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Contrast Enhanced Pulmonary Magnetic Resonance Angiography for Pulmonary Embolism: Building a Successful Program

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Abstract

The performance of contrast enhanced pulmonary magnetic resonance angiography (MRA) for the diagnosis of pulmonary embolism (PE) is an effective non-ionizing alternative to contrast enhanced computed tomography and nuclear medicine ventilation/perfusion scanning. However, the technical success of these exams is very dependent on careful attention to the details of the MRA acquisition protocol and requires reader familiarity with MRI and its artifacts. Most practicing radiologists are very comfortable with the performance and interpretation of computed tomographic angiography (CTA) performed to detect pulmonary embolism but not all are as comfortable with the use of MRA in this setting. The purpose of this review is to provide the general radiologist with the tools necessary to build a successful pulmonary embolism MRA program. This review will cover in detail image acquisition, image interpretation, and some key elements of outreach that help to frame the role of MRA to consulting clinicians and hospital administrators. It is our aim that this resource will help build successful clinical pulmonary embolism MRA programs that are well received by patients and physicians, reduce the burden of medical imaging radiation, and maintain good patient outcomes.

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Keywords

magnetic resonance imaging; magnetic resonance angiography; pulmonary embolism; artifacts

Introduction

The importance of identifying pulmonary artery embolism (PE) is well established (1-8). Unfortunately, symptoms are often non-specific, making a diagnosis of PE very challenging, based upon clinical presentation alone. As a result, imaging is frequently requested to exclude pulmonary embolus and the prevalence of disease in these patients is very low, often 5-10% (9).

Pulmonary CTA has become the widely accepted reference standard for diagnosis of PE. It is widely available in the emergency setting. CTA also requires only very short scan times using multidetector scanners, an important advantage when imaging severely dyspneic patients. CT also allows for the assessment of other possible causes for the patient's symptoms. However, CTA has important drawbacks. First, it requires the use of ionizing radiation that can increase the risk of malignancy later in life (10). This is especially troubling when imaging young patients. Second, it involves the use of iodinated contrast material that carries the risk of nephrotoxicity and occasional severe allergic reactions.

An alternative to CTA is contrast enhanced magnetic resonance angiography (MRA). With recent improvements in scanner technology, MRA shows tremendous promise in the task of detecting pulmonary embolism (11,12). MRA requires neither the use of ionizing radiation nor the use of iodinated contrast. These advantages make possible the routine use of multiphasic acquisitions and the potential for repeated contrast injections. This greater flexibility can lead to improved technical success rates through multi-phase acquisitions during a contrast bolus or the use of a repeated bolus and acquisition when the initial acquisition in the exam is compromised by poor bolus timing or patient motion (12).

There are, however, important disadvantages to MRA that have prevented it from being widely adopted for evaluation of pulmonary embolism. MRI examinations tend to be significantly longer than CT exams, limiting the suitability of long MRI protocols for severely dyspneic patients. The lower spatial resolution of MRA compared with CTA (~1-2 mm vs. <1 mm) has likely contributed to lower sensitivity for the detection of subsegmental pulmonary emboli (13-16). Further, relative lack of familiarity with MRA for this purpose may also contribute to technical inconsistency, the primary reason for the underperformance of MRA for the detection of subsegmental emboli in the PIOPED III study (17-20). Pulmonary MRA artifacts are also very different from those seen on CTA, and may reduce the accuracy of interpretation by radiologists less experienced with MRA. The sensitivity for MRA

Despite these challenges, we believe that pulmonary MRA is now emerging as a sufficiently mature technology to be used as a first line alternative to pulmonary CTA for the primary diagnosis of pulmonary embolism. Since 2008, our institution has offered a clinical pulmonary MRA program that has been embraced by our referring clinicians, including

physicians in the Department of Emergency Medicine (DEM). To date, we have scanned more than 700 patients with MRA to evaluate for pulmonary embolus using a simple and robust imaging protocol requiring approximately 10 minutes of table-time. MRA is typically used for patients for whom CTA is contraindicated or who are more sensitive to ionizing radiation (children and younger adults). The purpose of this article is to share our experience and to provide practicing radiologists, emergency medicine (EM) physicians, MRI technologists, radiology department administrators, radiology residents, and MRI physicists with the tools to set up a successful clinical pulmonary MRA program at their own institutions.

Imaging Protocol

Overview

Our pulmonary MRA protocol consists of six breath-holds, each lasting 15-19 seconds (Figure 1). The total time on the table is less than 10 minutes (often as low as 5-6 minutes), only slightly longer than the table-time required for pulmonary CTA. The core angiographic acquisition is a rapid heavily T1-weighted 3D spoiled gradient echo (SGRE) sequence:

1. Three-plane single-shot fast spin-echo (SSFSE) localizers
2. Pre-contrast T1 weighted 3D SGRE
3. Pulmonary arterial phase T1-weighted 3D SGRE
4. Immediate post-contrast T1-weighted 3D SGRE
5. Low flip angle post-contrast T1-weighted 3D SGRE
6. T1-weighted 2D axial or 3D SGRE with fat saturation

Fluoro-triggering combined with elliptical centric k-space filling is recommended for timing of the pulmonary arterial phase. The lower flip angle of Acquisition #5 is chosen to better approximate the Ernst angle for blood with the lower intravascular contrast agent concentration at the time of the acquisition (~1-2 min following injection). Acquisitions #4 and #5 may also be helpful if transient effects related to the contrast agent kinetics decrease the diagnostic quality of the pulmonary arterial phase acquisition (Acquisition #3) (11,21,22). A final post-contrast T1-weighted 3D spoiled gradient echo acquisition with fat saturation is performed to evaluate for any enhancing soft tissue abnormalities in the chest wall or upper abdomen. Typical acquisition parameters for pulmonary MRA (Acquisitions #2-5) are provided in Table 1. It would be relatively easy to include an additional, dedicated time-resolved dynamic perfusion scan prior to the pulmonary MRA itself. However, in the interest of keeping the exam time as short as possible, we did not include this in our clinical protocol. Figure 2 shows representative images from a normal patient, illustrating the full chest coverage, visualization of vessels to the subsegmental level, and the rationale for the sagittal slab excitation. Figure 3 shows examples of pulmonary embolism.

Hardware

While MRA of the pulmonary arteries can be performed at 3T – indeed, in our experience, the image quality at 3T is excellent – the majority of pulmonary MRA studies performed at

our institution are performed at 1.5T due to wider availability of these scanners. All of the MRI scanner vendors offer commercial pulse sequences that can accommodate the needs of pulmonary embolism MRA. We use 2 different models of 1.5T clinical scanners (Signa HDxt and Optima MR450w, GE Healthcare, Waukesha, WI) and use either an 8-channel coil (GE Healthcare, Waukesha, WI) or a 32-channel coil (32-channel Torso Array, NeoCoil, Pewaukee, WI; or GEMS Posterior/Large Anterior Arrays, GE Healthcare, Waukesha, WI) with 20-24 elements typically activated. Using a multichannel phased array coil with at least 8 channels facilitates the use of parallel imaging in the two phase-encoding dimensions. This helps to keep scan time to within a reasonable breath-hold (15-19 sec) without compromising spatial resolution.

Slab Excitation and Parallel Imaging

Excitation is performed in the *sagittal* plane, allowing the arms to remain at the patient's sides without any aliasing. The frequency-encoded readout direction is always oriented in the superior-inferior (SI) direction, the longest dimension of the imaging volume. We use a 2D auto-calibrated parallel imaging method (23) that results in a nominal 2-fold acceleration in each of the phase-encode dimensions (RL and AP). However, due to the need to acquire calibration data from the center of *k*-space during the scan, the net acceleration factor is ~3.7. Auto-calibrated methods (23,24) are generally preferable to methods requiring a separate calibration scan, due to potential differences in breath-hold position and potential calibration errors related to contrast administration between the calibration and the main acquisition. The scan time penalty to acquire auto-calibration data is relatively small.

The combination of a sagittal excitation slab and 2D parallel imaging makes it imperative that the entire anterior-posterior (AP) dimension of the patient is included within the prescribed field of view. If it is not, residual ghosting and noise amplification may result from the resulting ill-conditioned parallel imaging reconstruction. This is particularly problematic because these artifacts appear in the coronal plane through the middle of the imaged volume, often obscuring important lobar and segmental vessels in this region. The greatest AP dimension in most patients is through the breasts or in the lower thorax/upper abdomen. Therefore, it is important to review off-midline parasagittal and axial images through the lower thorax when prescribing the MRA volume.

In large patients or in patients who are unable to sustain a sufficient breath-hold to cover the complete AP dimension, it is important to adjust the protocol rather than allow insufficient AP coverage. We recommend decreasing the spatial resolution, either through increased slice thickness (with commensurate reduction in number of slices in the AP direction) and/or decreased number of phase encoding steps in the RL direction.

k-space Coverage and Spatial Resolution

To further minimize the number of TR intervals required, we acquire data only within an oval area in *k*-space in the two phase-encoding directions (25) and zero-fill the corners, an approach commonly referred to as “corner-cutting”. This approach leads to more isotropic spatial resolution and requires only 78% of the phase-encodes needed to sample a conventional rectangular area ($\pi/4=0.78$). A fractional echo read-out is used to minimize

both TE (decreased T2* decay and first moment related artifacts) and TR (decreased total scan time). Since a fractional readout is being used, homodyne reconstruction is needed to recover full spatial resolution in the read-out dimension. Therefore, partial Fourier sampling in either of the two phase-encoding dimensions should be avoided because it is not mathematically possible to reconstruct full resolution images in this situation – inadvertent blurring or other artifacts will result.

True spatial resolution should be approximately 2 mm in each of the phase-encoded dimensions and less than 1.5 mm in the frequency-encoded dimension. After acquisition, the dataset should be interpolated to facilitate visualization in multi-planar reformatted (MPR) images without “stairstep” artifacts (25). The most common way to interpolate images is by zero-filling k -space to a larger matrix size in all three dimensions. Scan time will depend on the size of prescribed volume, with typical acquisition (*i.e.* breath-hold) times of 14-19 seconds. Almost all patients, even those with pulmonary emboli, are able to hold their breath for this duration (12).

Contrast Injection

The injection protocol is critically important in achieving consistent high-quality images. We use 0.1 mmol/kg of gadobenate dimeglumine (Multihance, Bracco Inc, Princeton, NJ) at our institution. High relaxivity gadolinium based contrast agents (GBCA) (eg. gadobutrol (Bayer Pharmaceuticals, Wayne, NJ)) or intravascular GBCA's (eg. gadofosveset trisodium (Lantheus Medical Imaging, North Billerica, MA)) are viable alternatives. It is necessary to use a power-injector capable of injecting saline flush, and hand injection should be avoided.

The bolus length for small patients can be very short. For example, the volume of 0.1 mmol/kg of a GBCA with 0.5M concentration for a 50kg patient is only 10ml. Injected at 1.5ml/s, the bolus duration is only 6.7 seconds. Since the bolus does not disperse as broadly in the lungs as it might for aortic imaging, the bolus may be present for only a portion of the k -space acquisition. Figure 4 illustrates how washout of the contrast bolus before the end of the acquisition can cause blurring with elliptical-centric sampling. Images acquired using other sampling orders may also show artifacts from short bolus durations, but predicting their appearance is more difficult.

To avoid artifacts from mismatch of k -space sampling with the bolus duration, and to keep the injection protocol as simple as possible, we use diluted contrast media. Specifically, we use 0.1 mmol/kg of GBCA diluted with normal saline up to a total volume of 30 mL. This results in a bolus duration of 20 sec for all patients and ensures that a uniform bolus is present throughout the pulmonary arteries during the k -space acquisition. Although overall peak enhancement is reduced slightly, the total enhancement is more than sufficient to identify filling defects and the reduction in blurring ensures reliable visualization of segmental and often sub-segmental pulmonary arteries and pulmonary emboli. It should be noted that dilution of contrast is an off-label use of contrast, as is the use of commercially available GBCAs for pulmonary MR angiography. Other than 2D parallel imaging, the simple act of contrast dilution has led to the single largest improvement in image quality in our experience.

Breath Hold and Bolus Timing

Images should be acquired at end expiration when possible. Acquisition at end-expiration (not forced expiration) helps to avoid transient interruption of the contrast bolus due to influx of unenhanced blood from the inferior vena cava from an inadvertent Valsalva maneuver (26). Real-time fluoro-triggering should be used to time the contrast bolus to the pulmonary arterial phase.

Immediately after the pulmonary arterial phase acquisition, another breath-held acquisition is performed as soon as possible. While the pulmonary arterial phase acquisition is typically the most useful, this immediate post-contrast acquisition has provided superior or confirmatory visualization of vessels and emboli in many cases (27).

In addition, if the technologist feels the bolus timing is suboptimal or there is excessive motion artifact, he or she is encouraged to contact the radiologist or on-call resident to determine whether the injection should be repeated. We occasionally perform a second injection for a maximum dose of 0.2 mmol/kg (Figure 5). However, the need for repeated injections is very low and at our institution pulmonary MRA is a routine, unmonitored exam.

Image Interpretation

Overview

When interpreting a pulmonary MRA study, one may expect the arterial phase to provide the best image quality; however, this is not always the case. Motion artifacts are more common during the arterial phase, and a poorly timed bolus may degrade image quality.

Often, the arterial phase acquisition demonstrates good lung parenchymal enhancement (“perfusion”), although this is variable due to subtle differences between timing of the acquisition with respect to the arrival time of the contrast bolus. When good parenchymal enhancement is present, however, it can reveal perfusion defects, very helpful secondary signs for pulmonary emboli (Figure 6).

The pulmonary arteries are evaluated in a segment-by-segment method, similar to the evaluation of CTA images. An important difference between pulmonary MRA and CTA is the fact that completely occlusive pulmonary emboli can appear as abrupt vessel cut-offs on MRA, analogous to cutoff vessels seen in conventional angiography. This may make the identification of occlusive emboli more challenging on MRA than on CTA because an absent vessel may be more challenging to identify. The presence of associated perfusion defects visible on MRA (which are rarely appreciated on CTA) often mitigates this challenge.

The post-contrast T1-weighted scans and the 3-plane SSFSE localizer images are reviewed for incidental findings and alternative diagnoses. The SSFSE localizer images are the only T2-weighted images acquired during the examination and usually cover the spine as well as upper abdomen and neck. It is very important to carefully evaluate these “scout” images.

There are several artifacts that are unique to pulmonary MRA and can compromise the interpretation of the examination unless the radiologist is familiar with them.

Artifacts: Truncation and Corner-Cutting

Truncation artifact, often known as Gibb's ringing, is a well-described phenomenon that results from the fact that the k-space representation of any real object of finite size extends beyond the limits of sampling during MR data acquisition (28). Such truncation in k-space results in “ringing” in the image in the vicinity of high-contrast sharp edges, for example, near the edges of the pulmonary arteries in a pulmonary MRA. These “ripples” are usually correctly recognized as artifact; however, when ripples from one vessel edge superimpose on the ripples arising from the opposite vessel edge in the center of the vessel, an apparent central hypointensity can result.

This central decrease in signal intensity can be mistaken for a pulmonary embolism. This effect will occur in vessels that are 3-5 true pixels (not interpolated pixels) in diameter (Figure 7). Using the scan parameters listed above, this corresponds to the typical size of the lobar pulmonary arteries in the lower lobes. This artifact may not be appreciated on systems that aggressively low-pass filter the k-space data; however, low-pass filtering decreases the effective spatial resolution and can compromise the ability to see small segmental emboli. Importantly, this artifact, like pulmonary embolism, persists on arterial and delayed phases. Therefore, simple persistence across the multiple acquisition phases is insufficient to differentiate truncation artifact from embolism.

It is possible to differentiate truncation artifact from pulmonary embolism, as recently demonstrated by Bannas, et al (29). Truncation artifact should cause a signal drop of less than 18% (28) (Figure 7), while pulmonary emboli usually cause a much greater signal drop-out. Bannas et al. proposed using a 50% cutoff for differentiating true emboli from truncation artifact. If the signal decreases by more than 50%, the central hypointensity is likely due to pulmonary embolism; if signal drops by less than 50%, it is likely artifact. Using this approach, pulmonary emboli can be distinguished from artifact with a sensitivity of >99% and specificity of 90% (29).

Truncation artifact is more easily confused with pulmonary embolism when k-space corner-cutting is used, as we do in our practice to shorten scan time. Corner cutting leads to more isotropic spatial resolution than conventional sampling over a full rectangular area in k-space, resulting in a circularly symmetric truncation artifact (Figure 8). However, if the reader is aware of this artifact, the marked difference in relative signal drop-out between pulmonary embolism and truncation artifact makes it relatively easy to differentiate the two.

Artifacts: Contrast Bolus Timing

Dynamic changes in contrast concentration in the vasculature during the course of an acquisition can also result in artifacts, as described originally by Maki, et al. (22) and illustrated in Figure 4. Unlike truncation artifact, these artifacts do not persist on steady-state images. We use elliptical-centric k-space sampling to facilitate the use of fluoro-triggering. If the scan begins before the contrast bolus peak arrives, edge-enhancement of the vessels will result, as is commonly seen in the aorta on the pulmonary arterial phase acquisition.

Conversely, if the contrast bolus washes out of the vessel before the scan has been completed, the pulmonary arteries will appear blurred because high spatial frequency edge information is acquired last with elliptical centric phase encoding. This is a major cause of image quality degradation if the contrast bolus duration is less than the 15-19 sec acquisition time and the reason why we use a diluted contrast bolus. While it may seem counterintuitive to dilute the contrast bolus used for an MRA examination, the excellent signal to noise ratio in these studies allows the beneficial trade-off of slightly lower overall signal for markedly improved visualization of the pulmonary vasculature (12,30).

Artifacts: Patient motion

It is crucial to keep breath-hold time as short as possible because patients with suspected PE are often short of breath. In our experience, the pulmonary arterial phase images are most likely to have motion artifact. Out of our first 301 cases, fully 20% demonstrated better image quality on the immediately delayed phase than on the pulmonary arterial phase (27). This fact emphasizes the importance of both multiphasic examinations and diligent review of all of the acquired phases. In this regard, MRA has a significant advantage over CTA because radiation concerns limit CTA to a single acquisition. In fact, with MRA, it is even possible to perform a second injection while the patient is still on the table if poor image quality is observed on the first injection (Figure 5).

Artifacts: Parallel Imaging

The use of 2D parallel imaging in the right-left (RL) and antero-posterior (AP) dimensions may result in noise amplification (i.e. high “g-factor”) within the center of the image. This is usually not significant but can become severe if the patient's body extends outside the imaged volume in the AP direction or the coil design is not optimized for very large patients. The use of sagittal excitation is very helpful in preventing aliasing in the right-left direction. Nominal parallel acceleration factors greater than 2 in either the RL or AP directions tend to worsen noise amplification and are not recommended.

Other Pitfalls in Interpretation

Maximum intensity projections (MIPs) are often generated with MRA examinations and are an excellent means of providing a global overview of vascular anatomy. However, just as with CTA, MIPs should be used with care. An embolism with an adjacent sleeve of contrast will vanish on a MIP.

It should also be noted that focal defects of parenchymal enhancement during the arterial-phase (first) acquisition are not always caused by pulmonary emboli. If a portion of lung is hypoventilated, for example in the setting of obstructive small airways disease, the lungs respond with a compensatory physiologic vasoconstriction leading to physiologically appropriate perfusion defects that mimic those caused by pulmonary emboli. Therefore, a pulmonary artery filling defect or arterial truncation must be identified before concluding that a focal defect in lung enhancement is due to a pulmonary embolism.

Alternative Diagnoses

Because the consequences of missing the diagnosis of pulmonary embolism can be fatal, referring physicians often have a low threshold for requesting an imaging study to rule out pulmonary emboli. However, the symptoms of pulmonary embolism are highly non-specific – dyspnea, chest pain, tachycardia, occasionally hypoxia. Therefore, although the primary purpose of the imaging study is usually to “rule out pulmonary embolism”, the identification of other alternative diagnoses is also a high priority.

Even if MRA is shown to be as effective as CTA in identifying clinically significant pulmonary embolism, some might argue that the risk of missing a pertinent alternative diagnosis on MRA outweighs the small risk of a future radiation-induced cancer. It is true that the MRI methods described here are less sensitive for the detection of some lung pathologies that are best visualized with CT, most notably interstitial lung disease and emphysema. However, the low baseline MRI signal in lung improves the conspicuity of the alternative diagnoses that are most common in these patients, such as consolidation, aspiration or edema. Furthermore, cardiac, chest wall, and mediastinal abnormalities are well assessed with MRI due to its greater soft tissue contrast and better evaluation of post-contrast soft-tissue enhancement than CTA. Figure 9 shows several examples of infection, illustrating the excellent soft tissue contrast available with MR. Figure 10 shows several other alternative diagnoses that have been identified on pulmonary MRA.

Potential Barriers to Implementation

The largest multicenter trial evaluating the diagnostic efficacy of pulmonary MRA against CTA as a reference standard was the PIOPED III study (17), published in 2010 and based upon scans performed between 2006 and 2008. The conclusion of that study was that “magnetic resonance pulmonary angiography should be considered only at centers that routinely perform it well and only for patients for whom standard tests are contraindicated.”

The greatest challenge to the performance of pulmonary MRA in the PIOPED III study was inconsistent and often poor technical quality of the MRA acquisitions (17,19). 25% of the acquisitions were considered technically inadequate, with poor arterial opacification and motion being the primary limiting factors. While parallel imaging was used in PIOPED III when possible (18), the literature does not report the proportion of cases in which it was used nor whether it was implemented in 1D or in 2D. Furthermore, since the time of that study, there have been important advances in pulmonary MRA protocols: (1) the routine use of 2D parallel imaging in both phase-encode dimensions for higher spatial resolution and larger volumetric coverage, (2) diluted contrast bolus lasting the duration of the arterial-phase scan, and (3) the use of multiple acquisitions, rather than relying on only a single arterial phase.

A retrospective study of 301 clinical pulmonary MRA studies performed using the methodology described in this review was performed by Yarlagadda, et al (27). Studies were assessed for arterial opacification (good, fair, or poor in main/lobar, segmental, and subsegmental arteries), the relative amount of parenchymal enhancement (none, some, excellent), and for the presence of artifacts (none, mild, moderate, or severe). The arterial

opacification scores were combined into a single composite score following the PIOPED III methodology (19), using a 7-point Likert scale (0=excellent through 6=poor).

In the Yarlagadda et al. study, the contrast bolus on the “pulmonary arterial phase” acquisition was predominantly in the pulmonary arteries (59%) or pulmonary arteries and pulmonary veins (31%) but occasionally in the aorta (10%). At least some parenchymal enhancement was seen in 69% of studies and excellent parenchymal enhancement was seen in 32% of the studies. The composite image quality scores were significantly better than the PIOPED III image quality scores ($p<0.001$). In contrast to the 26% of the PIOPED exams that were scored in the best category, fully 60% of the exams in this study were scored in that category. Unfortunately, direct comparison of PIOPED III images with images obtained using this newer protocol was not possible because PIOPED III images were not made available for review by Yarlagadda et al. In this retrospective review of clinical pulmonary MRA studies performed on acutely ill patients, pulmonary MRA demonstrated a very high technical success rate, with improved arterial opacification when compared with the reported results from PIOPED III.

Clinical Effectiveness Versus Diagnostic Efficacy

Ironically, with improvements in CT technology, particularly MDCT, there is also the possibility that some patients may be unnecessarily treated for clinically insignificant isolated subsegmental pulmonary emboli (SSPE) that would not have been detected with earlier generations of CT, nuclear medicine V/Q scans, or even invasive DSA methods (10). The clinical importance of isolated subsegmental pulmonary emboli is uncertain and increasingly being questioned (31-34). It is thought by many that small emboli are formed in the deep peripheral venous system and filtered by the lungs in normal individuals (15,35-39). However, in most centers, the standard of care is to treat all patients with documented PE, regardless of size, with anticoagulation for 3-6 months (40,41), despite the known morbidity of anticoagulation.

In support of treating isolated SSPE, den Exter et al. (42) demonstrated that patients with SSPE had the same number of venous thromboembolic events (VTE) at follow up as did patients with larger emboli. Pena et al. (43) and Donato et al. (44), however, observed that patients with untreated isolated SSPE had no adverse events. It is likely that an individual patient's risk of a life threatening thromboembolic event is more closely related to the clot burden in the deep venous system, rather than the size of the initial PE. Carrier et al. (45) reviewed 22 studies in a meta-analysis and demonstrated a detection rate for isolated SSPE of 9.4% using MDCT, compared to 4.7% with single detector CT (SDCT). However, there was no statistically significant difference in the incidence of subsequent VTE in patients in these studies. This suggests that at least some SSPE that were missed on SDCT were not clinically significant. Some clinicians will choose not to treat low risk patients who have a single SSPE (46). Finally, Yoo, et al. (47) recently reviewed the literature and concluded that no randomized trials of sufficient quality have been published to determine the effectiveness of anticoagulation for patients with isolated SSPE. The uncertainty regarding the clinical relevance of SSPE seen on MDCT raises the question of whether diagnostic

efficacy or clinical outcome should be the clinically relevant comparison between MDCT and MRA in this clinical scenario.

There has been one publication to date evaluating the outcomes following the use of pulmonary MRA for primary evaluation for PE (12). This retrospective study included 190 consecutive clinical pulmonary MRA scans with 3-month and 1-year follow-up by medical records review. The negative predictive value of pulmonary MRA for subsequent VTE event was 97% (92-99%) at 3 months and 96% (90-98%) at 1 year of follow-up. These results compared favorably with those reported for pulmonary CTA (42).

Conclusion

Pulmonary MRA has matured into a more robust and better understood tool for the evaluation of pulmonary embolus. Using the techniques described in this manuscript, we have successfully integrated this tool into routine clinical use at our institution, with acceptance by referring clinicians, technologists, attending radiologists, and on-call residents. This streamlined protocol is performed routinely at all hours without direct physician supervision. The short MR table time is comparable to CT, helping patients tolerate the procedure. Furthermore, this short scan time also helps logistically to fit these urgent scans into an already busy clinical MR schedule.

Pulmonary MRA scans have excellent diagnostic efficacy when performed with consistently high technical quality (17,19). It is now possible to consistently achieve this high technical quality due to advances such as widespread 2D parallel imaging and improved contrast bolus injection protocols. Furthermore, continued innovations in pulse sequence technology and the use of intravascular contrast agents (gadofosveset and ferumoxytol) may lead to future improvements in diagnostic accuracy. Is it time for a PIOPED IV study? Or perhaps, given the controversial significance of isolated subsegmental pulmonary embolism, future multicenter pulmonary embolism imaging trials should focus not on diagnostic efficacy but rather on clinical outcomes.

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Abbreviations

AP	Anterior-Posterior
CTA	Computed Tomographic Angiography
DEM	Department of Emergency Medicine
DSA	Digital Subtraction Angiography
EM	Emergency Medicine
GBCA	Gadolinium Based Contrast Agent

MIP	Maximum Intensity Projection
MDCT	MultiDetector Computed Tomography
MRA	Magnetic Resonance Angiography
PE	Pulmonary Embolism
PIOPED	Prospective Investigation Of Pulmonary Embolism Diagnosis
RL	Right-Left
SDCT	Single Detector Computed Tomography
SGRE	Spoiled Gradient Echo
SI	Superior-Inferior
SSFSE	Single-Shot Fast Spin Echo
SSPE	SubSegmental Pulmonary Embolism
V/Q	Ventilation / Perfusion
VTE	Venous Thromboembolic Event

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Highlights

- Obtaining consistent high-quality pulmonary embolism MRA studies for Emergency Department patients is feasible.
- A simple, focused short MRA protocol is essential and is possible using existing commercially available methods.
- Extending contrast bolus duration to match acquisition length improves image quality.
- Pulmonary embolism MRA can also show important alternative diagnoses.
- Artifacts on MRA that differ from those on CTA are described.
- Strategies for overcoming potential barriers to implementation of a clinical pulmonary embolism MRA program are described.

Figure 1. Clinical pulmonary embolism MRA protocol. This short 5-10 min protocol is both well-tolerated by patients and also short enough to allow easy integration into a busy MRI schedule. Scan parameters for the 3D MRA are provided in Table 1. Review of T2-weighted localizer and post-contrast fat saturated T1 images is also very important for diagnosis of alternative diagnoses.

Figure 2.

Example of a normal pulmonary MRA performed at 1.5T. Pulmonary arteries are routinely well seen to the proximal subsegmental level as shown with these thin-slab MIP images. Inset in upper right shows a schematic of how the sagittal excitation avoids wrap from the arms into the field of view.

Figure 3. Examples of pulmonary emboli. Lobar (A, B) and segmental (C) pulmonary emboli (arrows) in three different patients. Parenchymal perfusion defects (*) are variable based on bolus timing with respect to the acquisition, even with the use of fluoro triggering.

Figure 4.

Importance of diluted bolus and bolus timing. With an elliptical centric acquisition, if the scan starts before the bolus arrives, the effect is an edge-enhanced image. If the scan starts late, the pulmonary arteries are blurred due to washout of contrast during the acquisition of peripheral k-space data. Diluting the bolus to last the duration of the acquisition helps avoid either of these filtering effects.

Figure 5. Utility of a second injection. Example of the utility of a second injection if the first acquisition is compromised by motion. This is a very unusual situation but can salvage an initially limited study. Bilateral large pulmonary emboli are hard to see during the first injection due to respiratory motion.

Figure 6.

Utility of lung perfusion defects. In this case, a small wedge-shaped perfusion defect was clearly seen and helped direct the radiologist's eye to the subtle cut-off of the subsegmental pulmonary artery supplying this area. On a follow-up scan 16 months later, the overall assessment of lung perfusion is much less well-seen, illustrating the variability of perfusion assessment possible with this pulse sequence, likely due to subtle differences in timing between the acquisition and the arrival of contrast in the parenchyma.

Figure 7.

Truncation artifact (Gibb's ringing) can mimic pulmonary embolism, although pulmonary embolism shows a much greater signal drop in the vessel than truncation artifact. This effect is greatest in vessels that are 3-5 pixels in diameter (true, not interpolated resolution). With the resolution used in this protocol, these most affected vessels are the lobar pulmonary arteries.

Corner Cutting

Full Sampling

Figure 8.

Effect of corner-cutting on appearance of truncation artifact (Gibb's ringing). The use of corner-cutting results in an isotropic resolution and makes it somewhat more difficult to differentiate Gibb's ringing from a true embolism. The trade-off is the shorter scan time with corner-cutting, resulting in fewer respiratory motion artifacts due to inability to complete the breath-hold.

Figure 9.

Pneumonia on pulmonary embolism MRA. (A) The initial CTA on this patient was equivocal. MRA was therefore ordered. The necrotic pneumonia with abscess (arrows) is better appreciated on MRA (left) than on CTA (right), illustrating the greater soft tissue contrast available with MR. The pleural effusion is also very well seen on the MRA (*). (B) Tree-in-bud opacities due to bronchopneumonia are well seen. (C) In another case of cavitary pneumonia, the importance of a multiphasic acquisition is demonstrated. The pneumonia is almost invisible on the pulmonary arterial phase image and progressively enhances during the subsequent acquisitions, acquired at approximately 1 min intervals.

Figure 10. Additional examples of alternative diagnoses identified on pulmonary embolism MRA. (A) Rib fracture. (B) Pericarditis. (C) Breast mass (fibroadenoma on subsequent breast biopsy). (D) Portal vein thrombus. (E) Peritoneal metastases (arrows), ascites, and pleural effusion (*).

Table 1**Pulmonary MRA Pulse Sequence Parameters for 1.5T**

Parameter	Value
FOV	35cm SI × 28-35cm RL × 26-34cm AP
Matrix	256 × 192 × 128-140
True resolution	1.3 × 1.8 × 2.0-2.4 mm ³
Interpolated resolution	0.7 × 0.7 × 1.0-1.2 mm ³
Excitation slab	Sagittal
TR/TE	3.2 ms / 1.1 ms, fractional readout
Flip Angle	28° (15° for 2 nd post-contrast “low flip angle” scan)
Bandwidth	±83 kHz
2D parallel acceleration	3.72
k-space order	Elliptical centric
k-space coverage	Elliptical “corner cutting” (0.78 of fully sampled rectangle)
Scan time	14-19 s