MRI of the Lung – ready … get set … go!

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Introduction

Magnetic resonance imaging (MRI) of the lung is a powerful evolving tool for scientific and clinical application. The key technique for MRI of lung morphology is based on resonant high-frequency signal of protons in tissues and liquids, so-called Proton- or ^{1}H-MRI. Empowered by recent technical advances, MRI has challenged its well-known limitations as defined by the low proton density in the lung and the fast signal decay due to susceptibility artifacts at air-tissue interfaces. The new modality in chest imaging is much appreciated, even in spite of the excellent performance of modern multiple row detector computed tomography (CT) scanners and the far lower price of X-ray. Being superior to X-ray and matching CT in detection of nodular and infiltrative lung disease, offering additional functional imaging capacities and all this without radiation exposure to the patient, lung MRI has become a valuable method for examinations in children and during pregnancy, for young patients with diseases which warrant frequent follow-up examinations or for any other application that would need to avoid radiation exposure, such as scientific studies, commercial clinical trials (therapy control) or assessment of patients for legal medical opinions.

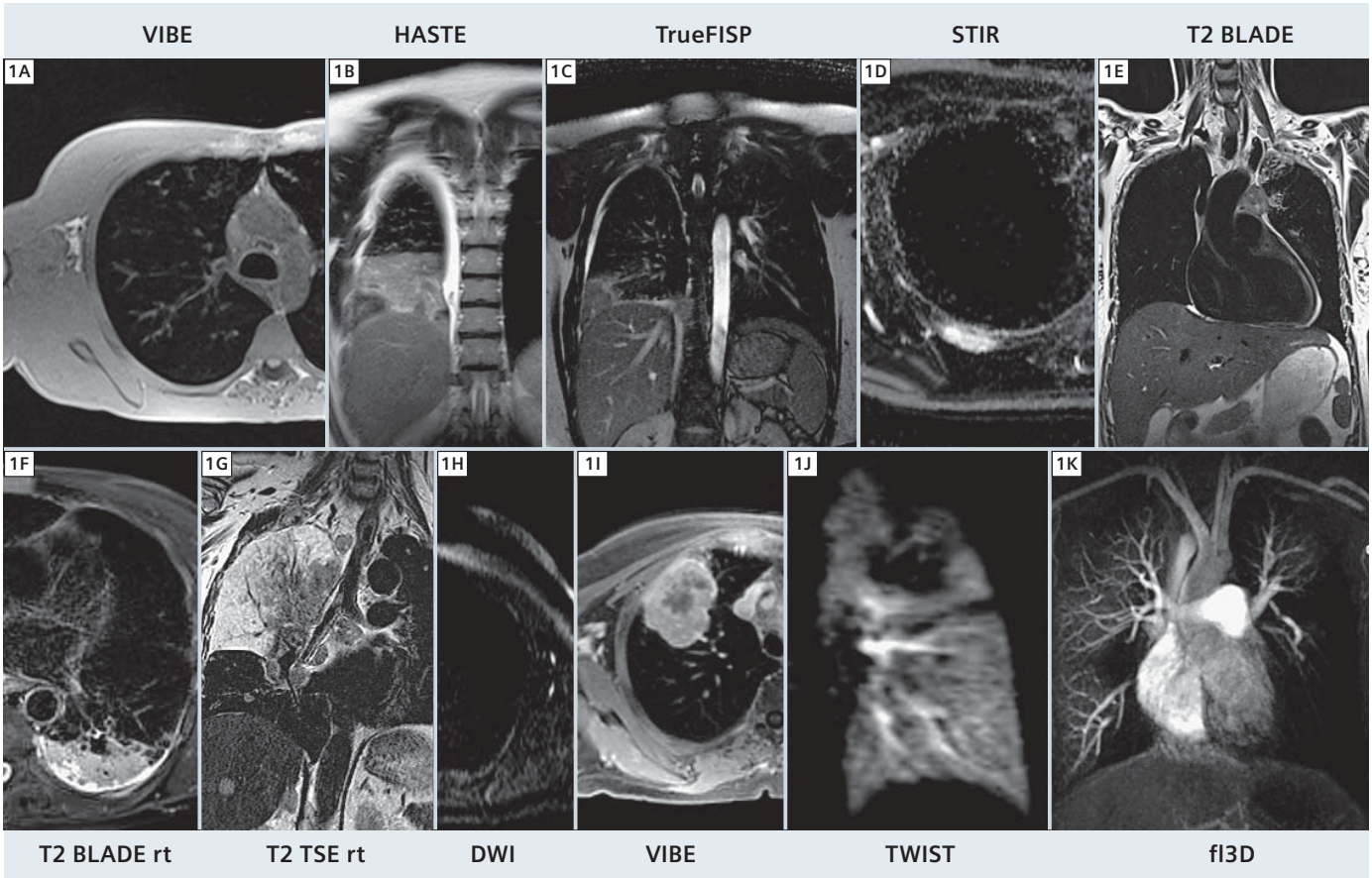
Clinical method

Fast sequences, preferably for breath-hold imaging with reasonably high spa-

Table 1: Sequences for lung MRI

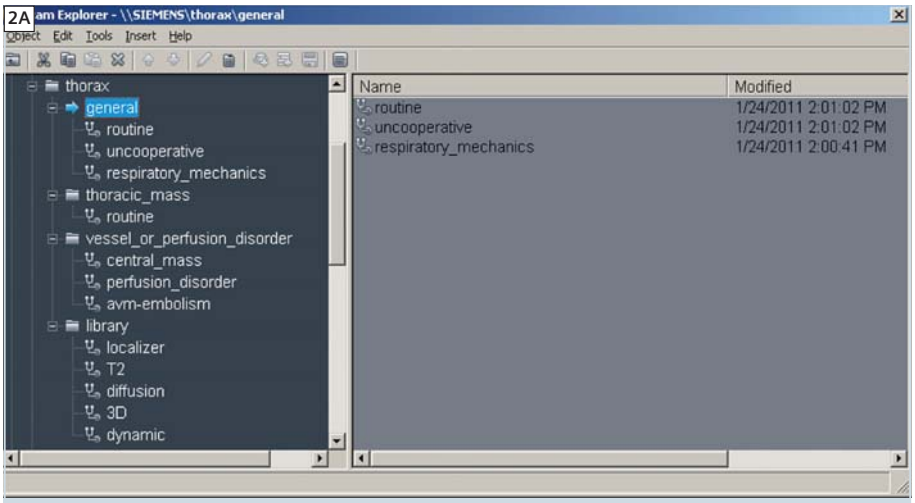
Sequence	Key pathology	Respiration manoeuvre	Spatial resolution	Temporal resolution	1.5T	3T
VIBE	pulmonary nodules	breathhold	high	low	+	+
HASTE	infiltrates	breathhold	low	high	+	+
TrueFISP	pulmonary embolism	free breathing	moderate	high	+	(–)
STIR or T2 BLADE fs	lymph nodes bone metastases	multiple breathholds	moderate	low	+	+
T2 BLADE	nodules and masses	multiple breathholds	moderate	moderate	+	+
T2 BLADE rt* T2 TSE rt*	masses	free breathing	moderate-high	low	+	+
DWI	nodules and masses	multiple breathholds	low	low	+	+
TWIST	perfusion deficit	breathhold	low	high	++	+
fl 3D	embolism AVM	breathhold	high	low	+	++

*rt = respiratory triggered

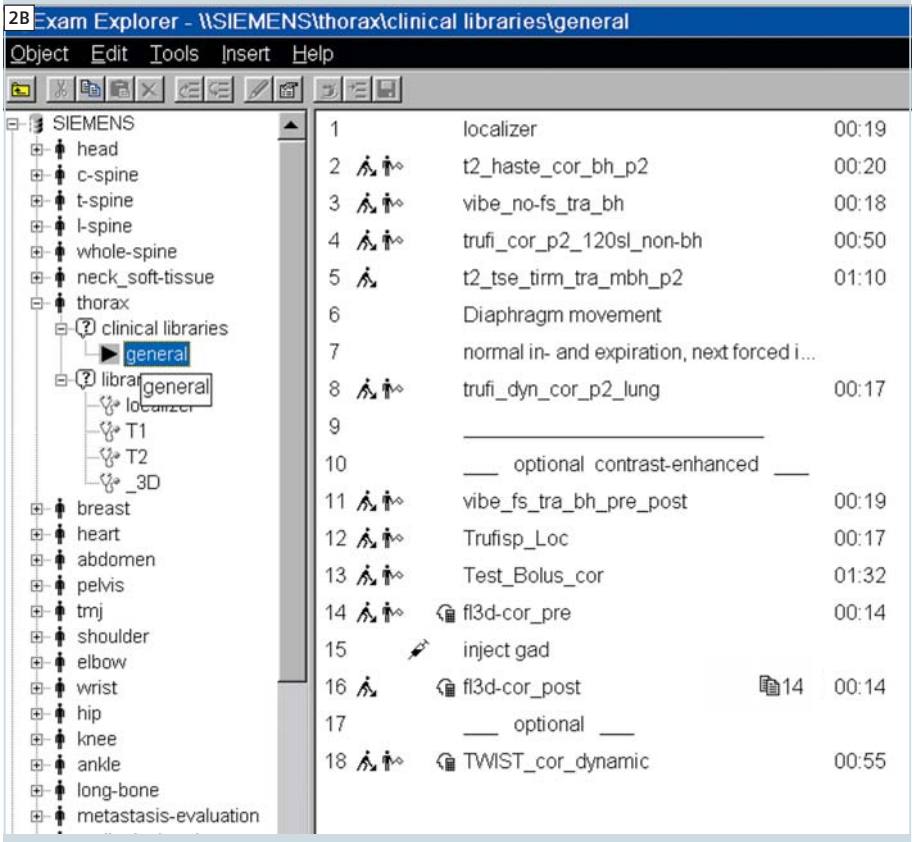


1 Available sequences for chest imaging. For details see table 1.

tial resolution and short echo time (TE), able to receive as much lung signal as possible within the short interval before signal decay are a technical challenge for both, hardware and sequence design [1]. Combining fast breathhold acquisitions with parallel imaging (iPAT = integrated Parallel Acquisition Techniques), high temporal resolution MR angiography (TWIST = time-resolved angiography with stochastic trajectories) rotating phase encoding (BLADE) and Navigator technology (PACE = prospective acquisition correction), lung MRI has become a fairly robust technique for broad clinical application [2]. Nowadays, the Siemens MAGNETOM user can select from a 'buffet' of protocols that have been optimized for imaging lung diseases (Fig. 1). A quick summary of the specific properties of the sequences is listed in Table 1. Suggested complete push-button protocols for specific pathologies are arranged in a protocol list at the scanner and are practically ready to go. Figure 2A shows the improved protocol tree with *syngo* MR D11D. Figure 2B gives a list of protocols that are implemented with software version *syngo* MR B17. The packages cover different aspects of lung pathology, from general purpose, to specific sequence combinations for imaging thoracic masses and high resolution angiography, to functional imaging with dynamic first pass lung perfusion imaging. The rationale for the protocol suggestion was to combine different sequence techniques to cover different weighting (T1, T2, balanced T1/T2), to appreciate the particular strengths of different techniques, to cover all planes in at least one acquisition and to have diagnostic quality in at least 3/5 series in the worst case (e.g. uncooperative patient). Room times from 15 minutes for a basic protocol, 20 minutes for a contrast-enhanced study, to up to 30 minutes for a comprehensive study including perfusion imaging, angiography and post-contrast volumetric imaging are adjusted to the needs of clinical workflow. Alternatives for patients who have difficulties holding their breath are offered. Free breathing real time imaging with TrueFISP and navigator-triggered acquisitions with BLADE T2-TSE allow for excellent image quality even in non-compliant patients. For practical reasons, it is not needed to use ECG-triggering and the non-contrast enhanced basic protocol covers most clinical questions. Robustness against cardiac pulsation and respiratory motion is achieved by short acquisition time and (multi-)breathhold-imaging or respiratory triggering.



2A Protocol trees for chest imaging in the Exam Explorer window.

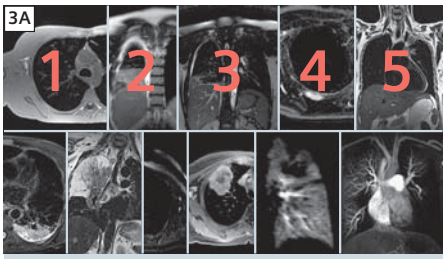


2B Chest imaging protocols as already installed with *syngo* MR B17.

'General' – the lung imaging protocol for general purposes

The first branch of the protocol tree contains a package for general purposes (Fig. 3). It will be used for most lung pathologies and large parts of it are integrated into the other protocol branches. The non-contrast-enhanced **'General Routine'** protocol (in-room time 15 min) comprises a coronal T2-weighted HASTE (T2w single-shot half-Fourier TSE) sequence with a high sensitivity for infiltrates and a transversal VIBE (T1w 3D-GRE) sequence with a high sensitivity for small nodular lesions (in particular the contrast-enhanced, fat saturated VIBE). Both are acquired in a single breathhold. This is followed by a coronal steady-state free precession sequence (TrueFISP) in free breathing. This sequence adds functional information on pulmonary motion during the respiratory cycle and heart function. Size, shape and patency of the central pulmonary vessels can be assessed. This part of the protocol is highly sensitive for central pulmonary embolism and gross cardiac or respiratory dysfunction [3]. A further advantage is the excellent robustness to motion. Despite potential susceptibility and off resonance artifacts the morphologic quality in lung imaging challenges the image quality of other parts of the protocol, e.g. of the VIBE sequence. A motion-compensated coronal BLADE (multi-breathhold T2w TSE) is added to improve depiction of masses with chest wall invasion and mediastinal pathology such as masses, lymph nodes or cysts (Fig. 4).

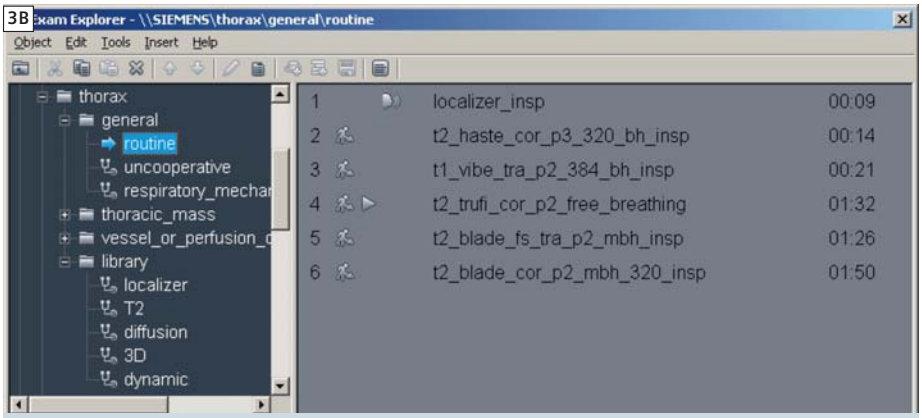
The protocol variant **'Respiratory Mechanics'** includes an additional coronal series to be placed on top of the diaphragm and acquired during instructed breathing with a temporal resolution of 3 images per second. This can be used for specific questions such as diaphragmatic palsy or lung tumor motion, e.g. to detect attachment and infiltration of a lesion to the chest wall. A final multi-breathhold transversal fat-saturated T2w TSE visualizes enlarged lymph nodes and skeletal lesions.



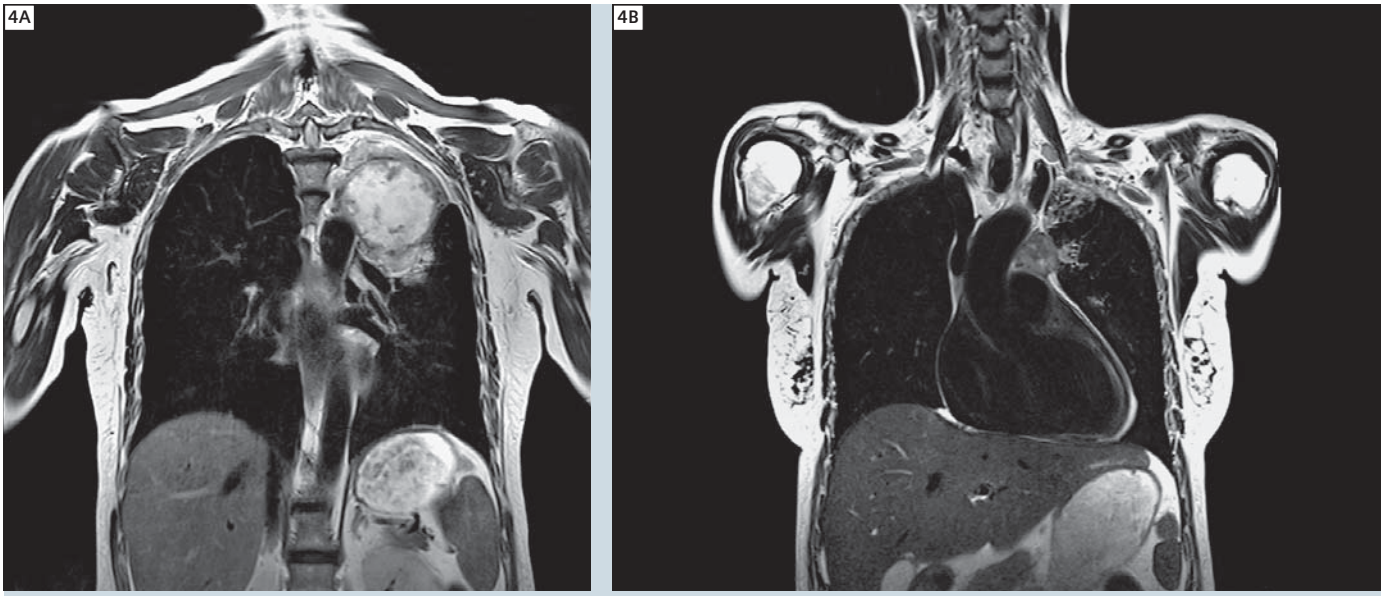
3A Selection of sequences for a 'General-Routine' protocol from the list offered in Fig. 1 and Tab. 1.

1: T1w VIBE, **2:** T2w HASTE, **3:** TrueFISP, **4:** STIR or T2 BLADE fs, **5:** T2 BLADE

In-room time 15 minutes



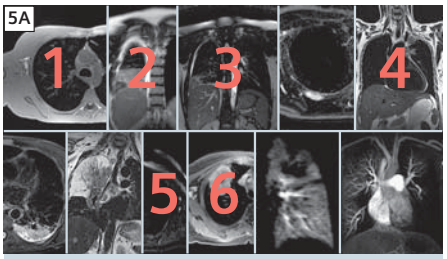
3B Detail of the protocol tree for general lung examinations.



4 Coronal multi-breathhold T2 BLADE acquisition in a patient with a large lung cancer in the left upper lobe and mediastinal lymph node metastases.

The protocol variation **'Uncooperative'** (to be used for patients who have difficulties holding their breath) comprises respiration-triggered versions of the T2-weighted TSE sequences (BLADE). Their application increases the total in-room time by approx. 10 minutes. This non-contrast enhanced **'General-Routine'** study covers the majority of clinical indications: Pneumonia, atelectasis, pulmonary nodules and masses, mediastinal masses (lymphoma, goiter, cyst, thymoma), phrenic nerve palsy, cystic fibrosis, tuberculosis, interstitial lung disease, acute pulmonary embolism. Detection rates for pulmonary infiltrates with the basic protocol match CT and make MRI a valuable alternative in particular for children, young patients and pregnant women. The sensitivity for lung nodules reaches 80–90% for lesions >4 mm (100% for >8 mm). Both capacities are appreciated in follow-up studies of cystic fibrosis patients using dedicated scores for the extent of disease. In lung cancer patients, MRI contributes to staging and atelectasis. Administration of contrast material contributes to detect tumor necrosis, chest wall or mediastinal invasion and pleural reaction/carcinosis. In many cases the further assessment of an unclear pulmonary or mediastinal mass, a pleural effusion of unclear origin or pulmonary embolism will warrant further contrast enhanced protocol elements. This is covered with the protocol branch **'Thoracic Mass'** which comprises the basic protocol plus additional contrast-enhanced fat-saturated breathhold-VIBE sequences (3D GRE) in transverse and coronal orientations. To cut down on imaging time, the transverse fat-sat-

5A

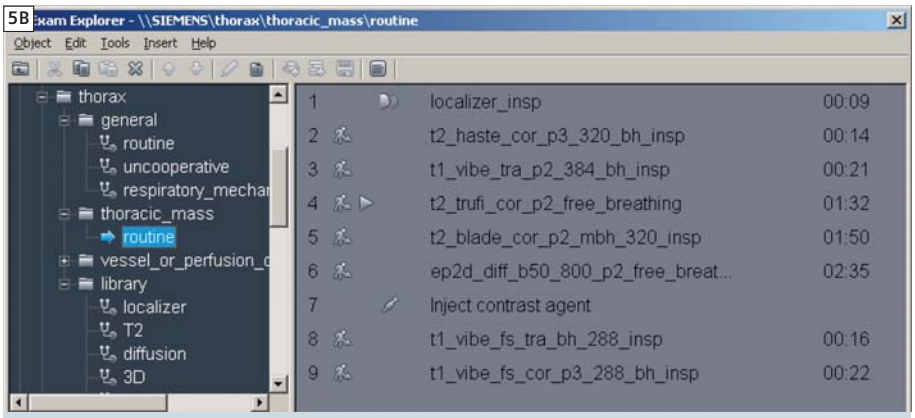


5A Sequence selection for the 'Thoracic Mass' protocol.

1: T1w VIBE, **2:** T2w HASTE, **3:** TrueFISP, **4:** T2w BLADE, **5:** DWI, **6:** T1w VIBE contrast enhanced

In-room time 20 minutes

5B



5B Protocol tree 'Thoracic Mass'.

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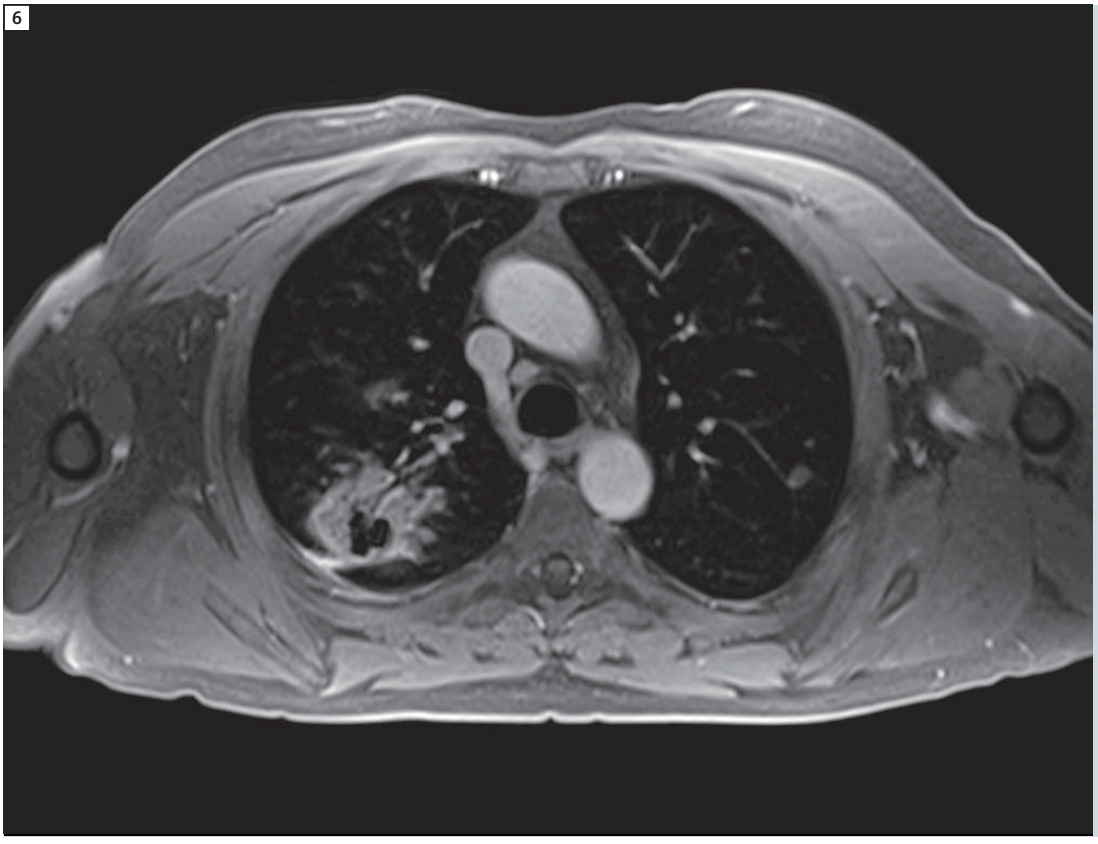
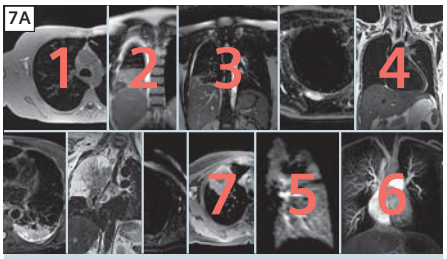


6 Contrast-enhanced VIBE of a lung granuloma in Wegener's disease. Note central necrosis with air-filled defect inside the large mass.

urated BLADE (multi-breathhold T2w TSE) is skipped in this protocol. Therefore total room time is not more than 20 min. Recognizing the potential value of diffusion-weighted imaging of the lung, the interested user will also find a suggestion for an optional EPI-DWI sequence in this protocol branch.

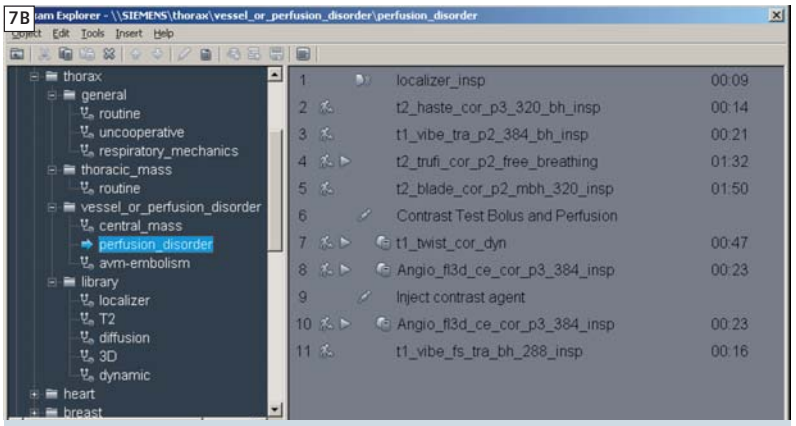
The indications for the contrast-enhanced 'Thoracic Mass' study include lung carcinoma, vasculitis (e.g. Wegener s granulomatosis, see figure 6), and masses of the mediastinum or mediastinitis. Contrast enhancement is also recommended in the case of pleural processes (unclear pleural effusion, empyema, abscess, pleural spread of carcinoma, mesothelioma). With their origin in 3D FLASH angiogra-



7A Sequence selection for the 'Vessel or Perfusion Disorder' protocol

1: T1w VIBE, **2:** T2w HASTE, **3:** TrueFISP, **4:** T2w BLADE, **5:** TWIST perfusion, **6:** fl 3D ceMRA, **7:** T1w VIBE contrast enhanced

In-room time 20 minutes

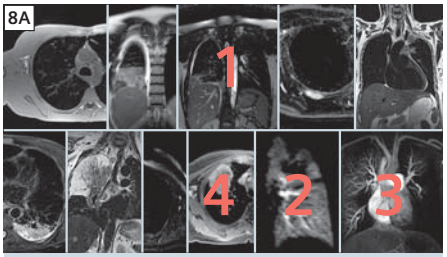


7B Protocol tree 'Perfusion Disorder'.

phy, the volumetric VIBE acquisitio ns have angiographic capacities with excellent visualization of pulmonary vasculature. Therefore, the additional VIBE acquisitions can serve as 'backup-angiogram' in case the image quality of the *k*-space centered FLASH 3D angiogram is impaired by respiratory motion, coughing or mis-timed contrast injection. This contributes to the sensitivity of the 'Thoracic Mass' program also for pulmonary embolism, which is a frequent condition in tumor patients.

'Vessel or Perfusion Disorder' – ceMRA and perfusion imaging of the chest

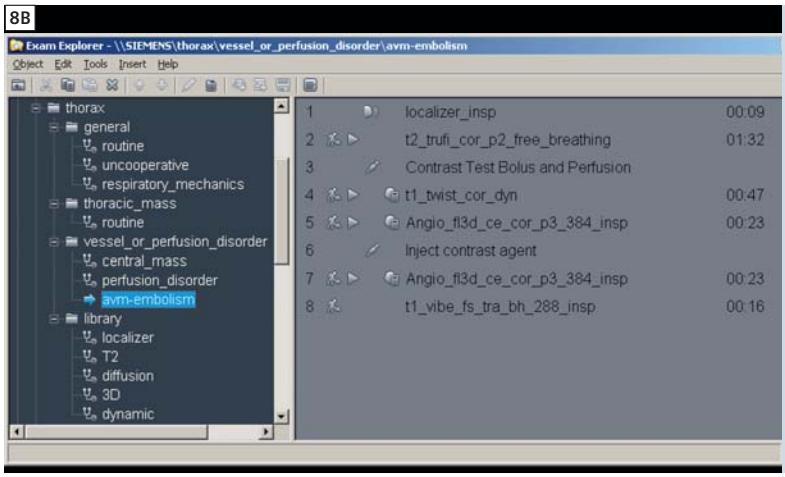
The collection of protocols for chest MRI is completed by a dedicated branch for the assessment of lung perfusion disorders (Fig. 7). The key sequence for imaging pulmonary vasculature is a T1-weighted 3D FLASH angiography with *k*-space centering of the contrast bolus. Three breathhold acquisitions (first a pre-contrast, followed by two contrast enhanced centered on the peak signal of the pulmonary artery and centered on the peak signal of the aorta) are used to produce subtracted 3D data sets for comprehensive viewing with a 3D-tool for multiplanar reformation (MPR) or maximum intensity projections (MIP). Optimum results will be achieved with an automatic power injection of a T1-shortening contrast agent (0.1 mmol/kg at 5 ml/s followed by a 20 ml sodium chloride chaser to produce a compact bolus). The optimum timing for contrast bolus injection can be identified with a simple test bolus injection and sequential single slice acquisitions. However, the protocol includes far more: A dynamic study of lung perfusion with full anatomic coverage. The applied TWIST sequence is the time-resolved variant of high resolution breathhold 3D FLASH angiography. Based on iPAT and data sharing, it allows for a 3D data acquisition with a temporal resolution of 1.5 seconds per image during free breathing. The resulting 4D data set can be displayed with the '4D-InSpace' application of a multi modality workplace, which allows to scroll through the series in a single image position or to scroll through the images of a 3D data set obtained at a single time point. For practical use, time stamps on the images directly indicate the interval between the start of acquisition (equal to the start of test bolus injection) to be used for timing of the high spatial resolution angiogram. To save storage capacities, it is recommended to select a single subtracted 3D data set at peak lung perfusion and a MIP series documenting the time course of contrast dynamics. Those willing to wait the additional 1–2 minutes computing time required for the reconstruction of 4D-TWIST (compared to single slice test bolus monitoring) are rewarded with a comprehensive lung perfusion study with excellent temporal resolution but still far higher spatial resolution than any scintigraphic technique. This time-resolved multiphase ceMRA is independent from the bolus timing and is therefore not only favorable in patients with severe respiratory disease and very limited breathhold capabilities, but also improves arterial-venous discrimination, e.g. in anomalies and shunts.



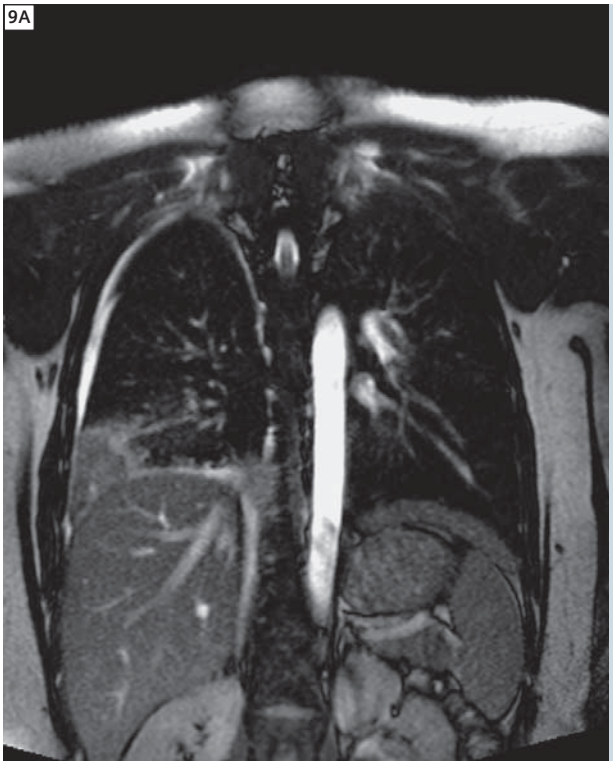
8A Sequence selection for the 'AVM-Embolism' protocol.

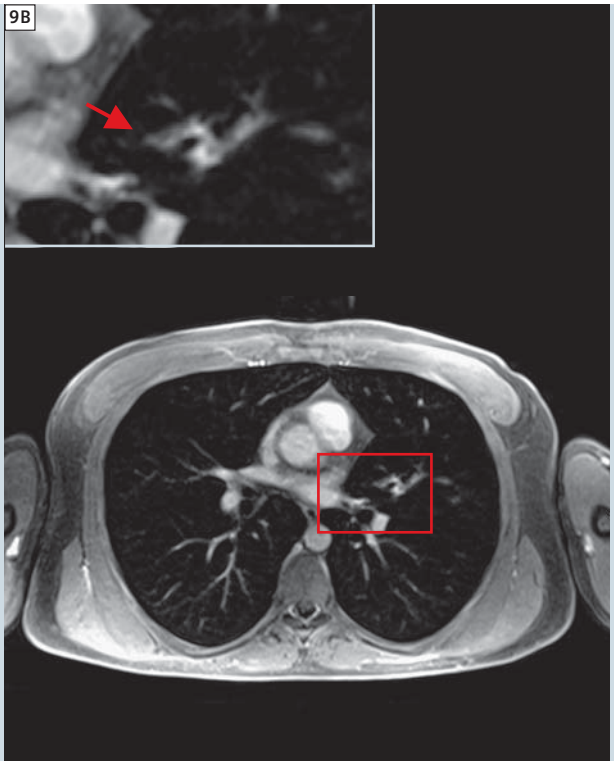
1: TrueFISP, **2:** TWIST perfusion, **3:** fl 3D ceMRA, **4**: T1w VIBE contrast enhanced

in-room time 15 minutes



8B Protocol tree 'AVM-Embolism'.

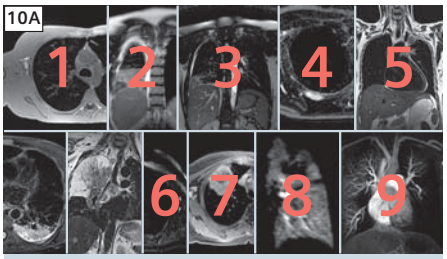




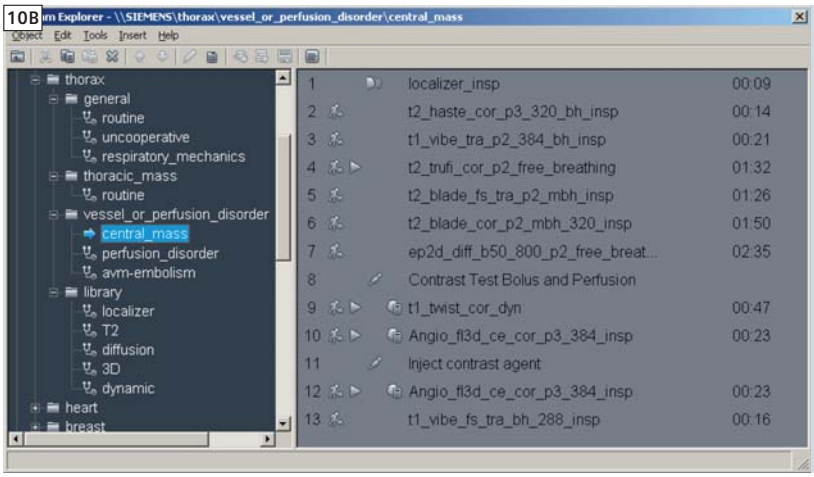
9 Two cases of acute pulmonary embolism. On the left a case with massive embolism and large thrombi detected with the TrueFISP series, on the right a small embolus within a segmental vessel, in this case detected with the VIBE.

The indications covered with the **'Vessel or Perfusion Disorder'** protocol include acute and chronic pulmonary embolism (PE), arterio-venous (AV) malformation (e.g. Osler's disease), lung sequestration, pulmonary arterial aneurysm, abnormalities of pulmonary venous drainage and any other pathology of lung vasculature. Specific indications for the TWIST perfusion appreciate the fact that this is the only part of the protocol which indirectly visualizes defects or absence of lung parenchyma due to emphysema or pneumothorax. Furthermore, functional lung perfusion impairment due to hypoventilation and hypoxic vasoconstriction can be easily detected (air-trapping in bronchiolitis, mucous impaction in cystic fibrosis). At this point, MRI includes specific functional information that would be difficult to obtain with CT.

However, conditions such as acute pulmonary embolism are an emergency. This requires immediate interaction and will not allow for typical scheduling lead times for an MR scanner. An abbreviated version of the protocol was prepared for this purpose (Fig. 8): It is limited to four sequences focusing on lung vessel imaging and lung perfusion. This can be accomplished within 15 minutes in-room-time which is considered acceptable to be squeezed into a full MR sched-



10A Sequence selection for the 'Central Mass' protocol.
1: T1w VIBE, **2:** T2w HASTE, **3:** TrueFISP, **4:** T2w STIR, **5:** T2w BLADE, **6:** DWI, **7:** TWIST perfusion, **8:** fl 3D ceMRA, **9:** T1w VIBE contrast enhanced
In-room time 30 minutes



10B Protocol tree 'Central Mass'.

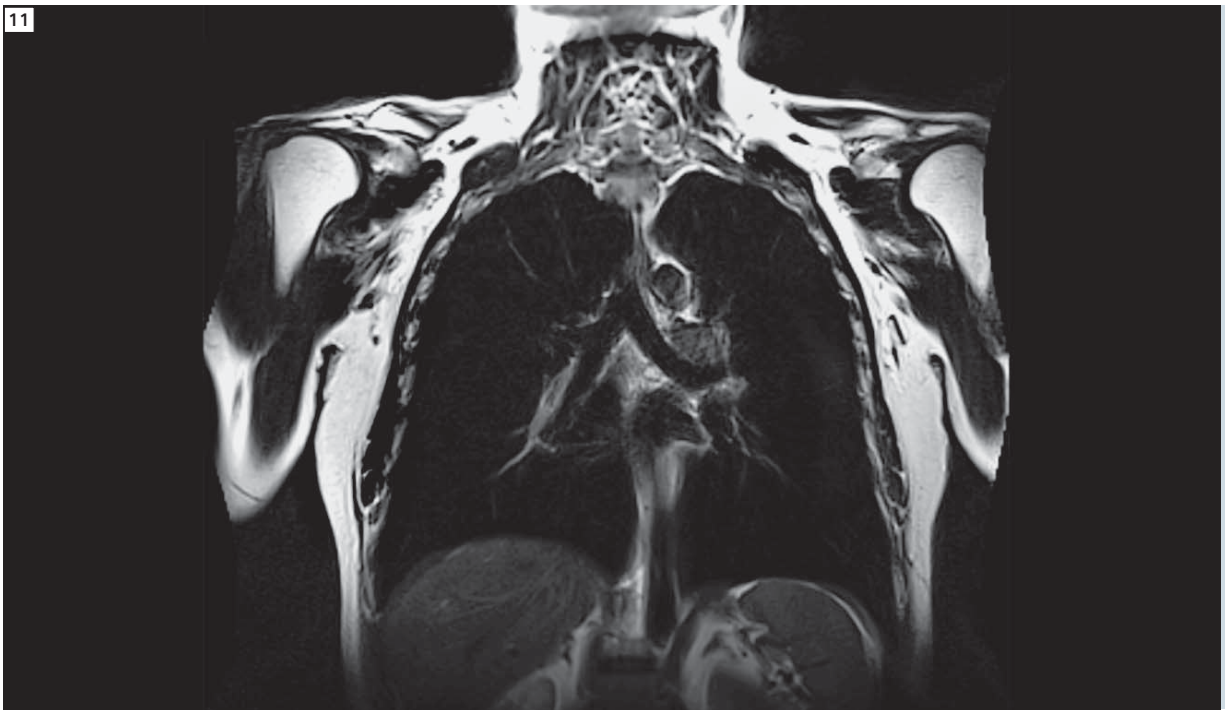
ule during the day. Nevertheless, this short examination provides comprehensive information on pulmonary embolism combining perfusion imaging with the diagnostic scope of a scintigraphy and lung vessel angiography comparable to CT scanning (Fig. 9). An important point is to start the examination with TrueFISP non-contrast enhanced series. In case of severe embolism the diagnosis can be made within the first 60 seconds of the examination with the option to immediately stop imaging at that time and to proceed to intensive treatment without any time loss compared to CT scanning.

'Central Mass' – have it all!

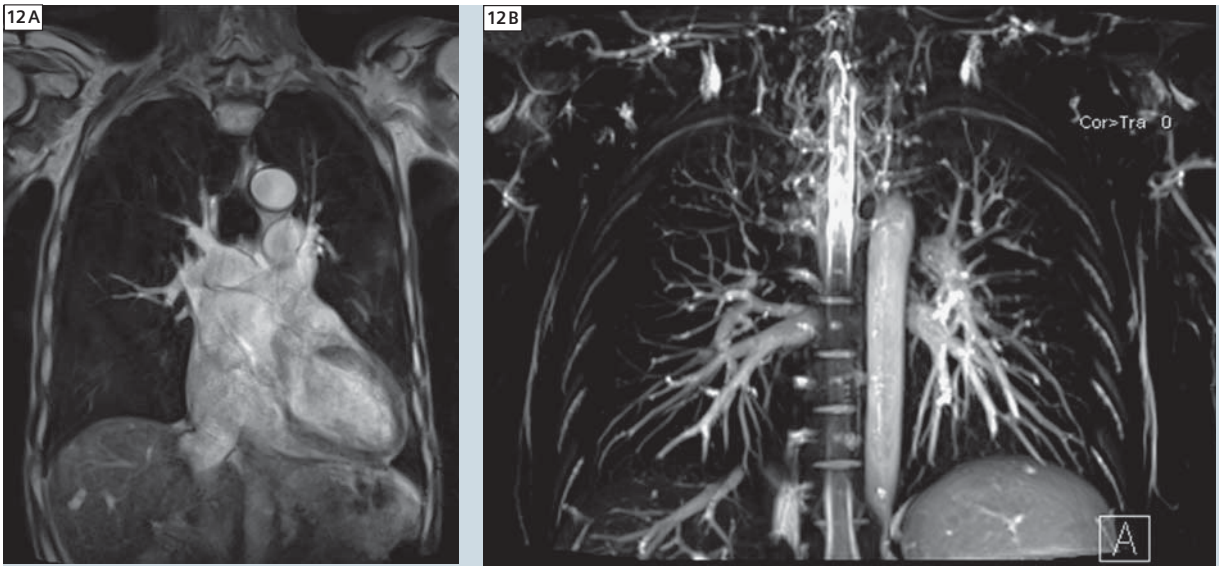
'Central Mass' is the most comprehensive package of the protocol tree, containing elements of all the aforementioned branches. It accounts for vessel involvement by central lung or mediastinal tumors with possible consequences for lung perfusion. This includes T2-weighted fat-saturated BLADE sequences as well as DWI. Typically, it would be used for the diagnosis of central masses with infiltration into the pulmonary arteries or aorta. 'Central Mass' is also a 'have it all' protocol for all cases in which one would like to cover any possible aspect with comprehensive imaging – however, since this takes approximately 30 minutes in-room-time, for daily routine and the majority of indications it would be practicable to use selective protocols.

Protocol adaptations for 3 Tesla

Originally, lung MRI protocols were developed for 1.5 Tesla systems. The majority of available publications are based on work with this field strength. Since high performance 3 Tesla scanners have become the benchmark on the clinical stage, serious effort was invested into transferring lung MRI technology to the higher field strength. Initially, it was discussed that increased susceptibility artifacts would make lung imaging even more difficult on these systems. However, systematic experimental work and application fine tuning have paved the road to the successful introduction of lung imaging into the high field world [4, 5]. In general, proton MRI of the lung is based on the effect that most relevant pathologies have intense signal and give optimum contrast against the black background of lung tissue. Consequently, transfer of the protocols to a 3T system has even improved the lesion to background contrast in infiltrative as well as solid lung lesions for all FLASH and TSE sequence types. In particular, lung nodule detection with the VIBE sequence as well as the detection of infiltrates with HASTE and STIR is improved on 3T images. This opens the perspective to invest the higher signal into higher spatial resolution or even faster image acquisition schemes. Contrast-enhanced studies after i.v. injection reach equal quality and with optimized technology first pass perfusion studies can be performed in a similar fashion [6]. Changes of image quality with transfer of the aforementioned sequence concept to 3T are therefore acceptable or even positive for most sequence types.
The exception concerns TrueFISP images, which show significant motion- and flow-related artifacts at the higher field strength. Delineation of vessel walls and other structures is still good, but lesion/background contrast does not improve. In combination, the effects result in an inhomogeneous signal of the pulmonary artery trunk and the large lobar vessels. Therefore, exclusion of severe pulmonary embolism with a quick free breathing TrueFISP acquisition on a 3T system is not favorable. To fill this gap in the protocol, a respiration-triggered SPACE-STIR sequence was adjusted for the visualization of central pulmonary vessels without contrast injection. The triggered acquisition scheme produces images of central mediastinal vessels with bright signal within 4-5 min and can be used on 1.5T as well as 3T. Due to triggering, the acquisition is robust even in uncooperative patients. The respiration-triggered SPACE-STIR sequence might therefore replace the free breathing TrueFISP throughout the whole protocol tree, although sensitivity and specificity for pulmonary emboli are subject to ongoing patient studies (Fig. 12).



11 Coronal multi breathhold T2w BLADE; healthy volunteer, 3T MAGNETOM Verio.

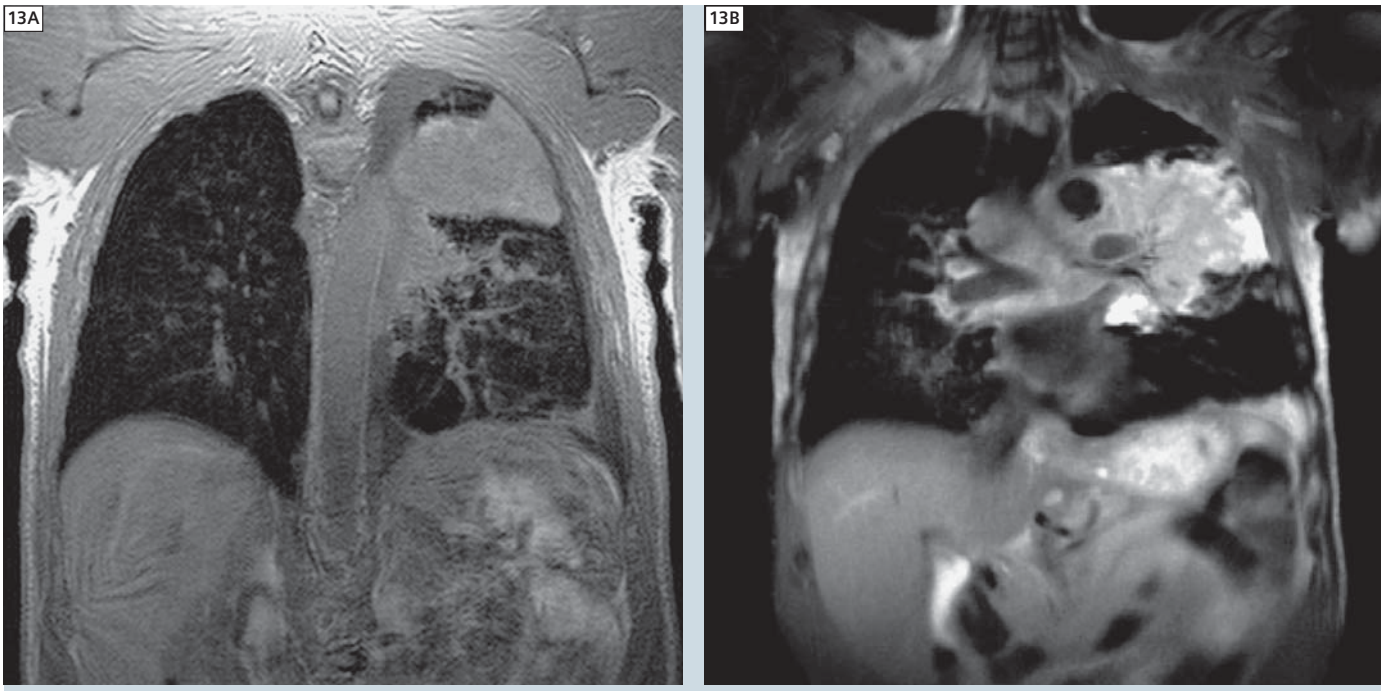


12 Coronal respiration triggered SPACE STIR acquisition in a 67-year-old man, using a 1.5T MAGNETOM Avanto (left). 30-year-old healthy volunteer using a 3T MAGNETOM Skyra (right).

Future perspectives

A quick glance at the current investigations on proton MRI of lung pathology illustrates the trend towards further improvement in robustness and reproducibility of image quality. Free-breathing self-navigated sequence designs, radial *k*-space methods including ultra-short-echo-time imaging and dynamic as well as quantitative lung imaging protocols for improved anatomical and functional lung assessment are currently under investigation.

A consortium of medical physics and radiology departments at Würzburg, Kiel, Heidelberg and Mannheim supported by the German Research Foundation (Deutsche Forschungsgemeinschaft; DFG) is currently on the way to developing 2D- and 3D imaging protocols based on the Siemens MAGNETOM Avanto platform for high-resolution lung MRI. One key sequence for 3D-MRI of the lung with full volume coverage is a self-navigated T1-weighted 3D FLASH with quasi-random *k*-space ordering. Under free-breathing condition five to seven full 3D acquisitions are acquired using additionally sampled non-spatially encoded DC-signals at the center of *k*-space as navigator. This approach is rather time efficient, since it does do not require separate RF excitations, and the DC-signal at the center of *k*-space contains sufficient information to reliably detect motion. Therefore, there are double benefits: Almost motion-free parallel acquisition of multiple breathing phases will either allow for detail motion analysis or for morphologic imaging without patient compliance. A key modification necessary for self-navigation was an extra data acquisition immediately after each imaging echo. Typical imaging parameters for the 3D-flash technique are: TE 1.2 msec, TR 3.8 msec, 7°,



13 Lung cancer patient with a tumor in the left upper lobe, adjacent atelectasis and pleural effusion. **(A)** Self-navigated coronal 3D FLASH of the posterior thorax, free-breathing. **(B)** Coronal radial TSE image of the same patient at carina level, free-breathing.

matrix : 256 x 320 x 44, FOV 370 x 450 x 220 mm³, resolution 1.4 x 1.4 x 5 mm³, total acquisition time 375 s (Fig. 13). In the same trend, Fourier decomposition ventilation-perfusion scanning is being developed as a robust technology for regional assessment of lung function with a non-contrast enhanced free breathing acquisition scheme. Periodic changes of parenchyma signal with inspiration depth (highest signal with lowest pulmonary air content in expiration) and heart action (lowest signal with maximum blood flow in systole) will be evaluated separately to produce ventilation and perfusion maps with comparable quality to a V/Q SPECT without the use of contrast media or radiation exposure to the patient [7]. Just these two examples indicate the dynamic development in the field of lung MRI and its bright future perspectives. In conclusion, lung MRI has made it from a niche technology to the doorsteps of clinical routine imaging. On MAGNETOM Aera and MAGNETOM Skyra lung protocols are ready to go! For key clinical questions lung MRI not only matches X-ray and CT, it offers additional functional imaging capacities. The protocol tree offers solutions for tricky problems of daily routine and makes MRI more than a good option for pediatrics and science. Dedicated parts of the protocol are fairly robust accounting for respiratory motion and heart action even in uncooperative patients. Experience with this young technology, e.g. in comparison with CT, is growing rapidly in an increasing number of centers worldwide. The perspectives for further developments are excellent and the degrees of freedom to adapt the suggested protocols for the users own purposes are large. Get ready ... get set ... go!

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