands volumetrically, increasing packing density and reducing the likelihood of recanalization [33]. Collateral recruitment functions as the biological mechanism that causes recanalization during tumour embolization procedures. The tumour acquires blood supply from nearby structures after the main feeding artery becomes blocked, which allows the tumour to obtain blood from phrenic intercostal and omental vessels, thus enabling treatment failure through blood refill into the tumour bed[16]. The solution to recanalization problems requires doctors to select devices carefully during the procedure while they monitor patients through imaging examinations to identify recurrences that need urgent treatment [16].

Hydrophilic Polymer Embolism (HPE)

The medical community has not yet recognized the problem of hydrophilic coating shedding from catheter systems. Histological studies have identified polymer fragments in the brain and lungs, which can lead to granulomatous inflammation and micro-infarcts. This phenomenon has created anxiety regarding the hazardous effects of cerebrovascular damage, which develops in patients who require several medical operations [49,50]

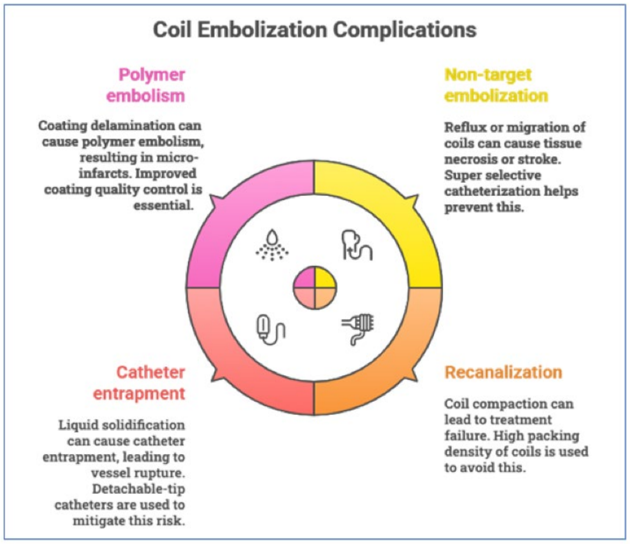
Catheter Entrapment

The use of liquid embolics (Onyx/NBCA) leads to a serious risk of developing this complication. The agent could harden through the catheter tip, which results in adhesive bonding between the catheter and vascular tissue. The process of forceful retrieval from a vessel can lead to two dangerous outcomes, which include vessel rupture and haemorrhage. The need for detachable tip microcatheters exists because this risk has become a common procedural risk [42]

EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

The latest advancements in embolization procedures combine digital intelligence and advanced biomaterials through specialized medical solutions that deliver personalized treatment. Scientists are developing advanced embolic agents that become solid under specific conditions of pH, temperature, or shear force to prevent backflow and unintentional vessel blockage [51,52]. Examples of such stimuli-responsive materials include: (i) thermosensitive hydrogels based on poly(N-isopropylacrylamide) (PNIPAM), which remain in a liquid state at room temperature for easy catheter injection but undergo rapid sol-gel transition at physiological body temperature (37°C), solidifying in situ within the target vessel; (ii) pH-sensitive systems such as chitosan-based hydrogels, which exploit the acidic microenvironment of tumour tissue (pH 6.5–7.0) to trigger selective gelation at the target site while remaining stable at the normal vascular pH of healthy tissue; and (iii) shear- thinning injectable gels formulated from alginate or hyaluronic acid composites, which flow freely under the mechanical shear stress of catheter injection but rapidly recover their gel-like consistency once injection ceases, anchoring within the target vessel and resisting proximal reflux [51,52]

Shape memory polymers and foams achieve better volumetric aneurysm sac filling than traditional metallic coils, which leads to lower recanalization rates [55,66] Bioresorbable and biodegradable embolic systems, which use polymeric microspheres and transient electronic implants, provide temporary vascular support or monitoring until safe resorption occurs, thereby decreasing long-term foreign-body complications[55,56]



Coating delamination can cause polymer embolism, resulting in micro-infarcts. Improved coating quality control is essential.

Reflux or migration of coils can cause tissue necrosis or stroke. Super selective catheterization helps prevent this.

Liquid solidification can cause catheter entrapment, leading to vessel rupture. Detachable-tip catheters are used to mitigate this risk.

Coil compaction can lead to treatment failure. High packing density of coils is used to avoid this.

Figure 9: Common complications of embolization and mitigation strategies

The combination of iodine and barium in radiopaque polymeric beads enables real-time detection of embolic flow patterns through cone-beam CT, which enhances both procedural precision and post-treatment evaluation [39,57]. Magnetically guided embolization provides a new method to solve the challenges associated with particles that follow fluid movement. Magnetic nanoparticles and microspheres can be directed through external magnetic fields to specifically target tumour-feeding blood vessels, which enables super-selective embolization procedures in complicated vascular systems [58,59]

The combination of computational fluid dynamics (CFD) and patient-specific vascular modelling enables pre-procedural simulation of embolic particle transport and flow alteration, supporting personalized embolization planning [60-62]. The use of artificial intelligence (AI) algorithms in angiographic image analysis enables automated vessel detection and tumour feeder identification while providing real-time guidance for procedures, which decreases operator differences and radiation exposure [62-65]

Three-dimensional (3D) printing technology creates customized vascular models for patients, which enable medical teams to practice their procedures and choose their equipment before they start their complex surgical operations. The technology of four-dimensional (4D) printing creates implants that depend on time and external stimuli to change their shape according to the patient's blood vessel structure[29,48,66-68]. Future directions include theragnostic embolization platforms combining embolic function with diagnostic feedback or adjunctive therapies.

Liquid metal embolics based on gallium alloys exhibit radiopacity, electrical conductivity, and photothermal properties, which enable physicians to use the materials in combination with embolization and hyperthermia treatment methods. The combination of intelligent materials with artificial intelligence-based planning systems and personalized production methods will create a new method for embolization that uses precision healthcare instead of mechanical methods.[69,70,71,72]

CONCLUSION

Endovascular embolization has developed into an advanced medical treatment system that combines multiple medical disciplines with biomaterials research and innovations in healthcare technology. The ongoing development of new embolic materials, device technology, imaging systems and digital intelligence systems has improved the safety and effectiveness and operational range of embolization procedures. The combination of smart polymers with AI-driven treatment planning and personalized patient modelling will create a new standard for customizable dynamic treatment, which will become essential for all non-surgical medical practices. The advanced medical treatment system of endovascular embolization now connects three distinct fields of clinical practice, which include modern medical treatment and biomaterials research and device manufacturing. The ongoing development of all intelligent materials and imaging technologies and artificial intelligence systems will enable smart materials to deliver their full clinical potential while enhancing patient treatment results. The most pressing areas for future research are the prevention of non-target embolization and the elimination of recanalization, as these two failure modes remain the primary drivers of procedural complications and long-term treatment failure despite decades of device advancement.

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