REVIEW

Endovascular coils: properties, technical complications and salvage techniques

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ABSTRACT

Endovascular coil embolization has become an accepted and often first-line treatment for ruptured and unruptured intracranial aneurysms. While the complications of endovascular therapy of intracranial aneurysms have been well vetted in the literature, there are few reports solely concerning the complications and salvage techniques related to either the technical aspects of coil deployment or to the devices themselves. In this review the structural details of commonly used endovascular coils, technical complications related to coiling and salvage techniques used when these complications occur are discussed.

INTRODUCTION

Endovascular coil embolization has become an accepted and often first-line treatment for ruptured and unruptured intracranial aneurysms. The International Subarachnoid Aneurysm Trial, the International Study of Unruptured Intracranial Aneurysms trial and others have reported in many publications that endovascular therapy of intracranial aneurysms has an initial lower morbidity and mortality rate related to treatment compared with microsurgery.[1–13] While the complications of endovascular therapy of intracranial aneurysms have been well vetted in the literature, there are few reports solely concerning the complications and salvage techniques related to either the technical aspects of coil deployment or to the devices themselves.[14–27] In this review we discuss the structural details of commonly used endovascular coils, technical complications related to coiling and salvage techniques to employ when these complications occur.

PLATINUM COILS AND DETACHMENT MECHANISMS

Most platinum coils used in intracranial aneurysm embolization are actually not pure platinum but rather an alloy, normally consisting of 8% tungsten in addition to platinum. This alloy has been shown to be a safe and inert alloy for deployment inside the vasculature.[28 29] We will expand on a review recently published by White *et al* which discussed the structural and physical properties of endovascular coils.[30]

Structural properties of coils

The intravascular behavior of a coil is the result of an interaction between the primary material, resistance to deformity (stiffness, secondary and tertiary structures) and the mechanism of detachment. Proprietary changes are generally based on a modification of one or more of these properties. All coils begin as a stock platinum alloy wire of a particular diameter (figure 1A). The diameter of the stock wire, which can be highly variable, is thought to be the most impactful factor in determining a coil's stiffness. The conventional thought is that the larger the diameter of the stock wire, the stiffer the coil. This straight stock wire is then wound around a mandrel, a straight metal rod in the case of coils, to give it the familiar 'slinky' structure. This is referred to as the coil's primary wind or secondary structure (figure 1A). The mandrel can also be of variable sizes such that coils can be wound to produce highly variable secondary structure sizes. Unfortunately, the diameter of this secondary structure is also the basis for the standard but often incorrect and confusing naming groups of coils. As an example, when the moniker "10" is used to refer to a secondary structure diameter of 0.010 inches, the actual diameters may be 0.012 inches or even 0.014 inches. Furthermore, the 18 group can have diameters from 0.0135 inches to 0.018 inches. Given that there are a variety of microcatheters with varied inner diameters, this creates compatibility issues between coils and microcatheters that cannot often be resolved with the information labeled on the box.

Once a secondary structure is established, a number of tertiary shapes and configurations are available to provide the advertised properties of being three-dimensional or helical coils (figure 1B). The size of the tertiary shape is what the coil manufacturers advertise as the 'size' or diameter of the coil. For example, a 5 mm coil will have a majority of coil loops that are 5 mm in diameter, irrespective of the tertiary shape. Some coil designs have smaller initial loops that confine the first loop(s) to within the aneurysm, have extremely soft loops that can fill very irregularly shaped aneurysms, or simply have no tertiary shape at all, allowing progressive folding and/or filling irrespective of the size or shape of the aneurysm.

Mechanical properties of coils

The mechanical properties of coils are determined by a number of combined parameters. The overall stiffness of the coil, as mentioned above, is mainly determined by the diameter of the stock wire (D_1). However, the outer diameter of the primary wind or secondary structure (D_2) can have a significant

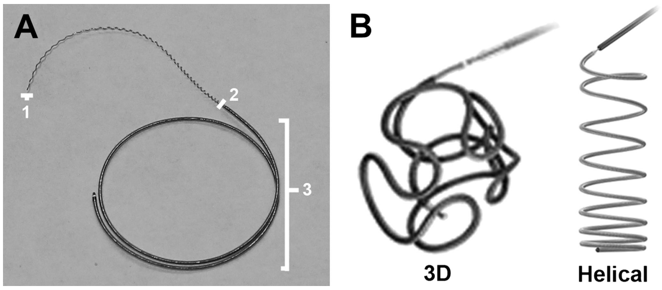

Figure 1 Coil structural characteristics. (A) A standard coil has three general structural properties: (1) the stock wire, (2) the primary wind and (3) the tertiary shape. (B) Comparison of three-dimensional (3D) and helical tertiary shapes.

effect. These two factors are often related by the calculation of the 'spring constant', or 'k' (figure 2). This equation basically states that the larger the stock wire diameter, the more stiff the coil. However, if the mandrel diameter is increased, leading to an increased diameter of the secondary structure, the stiffness can be decreased. As such, a large stock wire with a large secondary structure can theoretically have the same stiffness grade as a small stock wire with a smaller secondary structure.

Other changes in the mechanical properties of coils that may affect coil stiffness include (but are not limited to) the coil's pitch (ie, the amount of space between the turns of the primary wind, internal materials such as suture, bioactive coatings and fibers placed within the primary wind).

Detachment mechanisms of coils

The detachment mechanism of an endovascular device involves a termination of the relationship between the delivery, or 'pusher', wire and the coil. The engineering of this 'detachment zone' is frequently a proprietary endeavor. The most common coil detachment mechanisms are electrolytic, hydraulic, mechanical and electrothermal (figure 3). Electrolytic mechanisms involve a microsolder joint surrounded by an insulated connecting joint. This microsolder joint disengages when a current is passed through it over time. Hydraulic mechanisms involve 'pushing' the coil end out of the delivery tube with a column of fluid using a crank syringe. Mechanical detachment systems can be generally categorized into either release or pull-release mechanisms. Release mechanisms involve a passive holder that can be agitated once out of the delivery tube to release the coil. Pull-release mechanisms typically involve a stretched filament attached to the coil by a ball joint or ball cylinder which is held in place within the detachment zone of the pusher wire. The ball joint is held in place by another tube or filament running the length of the pusher wire that reduces the size of the opening such that the ball joint cannot be released. Once the tube or filament is pulled from the opening, usually by a hand-held detachment device, the ball joint is given enough space for the ball joint to pass through, consequently releasing the coil. Electrothermal mechanisms typically involve a polymer fiber that connects the coil to the pusher wire. When heated, the polymer fiber is disrupted, thereby releasing the coil.

$$k = \frac{D_1^4 G}{8 D_2^3 n} = \text{Stiffness} \propto \frac{D_1 G}{D_2 n}$$

Figure 2 General equation describing the relative contributions of the diameter of the stock wire (D_1) and the primary wind (D_2) to the spring constant or stiffness (k) of the coil. G = shear modulus, n = number of turns per unit distance.

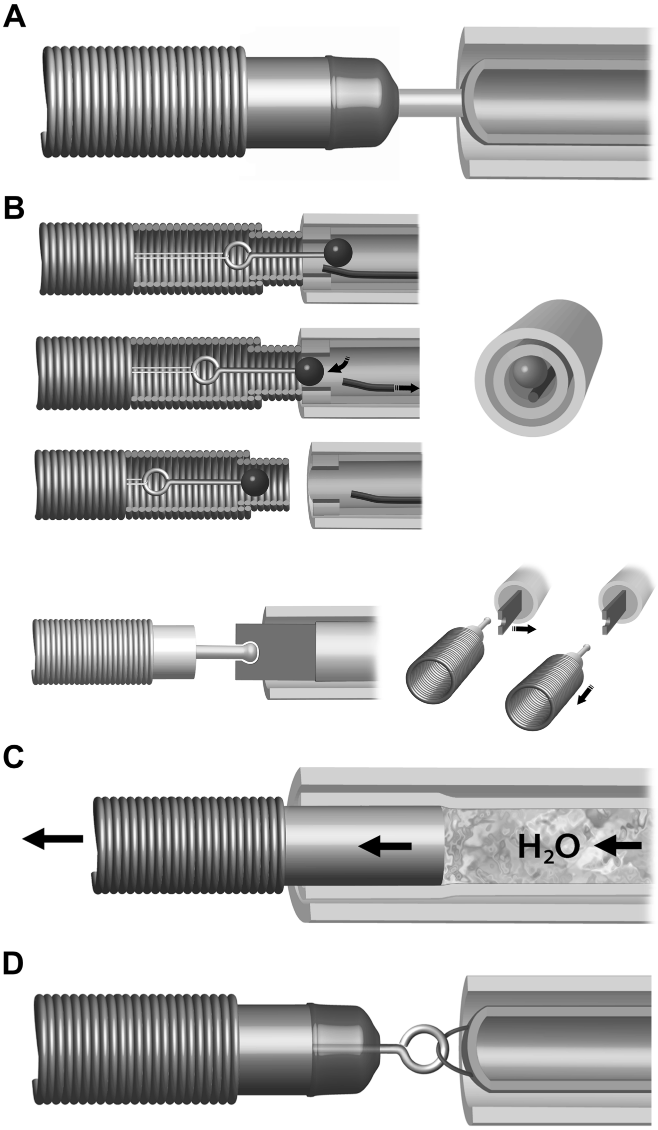

Figure 3 Coil detachment mechanisms. These basic illustrations demonstrate the general mechanism of detachment. The exact construction of these mechanisms is mostly proprietary and is not detailed here. (A) Electrolytic. (B) Mechanical. (C) Hydraulic. (D) Electrothermal (see text for details).

TECHNICAL CONSIDERATIONS, COMPLICATIONS AND SALVAGE TECHNIQUES

Once the microcatheter is placed within the aneurysm, coil deployment is seemingly straightforward. This could not be further from the truth. There are several technical considerations to keep in mind once coil deployment begins, hence several opportunities for complications to occur.

Before coil deployment begins, the first important step should be coil selection, which differs from lesion to lesion and institution to institution. The variety of coils in the marketplace is almost mind numbing at this point, but recent changes in company ownership will likely lead to consolidation and a condensed variety of offerings. For coil size, a general rule of thumb is to select coils based on the largest measured parameter of the aneurysm. Many practitioners undersize a coil for ruptured lesions and potentially oversize a coil for unruptured lesions. Aneurysm shape can also change the coil selection. Multilobular or complex-shaped lesions usually require a coil that can accommodate a complex shape (ie, non-helical). Most saccular aneurysms can accommodate most types of coils.

Desktop and mobile computing applications have recently been developed that aid before and during the coiling process by using volumetric analyses such that coil size and lengths can be used to determine the potential or current packing density, the only coiling parameter that has been clinically shown to be associated with coil occlusion durability. Once the coil types and coiling strategy are selected, the process of deployment can begin.

The process of coil deployment comprises placement of the distal loop, delivery of the coil body and detachment of the coil. As a coil emerges from the tip of a microcatheter, it first begins to form the distal coil loop and then subsequently folds to assume its tertiary structure. If the coil has been correctly selected, the coil should assume the overall shape of the aneurysm. This will, of course, depend on the kind and size of coil selected. If the coil body is either too big or too long, resistance to deployment will likely be experienced, thus causing movement of the microcatheter or coil out of the aneurysm or, worse, rupture of the aneurysm. Following successful placement of the chosen coil based on size and shape, the mechanical properties of the detachment zone can challenge the technique of the practitioner.

The detachment zone, which is often fairly inflexible, can still result in kickback of the microcatheter. On other occasions, if the microcatheter is along the wall of the aneurysm, the stiff detachment zone can also puncture the wall of the aneurysm. Improved understanding of the manufacturing process has provided many detachment zones that minimize microcatheter movement and potential rupture. Despite these improvements, the practitioner should expect a change in coil performance as the detachment zone is approached and react to minimize the forces that are transmitted or stored up as potential energy.

With manufacturing improvements, the relationship of the size of the pusher wire to the microcatheter has been carefully considered. While a more robust pusher wire can provide an improvement in tactile feedback, a very tight relationship between the pusher wire and microcatheter inner diameter can either push the microcatheter out of the aneurysm or can result in pulling the already detached coil out of the aneurysm. Care must be taken to ensure safe deployment and detachment. Once the coil is detached, the pusher wire has to be carefully removed to ensure complete detachment and prevention of either inadvertently pulling back the detached coil or kickback of the catheter out of the aneurysm. Caution must also be taken when removing the microcatheter as some forward tension likely exists in the microcatheter, which can thrust the microcatheter into the aneurysm, potentially displacing coils or, worse, rupturing the aneurysm.

Several complications have been noted to occur while completing the process of coil deployment. These complications include—but are not limited to—stretching, fracturing, knotting and interlocking of coils. Failed detachment or displacement of detached coils can also occur. We will consider all of these potential complications and offer salvage techniques that one can employ when they occur. Several considerations should come to mind when a coil complication occurs (table 1). All management options are orchestrated to maintain a patent lumen in the parent vessel. While the options discussed are procedural maneuvers, medical means to maintain vessel patency should also always be considered.

Table 1 Salvage technique considerations for coil complications

Complication	Considerations
Stretched coil	Length determines the salvage technique
	What is the degree of intraluminal movement/pulsation?
	Consider dual antiplatelet therapy
	When a snare is possible, keep the microcatheter close to the coil
Fractured coil	Deployed length is proportional to the risk of migration
	What is the degree of intraluminal movement/pulsation?
	Consider the use of flow arrest/balloon
	When a snare is possible, keep the microcatheter close to the coil
Migrated coil	Determine the ischemic risk versus retrieval risk
	Consider the use of flow arrest/balloon
	A coil is easier to retrieve if it is wedged
	Consider optimal placement for stent(s)
Knotted coil	Compare the size of deployed coil mass versus aneurysm neck
	Determine the amount of coil still in microcatheter
	What is the risk of creating a migrated coil?
	Determine difficulty of aneurysm catheterization versus removal
Interlocking coils	Determine the length of coil still in microcatheter
	Can the coil be completely deployed?
	Is the coil interlocked with the stent?
	Could the aneurysm be catheterized with another microcatheter?
	Is the coil interlocked with the stent?
Premature coil detachment	How much coil is in the microcatheter/aneurysm?
	Realize the potential for creating a migrated coil
	Does the coil move with retraction of the microcatheter and suction?
	When a snare is possible, keep the microcatheter close to the coil

Stretched coils

One of the most common complications that can occur with coiling is the stretched coil.[14 20 31] A stretched coil is essentially the unwinding of the primary wind (figure 4), that is, stretching out the 'slinky'. In an attempt to minimize this complication, the stretch-resistant property of a coil refers to one or more sutures that run inside the primary wind. This is an imperfect solution. Once a coil is stretched, there is little control of the coil and an almost infinite length of unwound stock wire exists which has no mechanical stiffness or integrity. Frequently, the coil can no longer be pushed or pulled from the aneurysm. Removal of the already deployed coil mass is difficult despite movement of the coil or the microcatheter. This complication often occurs when one is repositioning the coil in order to create a more ideal shape within the aneurysm. Another common scenario is when the microcatheter is jailed alongside or between the cells of a stent, which minimizes the 'painting' of the microcatheter as coils are being deployed. It is this point that augmented forces on the coil lead to an increased chance of stretching, kinking or fracturing of a coil.

Several salvage techniques have been described to address stretched coils. Three common techniques for dealing with stretched coils are: (1) stent placement to tack the stretched coil to the parent artery; (2) use of a snare device to grab the distal unstretched portion of the coil and withdraw the entire coil; and (3) removing the catheter and tying the stretched coil down at the groin puncture site and placing the patient on antiplatelet agents. Other techniques that have been described in the

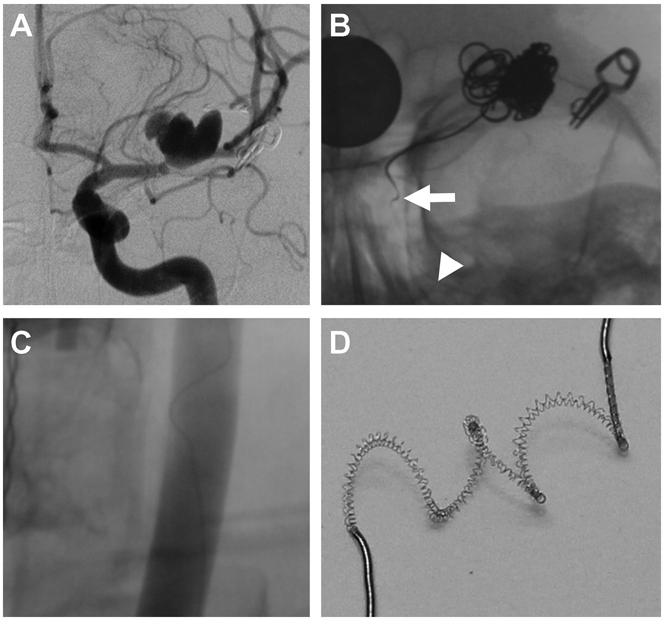

Figure 4 Stretched coil. Coil embolization of a left dissecting middle cerebral artery aneurysm (A) resulting in a stretched coil (B). The catheter was trapped in the aneurysm with a stent. Reduced movement of the catheter tip during coiling facilitated stretching. (B) The arrow shows the transition between primary wind and the stock wire (arrowhead). (C) The stretched coil can be seen in the common carotid (C). (D) Close-up photograph showing the coiled stock wire and the primary wind.

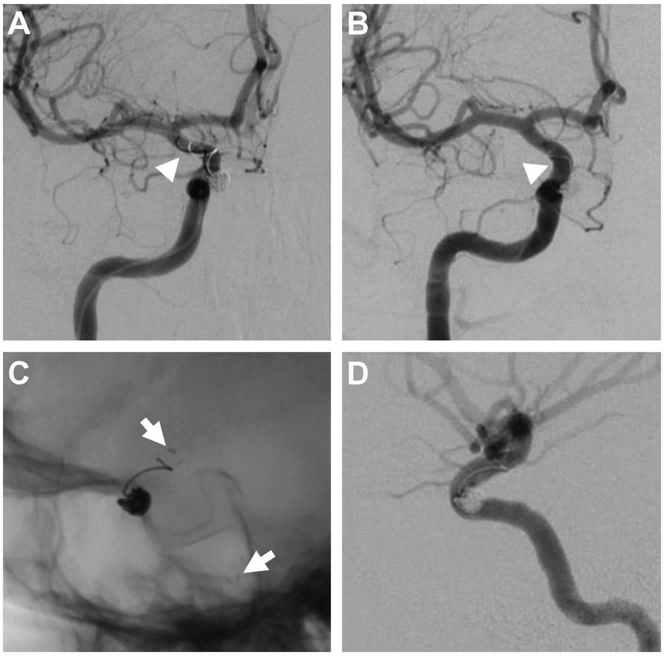

Figure 5 Migrated coil. Coil embolization of a posterior carotid artery aneurysm resulting in a migrated coil. (A) The subtracted image demonstrates the pulsatility of the migrated coil (arrowhead). (B) After deploying a stent to tack the coil to the parent vessel, demonstrated by overlap of the coil after subtraction (arrowhead). (C) Unsubtracted image demonstrating stent tines (arrows) tacking coil to the wall of the parent artery. (D) Subtracted image of C.

literature are: (1) balloon trapping of the coil, facilitating either the removal of or complete placement of the coil; (2) using a microwire as a snare device to remove the coil; and (3) trapping the stretched coil into the external carotid artery with additional coiling.[14 19 24 25 31]

Fractured coils

Although considered a rare occurrence, the constant repositioning of coils in aneurysms, resulting in constant reformations of the coil loops, can lead to stress and strain within the material of the coil leading to fracture.[16 17 19] Furthermore, manufacturing or structural defects in the stock wire can also lead to fracture of the coil. In most cases the coil is deployed and, during the folding of the coil, it breaks, leading to a disconnected isolated coil fragment within the aneurysm that can be prone to distal migration.

Similar to stretched coils, the management of fractured coils includes: (1) recovery of the fractured coil using a snare, Alligator (ev3; Irvine, California, USA) retriever device or shaped guide wire with or without the use of a balloon; or (2) placement of a stent at the aneurysm neck or other locations depending on the length of the fractured coil.

Migrated coils

Both undersized and/or unstable long coils can result in distal coil migration, especially in wide-necked aneurysms.[19 20 22–27 31–35] Coil migration can occur in several ways. The initial coil mass or part of it can be displaced upon deploying the second coil, especially when the initial coil is either short or improperly sized to the aneurysm or aneurysm neck (figure 5). Alternatively, an excessively long initial coil, especially in small aneurysms, can lead to bunching of the coil near the neck, which has the potential to unravel either after detachment or movement of the catheter. This can result in herniation of coil loops out of the aneurysm and potential distal migration. Even when herniated loops of coil are not disconnected, these coils ‘in the breeze’ can still be a nidus for thrombus formation.

Salvage techniques for migrated coils depend on the site of migration and the degree of luminal compromise. For example, an ‘anchored migration’ in which the main body of the coil remains within the aneurysm can be managed with antiplatelet agents and close follow-up. Luminal compromise in the same situation would require placement of an endovascular stent. Demonstrative pulsation of the coil in the parent vessel lumen would also suggest the need for stent placement. The problem of coils detached from the aneurysm or coil body is commonly approached by: (1) coil retrieval using a snare or Alligator (ev3) retriever device to remove the coil/mass; or (2) placement of a stent to maintain the lumen to the parent artery to minimize thrombus formation.

When ‘chasing’ a migrated coil, it is important to weigh the risks of thromboembolic complications with the risk of hemorrhagic complication by vessel puncture/rupture. A smaller coil in a watershed region may produce a ‘manageable infarct’ while a retriever device in the same region may not. It is important to realize that, in an attempt to retrieve the coil, further migration could occur. As such, practitioners have often used balloon devices with a working port such that flow arrest can be maintained while a retrieval device is used through the working port of the balloon. Alternatively, a balloon guide catheter can be used for flow arrest proximal to the migrated coil. When retrieval is considered unlikely, a final salvage maneuver involves pushing the migrated coil to the most distal circulation where collateral flow is more likely to minimize ischemia.

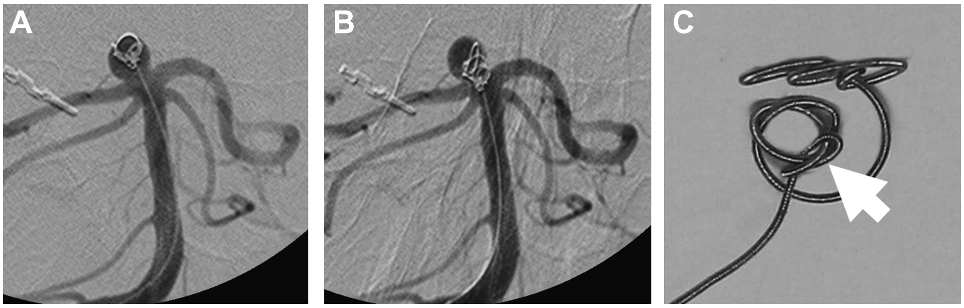

Figure 6 Knotted coil. Coil embolization of a basilar apex aneurysm resulting in a knotted coil. (A) Repetitive deployment and removal of the coil resulted in knotting of the coil. (B) Pulling both the catheter and coil mass was performed. (C) Photograph of the same coil showing the coil knot (arrow).

Knotted coils

Another rare complication of coiling is the knotted coil.[15 18] Repeated deployment and withdrawal of coils with subsequent movement of the microcatheter can lead to this complication. The coil loops within itself and the movement of the microcatheter changes the relationship of the deployed coil. This may lead to a change in the loop configuration and subsequent formation of a knot. The immediate result is that the coil cannot be withdrawn into the microcatheter. While difficult withdrawal is similar to a stretched coil, with a knotted coil, when carefully moving the coil and the microcatheter together, the coil mass should move (figure 6). If the coil is either stretched or fractured, the coil mass should not move.

With a knotted coil the coil cannot be pulled back into the delivery catheter, leaving only two possible situations for salvage: either to deploy the entire coil into the lesion or very carefully to remove the entire coil and the microcatheter together. When the entire coil (and coil mass) is removed, it should be fluoroscopically followed down to the sheath to ensure that it does not inadvertently migrate or become detached during its removal.

Interlocking coils

As the number of coils deployed into an aneurysm increases, the space available for coils to occupy decreases, thus putting strain on the coils already detached. This strain on the previously deployed coils can result in openings within the pitch of the primary wind that can catch the actively deployed coil resulting in an interlocked coil.[36] Coils can also become interlocked to stent cells. With an interlocked coil, like a knotted coil, it cannot be pulled back into the microcatheter and the coil mass should move in synchrony with the microcatheter unless caught on a stent. Because more than one coil is involved, this relationship is much more tenuous. Similar to the knotted coil, an attempt to deploy the rest of the coil would be the safest. Alternatively, agitating the coil mass, usually with another microcatheter, can sometimes dislodge the interlocked coil, thus allowing either removal of the coil through the microcatheter or complete deployment of the interlocked coil.

Premature coil detachment

There are numerous varieties of coils, all of which have the potential to detach prematurely. This can occur when either the coil is partially deployed in the aneurysm or while the coil is still within the catheter.[16 21 22] Excessive manipulation or force placed on the coil, either while navigating very tortuous anatomy or frequent in-and-out movements into the aneurysm, certainly increases the chances for premature detachment.

With a prematurely detached coil, the pusher wire is no longer connected to the coil itself; however, this does not necessarily mean the coil cannot be completely deployed. If the delivery catheter can either be navigated into or remains within the aneurysm, then the coil may still be deployed by carefully using the disconnected pusher wire. However, the potential for creating a migrated coil also exists. If the microcatheter cannot be navigated into the aneurysm, then an attempt can be made to remove the coil. When a segment of coil remains within the microcatheter, one can carefully remove the disconnected pusher wire and attach a syringe to the end of the microcatheter and apply significant negative pressure while withdrawing the microcatheter and coil. If this technique fails, it is wise to maintain the microcatheter as close to the detached coil as possible. This will facilitate the delivery of a snare device over the microcatheter to the coil and improve the chances of removal. If most of the coil has already been deployed, then removing it will likely be difficult and the salvage plan would be to remove the microcatheter and stent the free coil end to the parent vessel.

CONCLUSIONS

The effectiveness of neurointerventional techniques has resulted in an increased number of treated patients and devices created. Inherent to the creation of a device is device failure. While proper endovascular technique can minimize device complications, an understanding of the complex and miniature device relationships that can occur will further improve treatment outcomes. With this knowledge, the practitioner can develop general concepts for the facile management of the 'endovascular misadventure'.

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Competing interests PDP, who serves as the Chief of Neuroradiology at UT Southwestern Medical Center, was involved in the early development of endovascular technology and, as such, owns several patents and stock as well as receives royalties from Cordis Corporation (Miami, Florida, USA).

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