Imaging Follow-Up of Intracranial Aneurysms Treated by Endovascular Means
Why, When, and How?

Sebastien Soize, MD; Matthias Gawlitza, MD; Hélène Raoult, MD, PhD; Laurent Pierot, MD, PhD

Aneurysm treatment is dedicated to prevention of rupture (for unruptured aneurysms) or rebleeding (for ruptured aneurysms). Endovascular embolization has become the first-line treatment for intracranial aneurysms in the majority of cases in many institutions. This minimally invasive approach achieved lower morbidity and mortality rates when compared with surgical management. However, although successful in improving patient care, its durability has been noted to be its Achilles’ heel since the earliest application of this technology. Indeed, after endovascular treatment (EVT) ≈20% of patients will experience aneurysm or neck reopening after traditional endovascular coiling, necessitating retreatment in about half of them to maintain long-term protection over bleeding. Despite this issue, low rates of bleeding have been reported after EVT of ruptured aneurysms, and its clinical superiority over surgery seems to be maintained over time according to the long-term clinical follow-up of the International Subarachnoid Aneurysm Trial (ISAT) cohort. In the Cerebral Aneurysm Rerupture after Treatment (CARAT) study, the bleeding rate after coil embolization was 0.11% (mean follow-up time, 4.4 years), whereas in the International Subarachnoid Aneurysm Trial, the annual risk of bleeding after coil-treated aneurysms was 0.08%. In a large single-center study, the Barrow Ruptured Aneurysm Trial (BRAT), no bleeding was observed after 6 years in the coiling arm, but 4.6% of these patients were retreated.

Thus, one may question the clinical usefulness of performing imaging follow-up, balancing the small risk of bleeding after EVT with the cost-effectiveness of follow-up.

Although the primary end points of these studies were clinical, it is important to note that the majority of EVT patients had imaging follow-up performed at the discretion of the treating physician. For example, in the ISAT trial, 88.2% of the patients in the EVT arm (881 patients) had follow-up angiograms, generally performed 6 months after treatment and repeated at varying intervals. Moreover, during the follow-up of the patients enrolled in these studies, it was noticed that some patients underwent retreatment without any bleeding, so that bleeding may have been more common if these aneurysms were not followed. For example, 8.3% of the EVT patients in ISAT received late retreatment without prior rebleeding, whereas only 0.6% of them were retreated lately because of rebleeding.

Several mechanisms have been proposed to explain aneurysm recurrence, including coil compaction, aneurysm growth, coil migration through the aneurysm wall, coil penetration into the thrombus material of a partially thrombosed aneurysm, and abnormal inflammatory reaction of the aneurysm wall leading to growth.

Because recurrence is the main weakness of EVT, innovative technologies have been developed during the past decade to improve the long-term stability of EVT. New technologies were developed to improve aneurysm occlusion and coil density within the aneurysm sac and to treat complex aneurysms (large and/or wide-neck and/or bifurcation aneurysms) often prone to recur after simple coil embolization.

Several options became progressively available in addition to standard coil embolization with bare platinum coils, widening considerably the treatment options the neurointerventionist can offer: surface-modified coils (such as polyglycolic/polylyactic acid coated coils or hydrogel coated coils), balloon-assisted coiling, stent-assisted coiling, flow diverters, and recently flow disrupters. Each treatment option has its own advantages and drawbacks. The physical properties of the material used will be crucial to determine the best modality for performing the follow-up.

Another concern for all patients harbouring an intracranial aneurysm is the appearance of newly detected (ie, de novo) aneurysms in =5% to 10% of patients. However, although many of them will be of small size, some will carry enough risk of bleeding to require treatment. Then, imaging must be able to detect and follow them.

The possibility of aneurysm recurrence and of newly detected aneurysms, with the idea of providing an early
preventive treatment if necessary, justify imaging follow-up after EVT. This is all the more important as many individuals with coiled intracranial aneurysms have a potentially long life expectancy (for example, the mean age at entry into the ISAT trial was 52 years).1

A routine major concern for the patient is to know and understand when, for how long, and how the follow-up will be done. The following sections of this topical review are dedicated to the description and discussion of the current follow-up strategies after EVT of an intracranial aneurysm.

When to Follow—and for How Long?
To the best of our knowledge, there exists no guideline and no scientific data defining the optimal regime when and how long to follow-up. A large variety of schemes are used among different departments and different countries. The aneurysm’s characteristics, the patient life expectancy, the device used to treat the aneurysm, and the patient psychology are the main points taken into account when proposing a particular scheme of follow-up. The optimal follow-up will balance avoidance of bleeding with minimizing unnecessary expense and patient anxiety.

Typically, the first follow-up after EVT is scheduled 3 to 6 months after the procedure with further follow-up tests in varying intervals depending on the department’s regimen and the patient/aneurysm characteristics. Then, a classical scheme will include a 12- to 24-month follow-up and a midterm follow-up at 3 to 5 years.10,16 The post-EVT first year period is crucial because most recurrences occur during this period, justifying both imaging controls.10,16 The ideal frequency of examinations and length of follow-up is actually not determined, but more frequent follow-up may be indicated in patients harboring risk factors of recurrence (ie, ruptured aneurysms, large aneurysms, wide neck, and incomplete postoperative occlusion).13,14

The imaging modalities and intervals of follow-up can vary along the time depending on the degree of occlusion of the aneurysm and particularly if there is an evolution. Figure 1 proposes a classical follow-up scheme based on main data from the literature, with emphasis on the differences according to the degree of occlusion of the aneurysms (occlusion, residual neck, and residual aneurysm) and what to do in case of growing sac or neck. For patients followed up with noninvasive techniques (ie, magnetic resonance angiography [MRA]), the appearance or evolution of a small residual neck will lead to the realization of a concomitant digital subtraction angiography (DSA) to verify the diagnosis and ensure an accurate estimation of the size of the remnant. In case of good correlate, closer monitoring may be subsequently performed noninvasively.

About the question how long patients must be followed after coil embolization, recent data in the literature suggest that follow-up periods of 3 to 5 years may not be sufficient to detect relevant aneurysm recurrences. In a publication by Lecler et al16—including both a prospective cohort study and a meta-analysis—aneurysm recurrences between midterm (3–5 years after coiling) and long-term follow-up (>10 years after coiling) were detected in 12.4% of treated aneurysms. Risk factors for late aneurysm recurrence were an aneurysm size >10 mm, a grade 2 aneurysm (ie, residual neck) at 3- to 5-year follow-up MR (as graded by the modified Raymond Scale19), and a previous retreatment ≤5 years after the first embolization. We can unreservedly recommend the conclusion of Lecler et al16 that longer follow-up periods of ≥10 years or more should be considered in these patients.

Because of their relatively recent development, no data exist on the long-term (>10 years) stability of aneurysms treated by means of flow diverters or intrasaccular flow diverters. Late recurrences should be unlikely in these cases because of neointimal coverage of the aneurysm neck along the metal surface; however, the longest published follow-up results are ≤56 months and 41 months for flow diverters19 and the WEB device (Sequent Medical, Aliso Viejo, CA),20 respectively. Data on long-term stability are needed for these treatment modalities.

Another fact that has to be considered when following up patients with treated aneurysms is the development of de novo aneurysms. De novo aneurysms in the long term were discovered in 4.4% in the study of Kemp et al17 and in 9.1% of patients in the above-mentioned study by Lecler et al.16 Although not so rare, de novo aneurysms may have a risk for subarachnoid hemorrhage that is comparatively higher than the risk associated with similarly sized, small, initially discovered unruptured saccular aneurysms.17 Thus, 2 approaches exist, with some centers proposing a more intensive monitoring that can lead to the treatment in case of rapid increase in size, whereas others proposing a systematic treatment of the de novo aneurysm.17

How to Follow?

Digital Subtraction Angiography
DSA is the gold standard for the evaluation of aneurysmal occlusion after coiling. Because of its high spatial resolution with 3D imaging and dynamic information, DSA allows scoring recurrent flow in the aneurysm. Raymond et al18 scale is the most widely used: class 1 means complete occlusion; class 2 means residual neck; and class 3 means residual aneurysm.

DSA also has the advantage of not being impaired by device-related artifacts, meaning that whatever the occlusion device used, coils, stent, or intrasaccular flow disrupter, the analysis of aneurysmal residual flow remains accurate as to the device positioning and the artery permeability.21,22

However, DSA is an invasive procedure exposing the patient to complications such as cerebral thromboembolism (from silent microemboli to transient or permanent neurological deficit in 0.5% to 3% of procedures), contrast nephotoxicity or anaphylactic reaction, ionizing radiation, and hematoma on the puncture site.23

As neurological risks accumulate because of the required repeated procedures during the follow-up period, noninvasive imaging techniques are frequently preferred.

Magnetic Resonance Angiography
MRA is the noninvasive imaging of choice, with rare contraindications, including ferromagnetic metallic implants and pacemakers. MRA can be performed as gadolinium
contrast-enhanced (CE) or as time-of-flight (TOF) MRA. TOF-MRA depicts inflow in the arteries without requiring gadolinium use. Common drawbacks are a lower sensitivity to slow and turbulent blood flow that is why a lower sensitivity for slowly perfused aneurysm remnants may occur. Moreover, a subacute thrombus with high T1-weighted imaging signal intensity may simulate an intrasaccular residual flow. Another disadvantage is that a high-resolution TOF-MRA takes several minutes to be acquired making TOF-MRA more prone to motion artifacts. On the contrary, the use of CE-MRA increases the costs of imaging and requires a contrast timing together with a narrow interval of scanning.

**Coiled Aneurysms**

As therapeutic consequences may derive from follow-up imaging, the diagnostic accuracy of MRA was demonstrated in comparison with DSA of reference in 5 main meta-analyses focused on coiled aneurysms (Figure 1). Three of them compared TOF-MRA and CE-MRA demonstrating that both are equally suitable for aneurysm surveillance, with high sensitivity and specificity values to detect aneurysm recurrence (Table 1). Although aneurysm remnants might be missed on MRA, their small sizes usually do not require retreatment.

About TOF-MRA, it was shown on a direct comparison that 3T high field offers a better detection of the recurrence than 1.5T field with a better interobserver agreement although similar performance between both magnetic fields was previously shown on a larger cohort but comparing 2 different groups of patients. With TOF-MRA, coils are visible and appear as a signal void created by artifacts because of platinum (which is absent or less visible with CE-MRA). These slight artifacts did not hamper recurrence identification and were lower at 3T because of the fact that higher-field strength provides a better signal:noise ratio and a superior spatial resolution.

About CE-MRA, a trend toward higher performance was observed at 3T and with CE-MRA better able to distinguish aneurysm remnant from neck remnant than TOF-MRA. Further data on this topic are needed.

In clinical practice, there is no clear recommendation and various practices exist, from centers exclusively using 3T-MRA for follow-up to those using regular DSA. However, DSA is required in every case of aneurysm recurrence detected on MRA, potentially requiring retreatment.

**Other Embolization Devices**

A stent appears as a tiny endoluminal signal void, with artifacts originating from the markers or the stent material itself (Figure 2). MR imaging of stents remains difficult because of a combination of magnetic susceptibility artifact and Faraday cage effect. These 2 artefacts may result in the appearance of occlusion or false stenosis of the artery in which the stent was deployed. Few studies assessed the value of MRA for non-invasive follow-up of aneurysms treated with stent-assisted coiling. They mildly suggest that CE-MRA might be superior to TOF-MRA in these cases, as the latter seems to be more prone to artifacts from the stent, thus resulting in difficulties to evaluate the parent artery and the aneurysm neck.

The same holds true for flow diverter stents, which are composed of braided strands of cobalt chromium and platinum and 4 radio-opaque platinum markers. In a recent study on patients treated with flow diverter stents, Attali et al found that at 3T, aneurysm recurrence can be detected using CE-MRA with a sensitivity of 83% and a specificity of 100% when compared with TOF-MRA with sensitivity and specificity values of 50%

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**Table 1. Pooled Diagnostic Metrics of TOF-MRA vs CE-MRA**

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Journal</th>
<th>TOF-MRA, %</th>
<th>CE-MRA, %</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sensitivity</td>
<td>Specificity</td>
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<tr>
<td>Kwee and Kwee</td>
<td>2007</td>
<td>Neuroradiology</td>
<td>83.3</td>
<td>90.6</td>
</tr>
<tr>
<td>Weng et al</td>
<td>2008</td>
<td>Interv Neuroradiol</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>van Amerongen et al</td>
<td>2014</td>
<td>AJNR</td>
<td>86</td>
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CE-MRA indicates contrast-enhanced magnetic resonance angiography; and TOF, time-of-flight.
and 100%, respectively. However, both techniques performed poorly with regard to the evaluation of the vessel lumen. Time-resolved CE-MRA also showed better results than TOF-MRA (sensitivity of 96% and specificity of 85%) for aneurysm occlusion confirmation but overestimated luminal stenosis and demonstrated lower quality vessel reconstruction images when compared with DSA.

In clinical practice, imaging follow-up of patients with stents always requires at least 1 DSA examination, often performed between 6 and 12 months after the embolization, when stopping 1 antiplatelet therapeutic is considered. An MRA is simultaneously performed for further comparison in follow-up imaging. In case of in-stent stenosis or no good flow through the stent seen on MRA, a new DSA will be necessary to confirm or refute MRA findings. If the diagnosis of in-stent stenosis pattern is confirmed, a close follow-up with a yearly DSA (or more in case of neurological symptoms) will monitor potential modifications. Different evolution depending on the pathomechanism of the stenosis can be observed and will determine further monitoring. Clot deposits into the stent mesh will quickly disappear after the addition of a supplementary antiaggregant (leading to space the follow-up), whereas in the case of endothelial hyperplasia, the stenosis will continue to increase (leading to pursue the close follow-up).

Drawing a parallel between the WEB device and stents of equivalent composition, it seems reasonable that the same artifacts will affect MR images. One study assessed CE-MRA value on 15 patients treated with the WEB device, which is composed of nitinol with distal platinum markers. It concluded that CE-MRA failed to identify 3 out of 5 inadequately occluded aneurysms. Consequently, DSA remains the method of choice to follow aneurysms treated with the WEB device. A CE-MRA can be obtained in conjunction with DSA to serve as a baseline measure.

Computed Tomography Angiography
Computed tomography angiography (CTA) is a widely available, low-cost, and noninvasive method with short examination times, but imaging of coiled aneurysm is severely hampered by beam-hardening artifacts caused by the platinum coil mass. Thus, CTA is not suitable for coiled aneurysm follow-up, and DSA remains required in case of magnetic resonance imaging contraindication.

Few data exist on the value of CTA for the follow-up of aneurysms treated with stents, flow diverters, and flow disrupters, and if CTA is to be an alternative to DSA for surveillance and restenosis detection, the utility of this method in these instances will have to be determined. Studies focused on the agreement between CTA and DSA for in-stent evaluation. However, 64 multidetector CTA suffered from less artifacts induced by stents than TOF-MRA at 3T. In the near future, the development of novel metal artifact-reduction algorithms or use of dual-energy CT may increase CTA significance.

Still, flat-panel detector CTA using intra-arterial or preferentially intravenous contrast medium (for noninvasivity) is increasingly used for visualization of stent devices and aneurysm lumen analysis. It allows assessment of wall apposition and kinking of stents, along with intrasacular flow, with high-resolution directly in the angiography suite. Applied to WEB, it allows determination of the aneurysm occlusion and of the device position and deployment.

Data are scarce on this topic, and controlled studies with larger patient numbers are needed to assess both CTA and DSA accuracies and limitations.

| Table 2. Imaging Modalities Accuracies for Follow-Up in Regard to the Device Used |
|---------------------------------|-------|-------|-------|-------|-------|
| Coils                           | CE-MRA| TOF-MRA| Radiographs | CTA |
| Stent                           | +++   | ++     | +       | ?    |
| Flow diverter                   | +++   | +      | ?       | +    |
| Flow disrupter                  | +++   | +      | ?       | ?    |

+++ indicates excellent accuracy, recommended modality for routine follow-up; ++, moderate accuracy, can be used in specific cases; +, low accuracy, limited place in routine actually; ? not evaluated; CE-MRA, contrast-enhanced magnetic resonance angiography; CTA, computed tomographic angiography; DSA, digital subtraction angiography; and TOF, time-of-flight.
performance in aneurysm follow-up after stent or intrasacral disrupter device use, and specificity for aneurysm remnants and intimal hyperplasia in comparison with other imaging methods, DSA and MRA in particular.

Other Techniques
Plain skull x-rays and transcranial color-coded duplex sonography have also been proposed for the detection of aneurysm recurrence after coil embolization. Radiographs evaluate the compaction of the coil mass in comparison with a baseline image. Although it seems to be an effective and quick test, it was shown to be less accurate than MRA. For its part, transcranial sonography have also been proposed for the detection of aneurysm clipping versus neurological clipping of ruptured cerebral aneurysms: a 10-year follow-up of the UK cohort of the International Subarachnoid Aneurysm Trial (ISAT). Lancet. 2015;385:691–697. doi: 10.1016/S0140-6736(14)60795-2.


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Topical Reviews

颅内动脉瘤血管内治疗后的影像随访
原因、时间和方式

动脉瘤的治疗致力于预防动脉瘤的破裂（对于未破裂的动脉瘤）和再出血（对于已破裂的动脉瘤）。在许多动脉瘤治疗中心，血管内栓塞已经成为治疗大部分颅内动脉瘤的一线治疗方案。与传统手术治疗方式相比，这种方法方式实现了较低的发病率和死亡率

尽管血管内治疗能够成功地提高患者的康复速度，但是，自这项技术被应用以来，耐久性一直被认为是它的致命弱点。事实上，在血管内治疗（endovascular treatment, EVT）后，大约 20% 的患者会发生动脉瘤或者动脉瘤颈部重新开放，这迫使其中大约一半的患者需要再次治疗以获得长期预防出血的保护

除了镍铂弹簧圈的标准弹簧圈栓塞之外，其他几种技术也越来越成熟，如表面涂层弹簧圈（如聚乙烯涂层弹簧圈或凝胶涂层弹簧圈）、球囊辅助栓塞、支架辅助栓塞、血流分流器以及最近新研发的血管断流器，这大大地扩展了神经介入医生可以提供的治疗方案

每项治疗技术都有它自己的优点和缺点，因此所使用的材料的物理性质对决定最优的影像检查形式至关重要

所有存在颅内动脉瘤的患者所关心的另一个问题是新发（即从头发生的）动脉瘤的外观，大约有 5%～10% 的患者会出现新发动脉瘤。虽然许多新发动脉瘤的尺寸都较小，但是一些具有出血风险的新发动脉瘤仍需要治疗。所以，对这些患者来说，必须要进行影像随访以发现和跟踪动脉瘤的发展

EVT 后存在动脉瘤复发和新发动脉瘤的可能性，为了在必要时采取早期预防性治疗，就需要进行影像随访。由于许多接受动脉瘤栓塞治疗的患者的预期寿命较长（例如，参与 ISAT 试验的患者的平均年龄是 52 岁），所以这一点显得尤为重要

对动脉瘤患者来说，常规需要了解和理解的内容包括何时进行随访、随访需要持续的时间以及如何进行随访。本综述以下内容将阐述和讨论目前颅内动脉瘤 EVT 后的随访策略

何时随访及持续多久?

了解了目前没有指南和科学数据定义何时进行随访和随访持续多久的最佳制度。因此，不同的国家和不同的中心采取了大量不同的方案。在制定一个特定的随访方案时，主要需要考虑动脉瘤的特性、患者的预期寿命、用于治疗动脉瘤的装置和患者的心理状态来选择最佳的随访方案需要平衡避免出血，尽量减少不必要的费用和减少患者的焦虑情绪这三方面

一般来说，EVT 后的首次随访通常安排在术后 3～6 个月，后续的随访的时间间隔不定，这由该中心的制度和患者的动脉瘤的特性所决定，并且，经典的随访方案应包括一次在术后 12～24 个月的随访
一次在术后3~5年的中期随访。EVT后的第一年至关重要，因为大多数动脉瘤复发就发生在这一时期，这证明了影像随访的合理性。随访的形式和时间间隔可以根据随访的目标和患者的风险因素来定制。图1是根据文献的主要数据所提出的一个经典的随访方案，该方案重点关注动脉瘤的闭塞程度（闭塞、残余颈部和残余动脉瘤）和动脉瘤的进展，尤其是如果存在动脉瘤进展。

图1建议的适应于不同闭塞等级的随访方案。注：DSA：数字减影血管造影；NR：残余颈部；*特别是如果存在危险因素（尺寸>10 mm；3~5年的NR；栓塞后5年内再治疗）。
塞的动脉瘤的 meta 分析，通过与 DSA 相比，证明了 MRA 诊断的准确性 (图 1)。5-9 项 meta 分析中的其中 3 项比较了 TOF-MRA 和 CE-MRA 26-28，提示二者同等适用于动脉瘤的检测，且对检测动脉瘤的复发具有高敏感性和高特异性 (表 1)。虽然 MRA 可能会忽略残余动脉瘤，但我余动瘤尺寸小，通常不需要再治疗 29。

至于 TOF-MRA，直接对比的结果显示，3T 磁场与 1.5T 磁场相比能更好地检测出动脉瘤复发，且具有较好的观察者间一致性 30，尽管先前发表的一个大型队列研究的结果表明两种磁场的性能相似，但是它对比了 2 组不同的患者。在 TOF-MRA 中，由于铂的存在，弹簧圈是可见的且以伪影产生流空效应的形式出现 (在 CE-MRA 中，弹簧圈是缺失的或不可见的)。这些轻微的伪影并不阻碍动脉瘤复发的鉴定，且伪影在 3T 磁场中比 1.5T 磁场中低 26-28，因为高磁场提供更好的信号 / 噪声比和一个更好的空间分辨率。

至于 CE-MRA，在 3T 高场观察到高性能趋势 26-28，且与 TOF-MRA 相比，CE-MRA 能更好地鉴别残余颈动脉和残余动瘤 29。这个方面需要进一步研究。

在临床实践中，目前没有确切的推荐且存在不同影像随访形式，从有的中心仅使用 3T-MRA 到有的中心常规使用 DSA。但是，每一例由 MRA 检测出的动脉瘤复发的患者都需要做 DSA，因为他们可能需要再次接受治疗。

其他栓塞装置

在 MRA 图像中支架表现为一种微小的腔内流空信号，伴有或目标标记物或支架材料本身的伪影 (图 2)。因为磁敏感伪影的混合和法拉第笼效应，支架的磁共振成像仍然是很困难的。这 2 种影像可能会导致出现闭塞或支架植入后的动脉假性狭窄 34-35。一项研究评估了 MRA 对支架辅助栓塞治疗动脉瘤的无创性随访的价值 34-35。这些研究认为 CE-MRA 可能优于 TOF-MRA，因为后者似乎更容易从支架产生伪影，从而导致难以评估载瘤动脉和瘤颈。

这同样适用于血管分流器。它是通过将弹簧圈放在动脉瘤的远端和近端动脉之间来实现的。最近的一项关于血管分流器支架治疗患者的收益率，Attali 等 36 发现，在 3T 磁场下，使用 TOF-MRA 检测出动脉瘤复发，其敏感性和特异性分别为 83% 和 100%，而 TOF-MRA 的敏感性和特异性分别为 50% 和 100%。然而，这种技术在评估血管管腔方面的表现并不佳。时间分辨 CE-MRA 在证实动脉瘤闭塞方面优于 TOF-MRA (敏感性 86%，特异性 65%)，但是与 DSA 相比，时间分辨 CE-MRA 高估了血管狭窄且血管重建的图像质量较低 37。

在临床实践中，支架植入患者的影像随访通常需要至少 1 次的 DSA 检查，且通常在检测后的 6 - 12 个月之间进行，此时考虑停止抗血小板治疗。在影像随访时，为了进一步比较，MRA 和 DSA 同时进行。如果 MRA 发现支架内再狭窄或没有很好的血流通过支架，那么在支架内再狭窄的确诊被证实，则需要更加密切的随访。每年 1 次 DSA 检查 (或在出现神经系统症状的患者中更加频繁) 将监测其变化趋势。根据假性动脉瘤的病理机制不同，可以观察到狭窄的不同进展，然后确定进一步监测方法。在加脉血栓栓塞后聚药，沉积在支架网中的血块将快速消失 (随后导致空间形成)，而在血管内皮再生的情况下，狭窄将会继续增加 (随后导致更加狭窄)。

CTA

CTA 是一种广泛应用、成本低和检查时间短的无创性方法，但是由铂弹簧圈引起的线束硬化伪影是造成栓塞的动脉瘤成像的严重障碍。因此，CTA 不适用于弹簧圈栓塞动脉瘤的影像随访，并且如果有磁共振成像禁忌证则仍然需要 DSA 检查。

很少有关于 CTA 评价支架、血流分流器和血流断流器治疗动脉瘤的数据存在，并且如果 CTA 是一种替代 DSA 的监测和检测再狭窄的手段，那么在这些情况下 CTA 的效用将会被确定。研究主要集中在 CTA 和 DSA 评估支架的一致性 40。但是，3T TOF-MRA 相比，64 排 CTA 产生较少的由支架诱导的伪影 40，对于 TOF-MRA 可以结合 DSA 作为基线评估的方法。

表 1 TOF-MRA vs CE-MRA 的合并诊断指标

<table>
<thead>
<tr>
<th>作者</th>
<th>年份</th>
<th>杂志</th>
<th>TOF-MRA, %</th>
<th>CE-MRA, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwee 和 Kwee</td>
<td>2007</td>
<td>Neuroradiol</td>
<td>83.3</td>
<td>90.6</td>
</tr>
<tr>
<td>Weng 等</td>
<td>2008</td>
<td>Interv Neuroradiol</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>van Amerongen 等</td>
<td>2014</td>
<td>AJNR</td>
<td>86</td>
<td>88</td>
</tr>
</tbody>
</table>

注：CE-MRA；增强磁共振血管造影；TOF：时间飞跃。

表 2 使用不同装置后不同影像随访方式的精确度

<table>
<thead>
<tr>
<th>装置</th>
<th>DSA</th>
<th>CE-MRA</th>
<th>TOF-MRA</th>
<th>X 线平片</th>
<th>CTA</th>
<th>91.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>弹簧圈</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>?</td>
<td>96</td>
</tr>
<tr>
<td>支架</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>?</td>
<td>+</td>
<td>88</td>
</tr>
<tr>
<td>血流分流器</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>血流断流器</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

注：+++ 表示非常精确，推荐作为常规随访方式；++ 表示中度精确，可在特定的情况下使用；+ 精确度低，在实际应用中有限制；? 未评估；CE-MRA：增强磁共振血管造影；CTA：计算机断层扫描血管造影；DSA：数字减影血管造影；TOF：时间飞跃。
机断层扫描（computed tomography，CT）可能增加 CTA 的在该方面应用意义。不过，使用动脉或静脉注射造影剂的平板探测器 CTA 越来越多地被应用于支架的可视化和动脉瘤管腔分析。平板探测器 CTA 在造影条件下具有高分辨率，可用于评估支架的贴壁和扭曲情况以及囊内血流。应用在 WEB 上，平板探测器 CTA 可以确认动脉瘤闭塞与支架位置和效果。

这方面的数据比较缺乏，因此需要大样本的对照研究来评估 CTA 在支架或囊内断层治疗后的动脉瘤的随访中的表现，以及 CTA 与其他成像方法相比，特别是与 DSA 和 MRA 相比，它对残余动脉瘤和内膜增生的检测特异性。

其他技术

头颅 X 线平片和经颅彩色多普勒超声也被提出用于检测弹簧圈栓塞后的动脉瘤复发。可通过将头颅 X 线平片与基础图像相比来评估弹簧圈的紧贴程度。虽然这似乎是一个快速和有效的检测方法，但是与 MRA 相比它的准确性大大降低。平板探测器 CTA 在造影剂注射后会增加 CTA 和 MRA 在动脉瘤弹簧圈栓塞后合适的影像随访形式，但是 DSA 对评估其他治疗装置来说仍然是必要的。

结论

血管内治疗后的动脉瘤影像随访对发现有出血风险的状况十分重要（动脉瘤复发和新发动脉瘤）。虽然在 EVT 治疗的第一年影像随访十分重要，但是似乎在中期和长期一直延续影像随访也很有意义。目前没有关于监测频率和采取影像随访的指南，但是监测是适用于一个个别例的基础之上。MRA 是动脉瘤弹簧圈栓塞后合适的影像随访形式，但是 DSA 对评估其他治疗装置来说仍然是必要的。

表 2 总结了不同治疗装置的不同影像随访形式的诊断精确度。

![图 2 一例支架辅助栓塞动脉瘤的 DSA 和 MRA 图像。(A) 一位 51 岁女性患者左眼左侧后上内动脉瘤弹簧圈栓塞后的造影图像（A），支架辅助栓塞治疗后的造影图像（B）显示稳定和完全的动脉瘤闭塞。2 个箭头所指的是支架的两端。同时 TOF-MRA（C）和 CE-MRA（D）显示稳定和完全的动脉瘤闭塞，但是颈内动脉存在不真实的缩小（箭头所指）。](image)

参考文献

颅内动脉瘤血管内治疗后的影像随访
原因、时间与方式

Imaging Follow-Up of Intracranial Aneurysms Treated by Endovascular Means
Why, When, and How?

Sebastien Soize, MD; Matthias Gawlitza, MD; Hélène Raoult, MD, PhD; Laurent Pierot, MD, PhD

（Stroke. 2016;47:1407-1412. 南京军区南京总院神经内科 王芳 译 刘新峰 校）

动脉瘤的治疗致力于预防动脉瘤的破裂（对于未破裂的动脉瘤）和再出血（对于已破裂的动脉瘤）。在许多动脉瘤治疗中心，血管内栓塞已经成为治疗大部分颅内动脉瘤的一线治疗方案。与传统手术治疗方式相比，这种微创方式实现了较低的发病率和死亡率1-4。尽管血管内治疗能够成功地提高患者的康复速度，但是，自这项技术被应用以来，耐久性一直被认为是它的致命弱点。事实上，在血管内治疗（endovascular treatment，EVT）后，大约20%的患者会发生动脉瘤或者动脉瘤颈部重新开放，这迫使其中大约一半的患者需要再次治疗以获得长期预防出血的保护5。除了这个方面，有研究已经报道EVT后动脉瘤破裂的出血风险较低，并且ISAT（the International Subarachnoid Aneurysm Trial）队列的长期临床随访结果显示，似乎随着时间的推移，EVT与手术相比的临床优势逐渐显现6, 7。

在CARAT（the Cerebral Aneurysm Rerupture after Treatment）研究中，弹簧圈栓塞后的出血率为0.11%（平均随访时间4.4年），而在ISAT研究中，弹簧圈栓塞后的年出血率为0.08%8。在一项大型的单中心研究中，即BRAT（the Barrow Ruptured Aneurysm Trial），弹簧圈栓塞组在血管内治疗后6年内未观察到出血，但是这些患者中有4.6%的患者退出了研究9。

因此，有人可能会对进行影像随访的临床实用性提出疑问，这取决于如何平衡EVT后较小的出血风险与随访的成本效益。虽然这些研究的主要终点事件是临床事件，但是需要注意的是，大部分EVT患者是由主治医生决定是否进行影像随访。例如，在ISAT研究中，EVT组88.2%的患者（881例）进行了随访造影，并在不同的时间间隔后重复造影10。

此外，值得我们注意的是，在这些研究的患者的随访过程中，有些患者在没有任何出血的情况下接受了再次治疗，所以如果这些患者没有被随访，那么动脉瘤破裂出血可能会更加普遍11。例如，在ISAT研究中，EVT组8.3%的患者在右再出血先兆的情况下接受再次治疗，但他们中只有0.6%的患者是由于再出血而接受后期的再次治疗10。

研究人员已经提出了几种机制以解释动脉瘤复发，包括弹簧圈贴合紧密、动脉瘤生长、弹簧圈沿着动脉瘤壁移动、弹簧圈侵入到部分栓塞动脉瘤的血栓物质和动脉瘤壁的异常炎症反应导致动脉瘤生长12。

由于动脉瘤复发是EVT的主要缺陷，所以在过去的十年中研究者开发了一些创新性技术用以提高EVT的长期稳定性。新技术用以提高动脉瘤栓塞效率和动脉瘤囊内的弹簧圈密度，以及治疗简单弹簧圈栓塞后易发的复杂性动脉瘤（巨大和/或宽颈和/或分叉的动脉瘤）13, 14。

除了裸铂弹簧圈的弹簧圈栓塞之外，其他几项技术也越来越成熟，如表面涂层弹簧圈（如聚乙烯/聚乳酸涂层弹簧圈或水凝胶涂层弹簧圈）、球囊辅助栓塞、支架辅助栓塞、血流分流器以及最近新研发的血流断流器，这大大地扩展了神经介入医生可以提供的治疗方案15。

研究人员已经提出了几种机制以解释动脉瘤复发，包括弹簧圈贴合紧密、动脉瘤生长、弹簧圈沿着动脉瘤壁移动、弹簧圈侵入到部分栓塞动脉瘤的血栓物质和动脉瘤壁的异常炎症反应导致动脉瘤生长12。

对动脉瘤患者来说，常规需要了解和理解的内容包括何时进行随访、随访需要持续的时间以及如何进行随访。本综述以下内容将阐述和讨论目前颅内动脉瘤EVT后的随访策略。

何时随访及持续多久？
据了解，目前没有指南和科学数据定义何时进行随访和随访持续多久的最佳制度。因此，不同的国家和不同的中心采取了大量不同的方案。在制定一个特定的随访方案时，主要需要考虑动脉瘤的特点、患者的预期寿命、用于治疗动脉瘤的装置和患者的心理状态。最佳的随访方案需要平衡避免出血，尽量减少不必要的费用和减少患者的焦虑情绪这三点。

EVT后存在动脉瘤复发和新发动脉瘤的可能，为了在必要时采取早期预防性治疗，就需要进行影像随访。由于许多接受动脉瘤栓塞治疗的患者的预期寿命较长（例如，参与ISAT试验的患者的平均年龄是52岁），所以这一点显得尤为重要1。

对动脉瘤患者来说，常规需要了解和理解的内容包括何时进行随访、随访需要持续的时间以及如何进行随访。本综述以下内容将阐述和讨论目前颅内动脉瘤EVT后的随访策略。
一次在术后 3~5 年的中期随访。EVT 后的第一年至关重要，因为大多数动脉瘤复发就发生在这一时期，这证明了影像随访的合理性。虽然理想的检查频率和随访持续时间没有确切的定义，但是随访的频率越高往往意味着患者有复发的危险因素（如残余动脉瘤、广泛和术后不完全栓塞）。

随访的影像形式和时间间隔可以随着时间的推移而改变，这取决于动脉瘤的栓塞程度和动脉瘤的进展，尤其是如果存在动脉瘤进展。图1是根据文献的主要数据所提出的一个经典的随访方案，该方案重点关注动脉瘤的闭塞程度（闭塞、残余颈部和残余动脉瘤）和如何处理生长的囊或颈部。对采用无创技术（如磁共振血管造影（magnetic resonance angiography, MRA））的患者而言，如果有小的残余颈部的出现或进展，则将进行数字减影血管造影（digital subtraction angiography, DSA）以核实诊断和准确估计残余颈部的大小。如果相关较好，那么随后进行无创的更密切监测。

关于弹簧圈栓塞后随访应持续多久这个问题，目前的文献结果表明 3~5 年的随访时间可能并不足以检测到相关的动脉瘤复发。Lecler 等发表的一项前瞻性队列研究和 meta 分析表明，在 12.4% 的治疗动脉瘤中，动脉瘤复发在中期（栓塞后 3~5 年）和长期随访（栓塞后 10 年以上）中被检出。动脉瘤复发的危险因素包括动脉瘤尺寸 >10 mm，在 3~5 年内残余（magnetic resonance, MR）随访中为 2 级动脉瘤（即残余颈部）（由改良的 Raymond 量表分级）和在早期栓塞后 5 年内接受再次治疗。非常推荐 Lecler 等发表的结论，即存在这些动脉瘤复发危险因素的患者中，应考虑随访 10 年或者更长的时间。

由于动脉瘤长期随访是相对较新的治疗技术，所以目前没有关于这些方法治疗动脉瘤的长期 (> 10 年) 稳定性数据。由于动脉瘤颈部沿金属表面覆盖了内膜，所以这些动脉瘤应该不太可能在较高术后期复发；但是，目前的有关血流分流器和 WEB 装置的长期随访数据相对较少。由于栓塞后 5 年内没有重新治疗的报道，我们建议在栓塞后 5 年内观察和随访。

我们在随访动脉瘤治疗后的患者过程中所关心的另一个问题是新发动脉瘤的进展。Kemp 等的研究中，44% 的患者在长期随访过程中出现新发动脉瘤，而之前提到的 Lecler 等的研究中为 9.1%。虽然新发动脉瘤并不少见，但是其诱发蛛网膜下腔出血的风险相对于相同大小的、低的、首次发现的未破裂的囊状动脉瘤的诱发风险更大。因此，存在 2 种方法治疗新发动脉瘤。某些中心提出更密切的监测以在新发动脉瘤的大小迅速增长的情况下采取治疗，而其他中心提出系统性治疗新发动脉瘤。

### 如何随访？

#### DSA

DSA 是评估栓塞后动脉瘤闭塞的金标准。由于 DSA 的高分辨率和高可操作性，所以 DSA 被允许用于评估动脉瘤中的血流返。在动脉瘤分级上，Raymond 量表应用最为广泛：1 级表示完全闭塞，2 级表示残余颈部，3 级表示残余动脉瘤。

#### MRA

MRA 是首选的无创性成像技术，除了铁磁性金属植入物和心脏起搏器以外几乎没有禁忌证。MRA 可进行钆增强 MRA（contrast-enhanced MRA, CE-MRA）或时间飞跃 MRA（time-of-flight MRA, TOF-MRA）。TOF-MRA 不需要使用钆就能描绘动脉的血流流动。TOF-MRA 常见的缺点是对于血流缓慢的和湍流的血流的敏感性较低，这就是为什么可能会出现一个敏感性较低的和慢血流的残余动脉瘤。其次，T1 加权高信号的亚急性血栓可模拟囊内残余血流。另一个缺点是需要耗时几分钟来获得高分辨率 TOF-MRA 图像，这使得 TOF-MRA 更易产生运动伪影。相反，使用 CE-MRA 会增加成像成本和需要对比时间连同窄扫描间隔。

### 栓塞的动脉瘤

由于治疗结果可能受到随访影像的影响，参考 5 项主要的有关栓塞动脉瘤的方案。注：DSA：数字减影血管造影；NR：残余颈部。特别是如果存在危险因素（尺寸 >10 mm；3~5 年的 NR；栓塞后 5 年内再治疗）。

![图1 建议的适应于不同闭塞等级的随访方案](image)
塞的动脉瘤的 meta 分析，通过与 DSA 相比，证明了 MRA 诊断的准确性（图 1）14-23。5 项 meta 分析中的其中 3 项比较了 TOF-MRA 和 CE-MRA24-26。提出二者同等适用于动脉瘤的检测，且对检测动脉瘤的复发具有高敏感性和高特异性（表 1）。虽然 MRA 可能会忽略残余动脉瘤，但我认为动脉瘤尺寸太小，通常不需要再治疗28。

至于 TOF-MRA，直接对比的结果显示，3T 高场与 1.5T 场相比能更好地检测出动脉瘤复发，且具有较好的观察者间一致性29。尽管先前发表的一个大型队列研究的结果表明两种磁场的性能相似，但是它对比了 2 组不同的患者30。在 TOF-MRA 中，由于铜的存在，弹簧圈是可见的且以伪影产生流空效应的形式出现（在 CE-MRA 中，弹簧圈是缺失的或不可见的）31。这些轻微的伪影并不阻碍动脉瘤复发的鉴定，且伪影在 3T 的磁场中比 1.5T 的磁场中低25-27，因为高场强提供了更好的信号/噪声比和一个更好的空间分辨率。

至于 CE-MRA，在 3T 高场观察到高性能趋势26-28，且与 TOF-MRA 相比，CE-MRA 能更好地鉴别残余颈和残余动脉瘤33。这需要进一步研究。

CE-MRA 和 DSA 的合并诊断指标

### 表 1 TOF-MRA vs CE-MRA 的合并诊断指标

<table>
<thead>
<tr>
<th>作者</th>
<th>年份</th>
<th>杂志</th>
<th>TOF-MRA</th>
<th>CE-MRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwee 和 Kwee27</td>
<td>2007</td>
<td>Neuroradiology</td>
<td>83.3</td>
<td>90.6</td>
</tr>
<tr>
<td>Weng 等28</td>
<td>2008</td>
<td>Interv Neuroradiol</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>van Amerongen 等31</td>
<td>2014</td>
<td>A.JNR</td>
<td>86</td>
<td>66</td>
</tr>
</tbody>
</table>

注：TOF-MRA：增强磁共振成像；CE-MRA：增强磁共振血管成像；DSA：数字减影血管造影；TOF：时间飞跃。

CTA

CTA 是一种广泛应用、成本低和检查时间短的无创性方法，但是由铜弹簧圈引起的线束硬化伪影是造成双极的动脉瘤成像的重要障碍。因此，CTA 不适用于弹簧圈夹闭动脉瘤的影像随访，并且如果有磁共振或 CT 磁共振成像禁忌证则仍然需要 DSA 检查。

很少有关于 CTA 随访评价支架、血流分流器和血流断流器治疗动脉瘤的数据存在，并且如果 CTA 是一种替代 DSA 的监测再狭窄的手段，那么在这些情况下 CTA 的效用将会被确定。研究主要集中在 CTA 和 DSA 评估支架的一致性40。但是，3T TOF-MRA 相比，64 排 CTA 产生较少的由支架诱导的伪影41。

在不久的将来，开发新型金属伪影减少算法42 或使用双能量计算

### 表 2 使用不同装置后不同影像随访方式的精确度

<table>
<thead>
<tr>
<th>装置</th>
<th>DSA</th>
<th>CE-MRA</th>
<th>TOF-MRA</th>
<th>X 线平片</th>
<th>CTA</th>
<th>91.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>弹簧圈</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>?</td>
<td>96</td>
</tr>
<tr>
<td>支架</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>88</td>
</tr>
<tr>
<td>血流分流器</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>88</td>
</tr>
<tr>
<td>血液分流器</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>88</td>
</tr>
</tbody>
</table>

注：+++：非常精确，推荐作为常规随访方式；++：中度精确，可在特定的病例中使用；+：精确度低，在实际应用中有限；？：未评估；CE-MRA：增强磁共振血管成像；CTA：计算机重建扫描血管造影；DSA：数字减影血管造影；TOF：时间飞跃。
机断层扫描（computed tomography, CT）可能增加 CTA 的在这方面应用意义 43。不过，使用动脉或静脉注射造影剂的平板探测器 CTA 越来越多地被应用于支架的可视化和动脉瘤管腔分析 44。平板探测器 CTA 在造影条件下具有高分辨率，可用于评估支架的贴壁和扭曲情况以及囊内膜增生的检测特异性。这方面的数据比较缺乏，因此需要大样本的对照研究来评估 CTA 在支架或囊内断流器治疗后的动脉瘤的随访中的表现，以及 CTA 与其他成像方法相比，特别是与 DSA 和 MRA 相比，它对残余动脉瘤和内膜增生的检测特异性。

其他技术

头颅 X 线平片和经颅彩色多普勒超声也被提出用于检测弹簧圈的紧贴程度。虽然这似乎是一个快速和有效的检测方法，但由于它对弹簧圈移动的敏感度低，以及对血管内膜和支架的识别能力差，因此在支架辅助栓塞治疗后合适的影像随访形式，但是 DSA 对评估其他治疗装置来说仍然是必要的。

图 2 一例支架辅助栓塞动脉瘤的 DSA 和 MRA 随访图像。一位 51 岁女性患者的未破裂的右侧颈内动脉动脉瘤在治疗前的造影图像(A)。支架辅助栓塞治疗后 1 年的造影图像(B)显示稳定和完全的动脉瘤闭塞，但是颈内动脉存在不真实的缩小(假狭窄)(箭头所指)。CE-MRA(D)显示稳定和完全的动脉瘤闭塞，但是颈内动脉动脉瘤在治疗前的造影图像(A)。支架辅助栓塞治疗后 1 年的造影图像(B)显示稳定和完全的动脉瘤闭塞以及载瘤动脉通畅。2 个箭头所指的是支架的两端。同时 TOF-MRA(C)和 DSA 也显示完全的动脉瘤闭塞以及载瘤动脉通畅。