Magnetic Resonance Imaging During a Pandemic: Recommendations by the ISMRM Safety Committee

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The COVID-19 pandemic highlighted the challenges delivering face-to-face patient care across healthcare systems. In particular the COVID-19 pandemic challenged the imaging community to provide timely access to essential diagnostic imaging modalities while ensuring appropriate safeguards were in place for both patients and personnel. With increasing vaccine availability and greater prevalence of vaccination in communities worldwide we are finally emerging on the other side of the COVID-19 pandemic. As we learned from our institutional and healthcare system responses to the pandemic, maintaining timely access to MR imaging is essential. Radiologists and other imaging providers partnered with their referring providers to ensure that timely access to advanced MR imaging was maintained. On behalf of the International Magnetic Resonance in Medicine (ISMRM) Safety Committee, this white paper is intended to serve as a guide for radiology departments, imaging centers, and other imaging specialists who perform MR imaging to refer to as we prepare for the next pandemic. Lessons learned including strategies to triage and prioritize MR imaging research during a pandemic are discussed.
Level of Evidence: 5
Technical Efficacy: Stage 5

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Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) disease (COVID-19) has significantly disrupted everyday life across the globe. The healthcare industry has been deeply affected, and healthcare workers have had to care for patients with COVID-19 related illnesses and also patients presenting with urgent or emergent conditions whose COVID-19 positivity may be uncertain. Even as the medical world has improved testing capacity, personal protective equipment (PPE) shortages, and starts to approach mass vaccinations plus a more hopeful future less colored by COVID-19, recent experience has highlighted the problem of considering workflows and safety in the setting of a respiratory pandemic in general. Magnetic resonance imaging (MRI) is an essential diagnostic imaging modality for the diagnosis and management of many diseases. Therefore, continued access to timely MR imaging is essential to maintain during a pandemic. This white paper, submitted on behalf of the MR Safety Committee of the International Society of Magnetic Resonance in Medicine, is based on experience during the COVID-19 pandemic and is intended to serve as a resource for the MR community regarding the safe use of MR imaging during forthcoming pandemics. In addition to safe maintenance of clinical operations, this white paper also provides suggested guidance for continued access to MR systems for research.

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Pandemics: Modes of Transmission

To safely perform MR imaging in patients and research subjects during a pandemic, it is important to understand the relevant modes of transmission. It is challenging to inform an imaging strategy without an in-depth understanding of the applicable modes of transmission to implement appropriate preventive measures. Early in a pandemic the modes of transmission may not be well understood, which can lead to ineffective approaches from overly cautious to ineffectively protective to mitigate the transmission of disease. An essential objective is the protection of healthcare workers while maintaining access to essential imaging during pandemics. To achieve this goal it is essential to optimally utilize countermeasures such as the use of PPE and decontamination procedures that can reduce MR scanning time in order to balance protection with the need to perform essential scanning. Different modes of transmission are defined in Table 1. Early in a pandemic the mode(s) of transmission are uncertain, and therefore, it is recommended to have a cautious approach and consider transmission possible via all modes.

When a pandemic is associated with communicable asymptomatic infections, resources are stretched as all patients, research subjects, and even employees need to be considered potential infectious vectors. Hence, the knowledge of whether a patient or research subject is infected and communicable is key for planning, informing required PPE, as well as the necessary level of MR zone cleaning and mandatory time for air filtration. Where possible, pandemic screening questionnaires or testing strategies for imaging subjects should be integrated into the recommended imaging workflow to conserve PPE and optimize access to MR imaging.

Where possible it is recommended to classify patients as pandemic positive, negative, or indeterminate using laboratory-based or rapid testing combined with screening questionnaires and temperature testing as appropriate. It is advisable to consider patients with typical pandemic symptoms, those with possible exposures or high-risk behaviors as pandemic indeterminate until the results of testing are available. Pandemic indeterminate patients should be managed the same as pandemic positive patients until the results of testing are available. Asymptomatic patients with negative screening results can be classified as pandemic unknown–low risk. Classifying patients as pandemic negative should be limited to those who have a negative laboratory based or rapid test result. It is recommended to refer to local institution guidance regarding the time frame for repeat testing for asymptomatic pandemic positive patients. Regardless of past pandemic testing status, all subjects and accompanying family members should complete a screening questionnaire prior to presenting to the MR imaging center.

TABLE 1. Modes of Transmission in a Pandemic

Mode of Transmission	Definition	Mitigation Strategies
Contact	Transmission via direct contact (hand-shake) or indirect contact (eg, doorknob)	PPE (gloves, gowns), frequent hand-washing
Droplet	Transmission over <1 m when exposed to larger droplets, smaller droplets, and particles	PPE (gloves, gowns, mask, eye protection), social distancing
Airborne	Transmission over distances >1 m via small particles, which remain in the air for longer periods of time	PPE (gloves, gowns, masks, eye protection), social distancing, negative airflow rooms, allowing adequate time for full room air exchange
Common vehicle	Transmission via food, water, blood products, medical devices, or drugs with potential to infect numerous people	Sterilization of surfaces, disposable equipment covers, careful attention to appropriately preserve food and water

Preparing the MR Practice for a Pandemic

As we look to the future to move past COVID-19, there are multiple lessons to be learned regarding preparation for and response to a pandemic. We must take the lessons learned and apply them to both the ongoing COVID pandemic as well as future pandemics to ensure access to MR imaging for patients and research subjects involved in clinical trials and other studies, where the treatment strategy is informed by the MR imaging result.

Clinical MRI Scanning

An essential goal for an academic radiology or other clinical department is to maintain access to MR imaging for urgent and emergent clinical scenarios in a pandemic. It is also imperative to ensure access to MR imaging for complications caused by the pandemic pathogen for which MR imaging

directs therapy. Organizing MR imaging personnel coupled with strategically balanced access to MR imaging is essential.

ORGANIZING IMAGING TEAMS. An effective strategy to consider is to organize frontline MR imaging personnel into separate groups or pods to prevent one communicable individual from exposing the entire frontline imaging team (Fig. 1). The pods should be configured by the size of the smallest nuclear group necessary to run a single MR scanner and manage associated imaging subject flows. The temporal staggering of in-person presence by team minimizes the number of people that can be infected by an individual and creates redundant teams that can maintain minimal essential operations in the event of outbreaks. The pod duration can be determined by the time from exposure to the pathogen to symptom development. For the pod model to be successful, it is critical for team members to self-report when symptomatic, when exposed to a symptomatic family member in their household, or after a probable exposure outside of work. The duration of quarantine period should be determined by consultation with the local institution's occupational health department, the regional or national healthcare authority. Pod organization necessarily limits access to MR imaging slots and prevents all imaging scanners from being able to be safely staffed. The duration of the pod staffing model should be determined by the prevalence of disease in the local environment, availability and efficacy of vaccines, prevalence of vaccination in the local environment, and the effectiveness of PPE in preventing transmission of disease.

ENSURING MR IMAGING AVAILABILITY. Early in a pandemic ramping down imaging availability may be appropriate while organizing personnel and determining necessary procedures for performing MR imaging safely for symptomatic and asymptomatic patients. After organizing the imaging team, MR imaging availability should be ramped up to meet semi-urgent clinical scenarios while considering broader needs in the healthcare system and research environment with a goal to further expand access to MR imaging as can be achieved safely.[1,2] It is important to consider strategies to increase MR scanner availability by shortening imaging protocols (see rapid imaging below) to only those sequences essential for making a diagnosis, and where appropriate, to consider alternative imaging strategies based on patient factors. For example, in patients with significant claustrophobia it is desirable to avoid the need for general anesthesia as this lengthens the in-room time, increases the complexity of surface decontamination, and potentially the time required for scanner room air exchange. Finally, fluctuation in MR imaging demand should

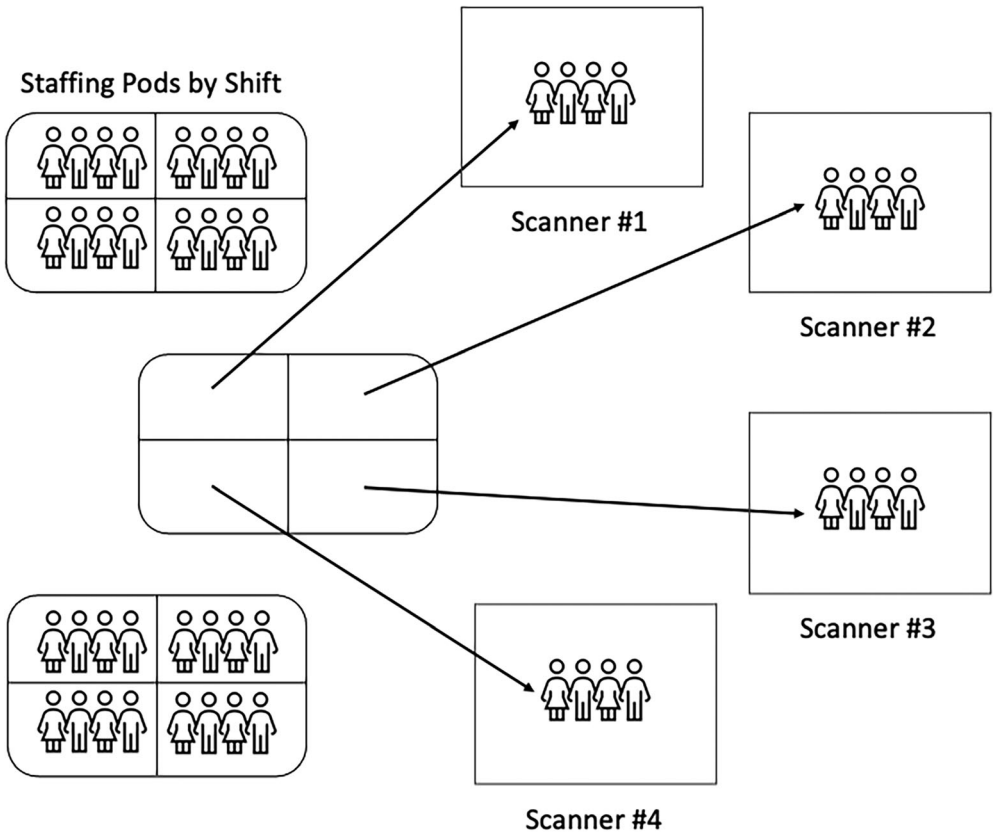


FIGURE 1: Schema detailing the staffing pod concept. MR frontline imaging staff are organized into separate pods. Pod size is determined by the number of staff necessary to run all aspects of a single MR scanning nuclear group. Staff only interact with those in their pod, containing exposures or infections.

be anticipated with greater demand than usual following reopening of the outpatient and surgical practices.

Patient Safety

Several facets of patient safety should be considered in the context of imaging during a pandemic. Patient safety issues need to be considered in the context of their disease status: pandemic disease positive, negative, indeterminate, or unknown–low risk. Depending on the prevalence of communicable asymptomatic infections it may be preferable to treat all patients as pandemic positive rather than changing the approach based on disease status. Considering all patients as positive has the disadvantage of using additional PPE and reduces efficiency of patient flow through MRI, but reduces pressure on laboratory testing services by obviating the need for testing specifically for the MRI appointment. When using PPE routinely for imaging subjects, the MR operation designated PPE stockpile should be continually monitored to ensure that MR operations can be maintained at the level directed by departmental or imaging center leadership. A goal of maintaining PPE adequate for MR operations for the number of days required to fulfill a new order is suggested. Additionally, the turnaround time for laboratory testing services may be impractical for the clinical urgency. Alternatives to laboratory-based testing including rapid testing strategies may be helpful to address efficiency concerns; the accuracy of such testing needs to be taken into account when integrating into the MR workflow. Questionnaires that inquire about symptoms, exposure to infected or potentially infected persons, and high-risk behaviors may be helpful in eliminating or limiting pandemic pathogen testing to a subset of individuals. It is important to engage patients in informed decision-making about the benefits of timely of MR imaging in the context of pandemic-specific and examination protocol-specific risks.

Patient classification as pandemic positive, indeterminate, unknown–low risk, or negative directly relates to PPE required, scanner and room cleaning, time for air circulation after scanning, and patient flow through the MR imaging area. PPE use by patients is necessary to protect other patients and personnel during a pandemic. The specific types of PPE required are related to the mode(s) of transmission applicable. Similarly, requirements for scanner and room cleaning as well as room air filtration time are dependent on patient disease status. Finally, certain pandemic specific patient symptoms such as dizziness, headaches, or heightened noise sensitivity may be exacerbated by the MRI environment and should be considered in the context of the known or suspected pandemic disease status.

Patient movement through the MR imaging area has different considerations for in- and out-patients. Pandemic disease positive or indeterminate in-patients should be transported directly to the scanner where possible, bypassing holding areas, with the goal to minimize the overall time such individuals spend in the MR imaging area. This altered workflow requires close coordination with transportation services. Pandemic disease negative in-patients on the other hand could be transported to MR imaging holding areas to streamline the workflow. Scheduling pandemic disease negative patients sequentially is suggested to improve efficiency. The outpatient imaging schedule should be similarly organized, with pandemic disease positive or indeterminate subjects separated in time and space from pandemic negative subjects. The number of individuals accompanying outpatients to the imaging area should be minimized and the waiting room should be rearranged to ensure appropriate social distancing between patients. Outpatients should be directed to arrive on time and to call the MR imaging area to reschedule if they will arrive more than 10 minutes beyond the reporting time. Where possible, different entrances and physical patient flows should be used for pandemic negative or unknown–low risk vs. pandemic positive or indeterminate patients.

The energy imparted to patients during an MRI examination has the potential to increase body temperature, and may exceed the patient's ability to dissipate heat in an acute febrile illness. Where possible, patient imaging should be performed at normal operating mode. Where image quality necessitates use of first-level SAR limits, careful attention to the patient is recommended for the examination duration. In this latter case, the room temperature should be adjusted accordingly in advance of imaging.

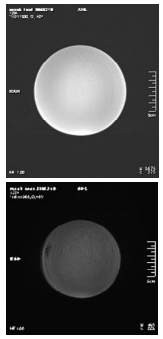
Ultra-high field systems (7 T and above) are increasingly available in clinical practice. As of 2020 more than 30+ such scanners have been installed around the world and are increasingly used in routine clinical practice. Imaging at ultra-high fields requires additional patient safety considerations during a pandemic including monitoring for local heating, exacerbation of pandemic-related symptoms such as dizziness, and increased attention to standard safety practices to mitigate risk of radiofrequency burns. Consequently, it is recommended to consider using lower field systems where the trade-off in image quality is acceptable. Imaging at ultra-high field strengths should be reconsidered in febrile or ventilated patients as well as those or require negative pressure chambers.

PPE safety in the MRI environment is an important consideration. Many masks, for example, have metal components which impart stiffness and assist in achieving a good seal over the bridge of the nose. It is recommended to have MR safe PPE to use specifically in the MR environment (Table 2). Although the hospital supply chain can help by using MR safe PPE, such PPE should also be provided to outpatients on arrival.

Specific Patient Safety Scenarios

- Pandemic positive patients or patients with indeterminate pandemic infection status with symptoms that may

TABLE 2. Masks and MR Compatibility

References	MRI Scanner	Masks Tested	MRI Safety Findings	MRI Artifact findings
Alfred[3]	3 T	3M 8210 	• No staples, aluminum nosepiece • Not fluid resistant Angle of Deflection	

Distance from bore (cm)	Duckbill (°)	3 M 1860 (°)	3 M 8210 (°)	3 M 8110S (°)	Face shield (°)
125	10	0	0	0	0
100	20	0	0	5	0
75	40	10	0	20	0
50	50	30	0	35	0
25	80	85	0	85	0

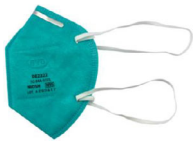
		BYD N95 DE2322 	• Aluminum nosepiece • No info on material of staple	
		3M 8110S 	• Steel staples, aluminum nosepiece • Not fluid resistant • See table above	

TABLE 2. Continued

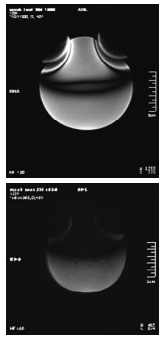
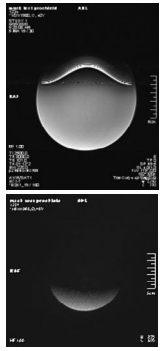
References	MRI Scanner	Masks Tested	MRI Safety Findings	MRI Artifact findings
		3M 1860 	• Steel staples, aluminum nosepiece • Fluid Resistance 80 mmHg • See table above	
		BSN Medical Australia Proshield N95 (duckbill) 	• See table above	
		Face shield 	• See table above	
Murray et al[4]	Siemens Avanto 1.5 T	1. 3M Aura respirator FFP3 1863	• 4× large ferromagnetic staples joining the elastic bands to the respirator itself	Considerable image artifact on gradient echo imaging

TABLE 2. Continued

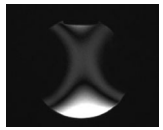
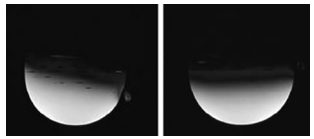
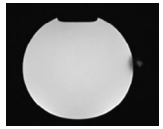
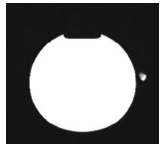
References	MRI Scanner	Masks Tested	MRI Safety Findings	MRI Artifact findings
			• Strong ferromagnetic attraction such that it was possible to lift the respirator from a flat surface using the magnet • Considerable translational/torque forces when close to the MRI magnet and completely lost contact with the phantom	
		2. Kolmi FFP2 respirator 3. Kolmi FFP3 respirator 	• Both showed strong ferromagnetic properties with the hand-held magnet • Could be lifted off a flat table by ferromagnetic attraction to the hand-held magnet • Both completely lost contact with the phantom when close to the MRI magnet	Considerable artifact on the gradient-echo imaging 
		4. Halyard Technology respirator FFP2 	• Did not exhibit evidence of ferromagnetism to the hand-held magnet or when resting on the phantom on the MRI table	Minimal artifact on gradient-echo imaging 
		5. Dahlhausen surgical facemask 	• No signs of ferromagnetism • Small aluminum strip present to allow the mask be formed over the nasal bridge	Minimal local artifact on gradient-echo imaging 
Cavin[5]	RIE Philips 1.5 T Ambition	1. Alpha Solway 3030 V 	• MRI Safe • No magnetic components	
		2. Alpha Solway S 	• MRI Safe • No magnetic components	

TABLE 2. Continued

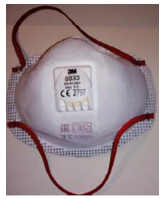
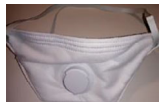
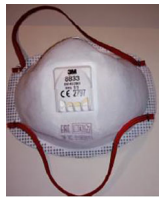
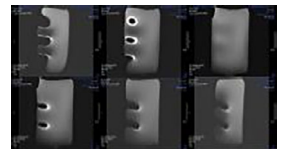
References	MRI Scanner	Masks Tested	MRI Safety Findings	MRI Artifact findings
		3. 3M 9332+ 	• MR Unsafe • Staples attaching to the mask are magnetic	
		4. 3M 8833 	• MR Unsafe • Staples attaching to the mask are magnetic	
		5. Cardinal Health RFVP 3FV 	• MR Unsafe • It has a magnetic metal band which undergoes considerable translational and torque forces when close to the MRI scanner bore	
Wesolowski and Davies[6]	1.5 T and 3 T	1. 3 M 8833 	• Conditionally safe • The metal strip across the nose is nonferromagnetic, but the staples holding the elastic are ferromagnetic and undergo some translational and torque forces when within approx. 20–30 cm of the bore entrance of a 1.5 T or 3 T MRI scanner • However, if securely fitted, there is no significant projectile risk in or around a 1.5 T or 3 T scanner. • We have not done fit-testing in the scanner room, but in our judgment they are manageable for staff positioning patients as at the bore entrance the pull did not feel strong enough to unseal the mask.	• Images of a phantom "wearing" this mask were obscured by large artifacts (>5 cm). 
		2. 3M Aura 1863 	• Safe for use by staff with caution (as described below) • The metal strip across the nose is nonferromagnetic, but the staples holding the elastic are ferromagnetic • They are larger than the 8833 staples and therefore undergo larger translational and torque forces when within approx. 50 cm of the bore entrance of a 1.5 T or 3 T MRI scanner.	• Patients should not wear this type of mask inside a 1.5 T or 3 T MRI scanner.

TABLE 2. Continued

References	MRI Scanner	Masks Tested	MRI Safety Findings	MRI Artifact findings
			• Although we have not done fit-testing in the scanner room, in our judgment, the pull could unseal the mask within approx. 50 cm of the bore entrance. • We recommend that staff wearing this mask should keep at least an arm's length away from the bore entrance	
		3. Easimask FSM18	• MR Safe • This mask has no ferromagnetic components • There are no detectable forces near or inside a 1.5 T or 3 T MRI scanner bore. • Other Easimask models such as FSM16 do contain metal (not tested here)	• No image artifacts were caused in images of a phantom "wearing" this mask.

Non-peer reviewed data for internal testing purposes not undertaken in accordance with American Society for Testing and Materials standards.

interfere with MR image acquisition: Patients with dyspnea, frequent coughing, involuntary movements, or altered mental status are challenging to image in the MR environment. If severe, coughing fits or involuntary movements may pose a potential for patient injury during MR imaging. Patient motion can also increase heating considerably in the MRI environment, especially at higher field strengths.[7] Alternative imaging methods should be considered in these patients. When MR imaging is determined medically necessary, the imaging protocol should be focused with integration of more efficient imaging techniques where possible. Sedation or general anesthesia may be necessary to ensure patient safety in the MR environment.

- Patient factors that limit the ability to wear recommended PPE for the duration of the MR examination: Alternative imaging modalities which are shorter and where the patient could tolerate PPE for the duration of the study should be considered. If MR imaging is specifically warranted, an abbreviated MR imaging protocol should be considered, with the goal to shorten the study while maintaining diagnostic utility to enable appropriate use of PPE throughout the MR examination. Despite these efforts, if patients are not be able to tolerate PPE use throughout the study additional attention is necessary to clean the room, scanner, and coil as well as ensure adequate air filtration.
- Use of anesthesia equipment in the MR scanner room: MR compatible ventilators must be utilized for patients undergoing MR imaging. If no such equipment is available patients should be continuously monitored with CO_2 capnography and bag ventilated by appropriately trained personnel by hand throughout the examination. Required air circulation and room cleaning is dependent on the mode of transmission, patient disease status, and whether an aerosolizing event occurred during the course of patient transport or imaging. Breaking the ventilator or hand bag air circuit (disconnecting the endotracheal tube from the ventilator/bag tubing) is considered an aerosolizing event and additional air circulation is required for pandemic pathogens communicable via aerosolized droplets.
- MR guided procedures: MR imaging guidance is helpful and sometimes necessary for procedural success. The timing of these procedures should be considered in the context of patient acuity and deferred where possible until the ramp-up of operations during the pandemic. Patient, room, and scanner concerns are based on the patient's infection status and specifics of the procedure and anesthesia required.
- Patients with tracheostomies: Patients with tracheostomies should have a mask placed to cover the tracheostomy. The tracheostomy should be treated similar to the nose and mouth of the patient.

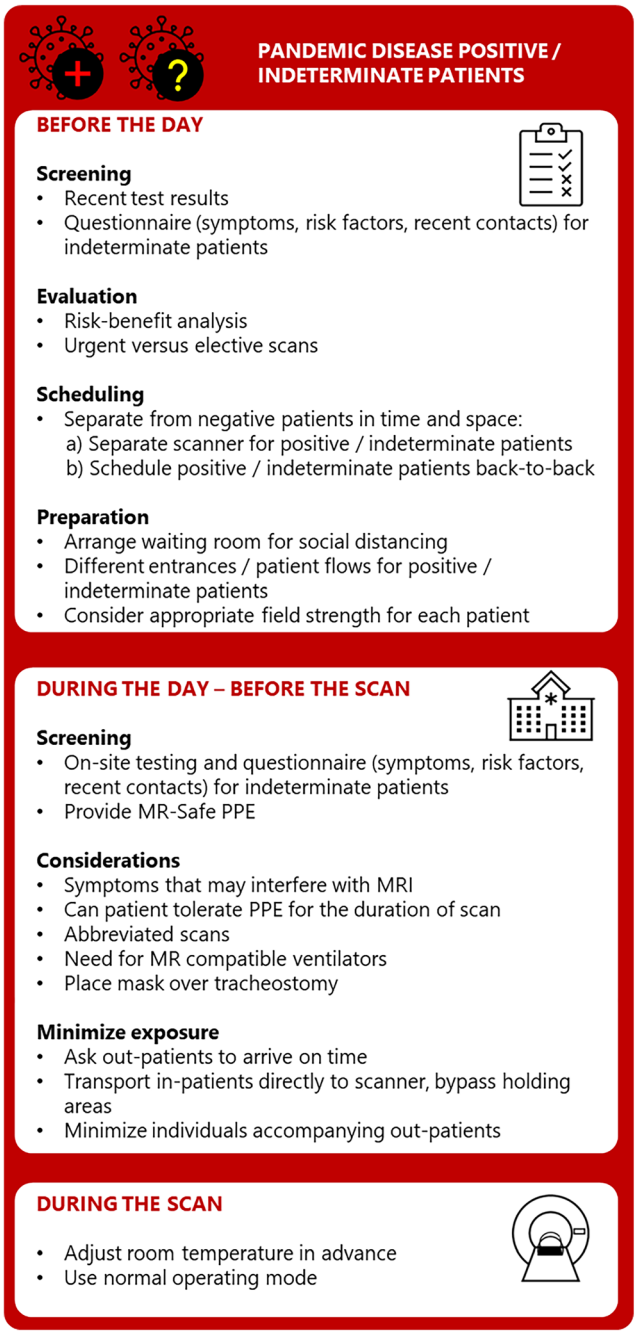


FIGURE 2: Summary of advance previsit, same-day prescan, and during scan guidance for MR imaging in pandemic positive or indeterminate patients.

The recommended workflow for pandemic disease positive/indeterminate patients is provided in Fig. 2. The recommended workflow for pandemic negative patients is provided in Fig. 3.

Personnel Safety

Multiple factors impact personnel safety when performing MR imaging during a pandemic. Knowledge of the imaging subject's pandemic disease status is helpful in achieving peak efficiency while maintaining appropriate precautions for imaging personnel. It is recommended that if a patient's disease status is unknown, imaging subjects should be tested if possible prior to MR imaging to determine their pandemic disease status. When reasonable based on clinical considerations, MR imaging of patients should be deferred until test results are known. Screening questionnaires are helpful in stratifying pandemic unknown testing status patients into indeterminate vs. unknown–low-risk groups and should be considered to streamline test utilization. Early in the pandemic response or in locations with limited testing capabilities, it is advisable to limit MR imaging to clinically urgent or emergent conditions or research protocols associated with treatment-impacting imaging time points.

Appropriate utilization of PPE by personnel and conservation of limited PPE stockpiles is critical to maintain sustained access to MR imaging during a pandemic. Guidance for PPE disposal may change over the course of a pandemic related to changes in understanding of risk with specific exposures as well as PPE availability. Patients may not be able to wear appropriate PPE in the MR scanner bore, increasing potential risk to personnel. The Safety In

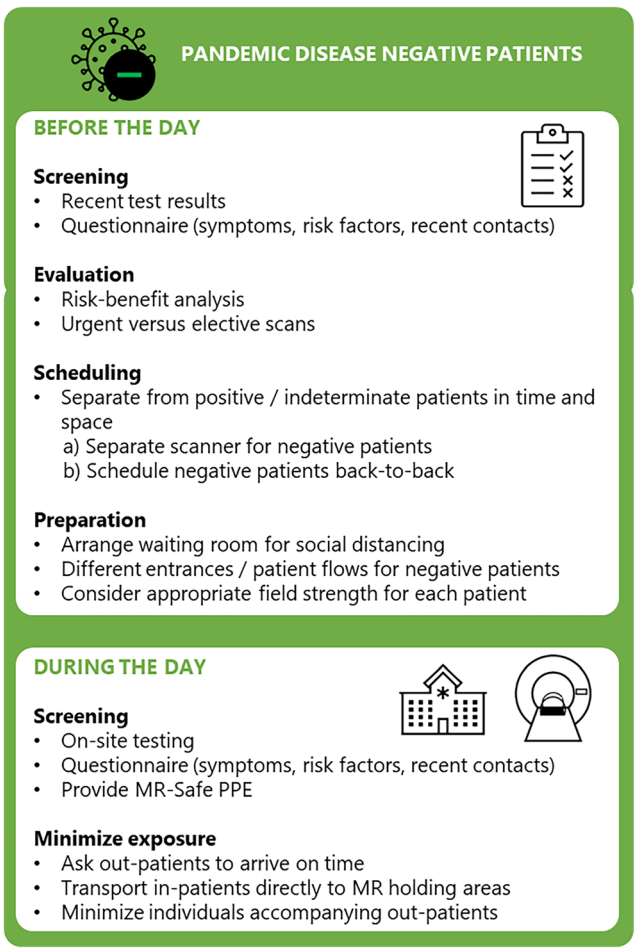


FIGURE 3: Summary of advance previsit and same-day considerations for performing MRI in pandemic negative patients.

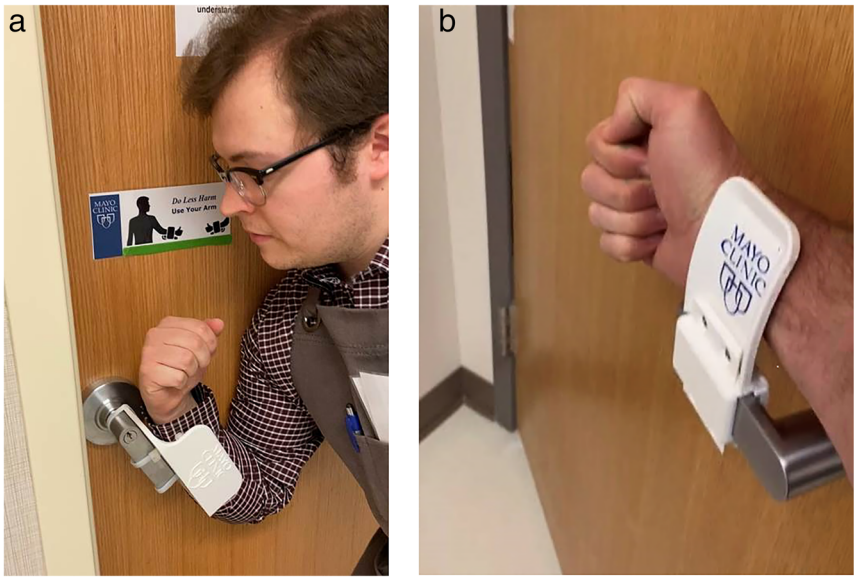


FIGURE 4: Three-dimensional-printed plastic door handle paddles to enable easy opening of doors with an elbow or forearm, reducing hand contact with the door latch. Different designs allow for opening while (a) pushing the door open or (b) pulling the door open. Images courtesy Dr Jonathan Morris, Mayo Clinic, Anatomic Modeling Unit, Rochester, MN.

Radiology HEalthcare Localised Metrological EnvironmenT (SIR HELMET) is a low-cost negative pressure barrier device that can be placed into MR scanner bores ≥65 cm as a method to reduce risk to frontline MR workers scanning patients with suspected stroke utilizing the head coil.[8] The SIR HELMET device is constructed of a 3 mm clear acrylic and is shaped as a hemi-cylindrical dome, creating a local negative pressure environment when attached to suction tubing. Other local solutions to PPE shortages are encouraged. For example, at the Mayo clinic in Rochester, MN the Anatomic Modeling Unit designed 3D-printed MR safe clear plastic shields for frontline workers, extending limited stockpiles of disposable eye protection. Similarly, the University of Wisconsin-Madison created a similar device, known as a "Badger Box," to create a local negative pressure environment for medical imaging examinations.[9]

It is important to adopt effective cleanliness practices throughout the MR imaging environment to prevent secondary spread of the pathogen between personnel via the contact mode of transmission. Cleaning strategies should be adopted for each MR safety zone with an understanding of imaging subject movement through the imaging area. Surfaces contacted by an imaging subject should be sterilized before coming into contact with a different imaging subject or personnel. Similarly, surfaces including the scanner consoles, keyboards/mice, and desktops should be sterilized when transitioning between personnel. It is important to note the length of time that a surface needs to remain wet for a sanitizer to be effective (Table 3). PPE is an adjunct to comprehensive surface sterility and should always be worn especially when performing surface sterilization procedures. Cleaning strategies before and during the day are summarized in Fig. 5.

Specific practice changes may be warranted such as transitioning personnel at a specific point of the MR workflow. For example, it would be disruptive to MR imaging subject flow to transition between scanning technologists during an imaging study due to the requisite sterilization process required for the scanner console, desk, keyboard, and chair. This should be taken into account when transitioning between staff member roles and between work shifts.

TABLE 3. Wet Surface Time for Cleaners

Disinfection Agent	Wet Contact Time Required for Virucidal and Bactericidal Effect (Minutes)
3M HB Quat 25 L	10
3M Disinfectant Cleaner RCT 40 L	3
Oxivir TB wipes	1
Oxivir 1 wipes	1
Sani-Cloth Prime	1
Sani-cloth bleach wipes (gold top)	4
Super Sani-Cloth (purple top)	2
Sani-Cloth plus (red top)	3
Sani-Cloth AF3 (gray top)	3

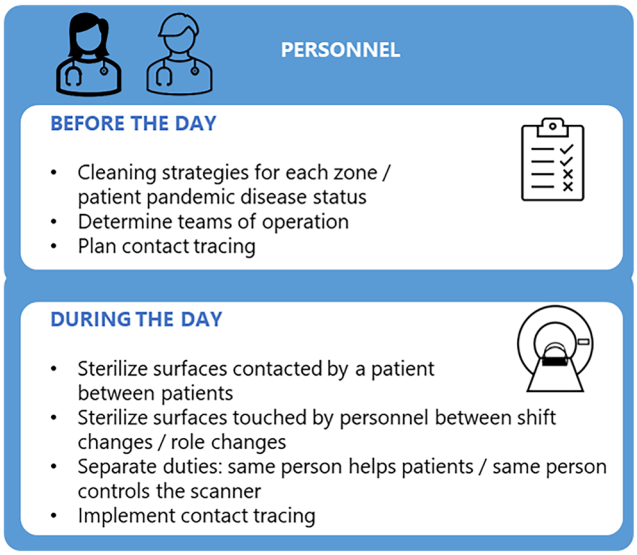


FIGURE 5: Summary of cleaning strategies in the MR environment before and during the day of scanning.

Figure 6 summarizes recommended disinfection strategies between patients and at the change of personnel shifts. If possible, the scanner control room should be isolated from the patients' access path to the scanner with one operator controlling the scanner and another helping the patients in and out of the scanner to minimize mutual exposure.[10] Finally, changes in the maximum allowed number of individuals in Zones III and IV should be considered to ensure adequate patient monitoring while maximizing personnel safety.

When the mode of pathogen transmission is known, an appropriate policy regarding high-risk droplet precautions should be established for the MRI environment. Planned imaging of patients who are pandemic positive or indeterminate pandemic status, with symptoms that could lead to droplet production (sneezing, coughing) or who require sedation with mechanical ventilation should trigger a plan to ensure adequate room air filtering between patients. As the majority of MR scanner rooms are not built with a negative pressure ventilation system, it is imperative to minimize aerosolization in Zone IV. It is recommended that patients requiring mechanical ventilation follow a workflow that maintains continuity of the respiratory circuit while in Zones III and IV, as this obviates the need for additional air circulation related to aerosolization of small particles. However, if the circuit becomes disconnected or the patient requires suction while in Zones III or IV, room circulation time should be adjusted to filter the bulk air to allow air turnover seven times between patients.[11] Where possible a fresh supply of air is recommended for air exchange; if recirculated air is needed high efficiency particulate air (HEPA) or other high-efficient filtration is required to ensure removal of small droplets.

MR imaging personnel teams should implement protocols to handle contact tracing in the department. At a minimum, a detailed log should be kept with personnel shift start and stop times, specific tasks assigned, and MR imaging subjects they came into contact with. It is recommended that the log also capture information about breaks or other gaps in assigned activities. A process should be developed to make decisions about quarantining an entire workgroup or pod versus identifying limited exposure of a few personnel in the pod. Personnel need to be reminded to keep vigilant about exposures both while working and on break time. Break rooms and eating areas should be rearranged and signage placed indicating appropriate guidance for safe use of these areas during a pandemic. PPE cannot be used while eating; as such it is critical for staff members to socially distance and avoid congregating together while eating.

Personnel safety can also be impacted by limiting the number of individuals accompanying imaging subjects into the MR environment. For in-patients, accompanying individuals should be limited to transporters, nursing personnel, or anesthesia personnel; family members should be restricted to pediatric patients or those patients requiring the presence of a caregiver to successfully complete the MR study. In these cases, only a single family member or caregiver should be permitted to accompany the patient. Family members and caregivers should go through the same screening process as the patient with the exception of pandemic testing, and should be required to wear appropriate PPE such as masks and face shields.

Pandemic Cleaning Recommendations by American College of Radiology MRI Safety Zone

Each American College of Radiology (ACR) safety MR imaging safety zone has different considerations for surface cleaning and air circulation cadence. ACR safety zones are defined in the ACR Manual on MR Safety.[12] Each MR safety zone is considered separately.

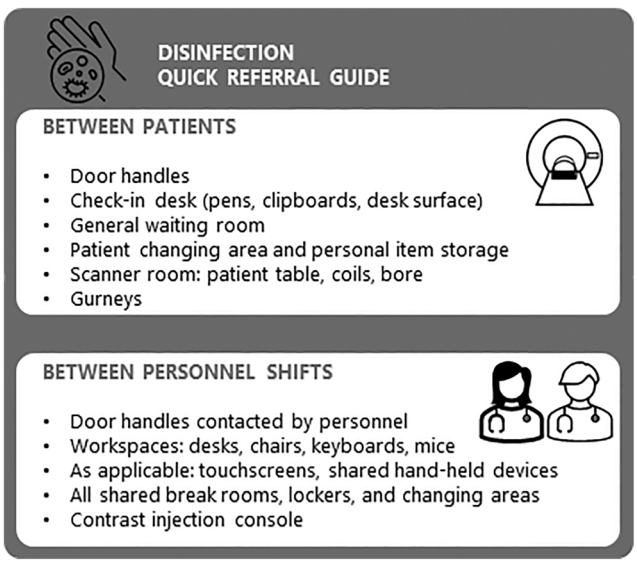


FIGURE 6: Summary of recommended disinfection strategies between patients and at the change of personnel shifts.

ZONE I. Appropriate PPE use should be encouraged by all facility visitors. A semi-automated mechanism for detecting MR imaging subject arrival for both in-patients and out-patients is recommended to restrict timing of entry to the facility. One option is to encourage use of imaging subject devices to alert staff to their arrival. Encouraging out-patients to call on arrival to the exterior of the imaging facility is suggested; personnel can restrict entry to those individuals arriving early or late as appropriate. Additional safety measures include automatic door opening/closing mechanisms or doorknob handle extensions which can be operated by an elbow rather than a hand (Fig. 4). Frequent and intermittent cleaning is recommended for all surface doorknobs, intercoms, or other mechanisms contacted by visitors to the imaging area.

ZONE II. PPE should be enforced in Zone II, and individuals wishing to enter this area should be screened for appropriate PPE use, or a relevant exemption prior to entry. Cleaning of Zone II should be performed periodically. The objective is to ensure that a chair or table in the waiting area is used by one family group and cleaned prior to use by an unrelated family group. Similarly, counters, pens, clipboards, check-in computer keyboards and mice, and lockers should be cleaned after each use. When staffing is insufficient to allow immediate cleaning signage should be applied demarking potentially contaminated areas and directing individuals to avoid use.

ZONE III. Cleaning of surfaces in Zone III should be performed after each imaging subject transitions out of the area. As noted above workstations, work desks, and other items used by transiting staff (nurses, transporters) should be cleaned prior to bringing in another imaging subject. Equipment should be used by a single imaging staff member and the equipment should be cleaned when transitioning to another staff member. Equipment refers to MR console keyboards, MR intercom, mice, desk surfaces, and chairs as well as MR coils, padding, pulse oximeter etc.

ZONE IV. Items within Zone IV that come into contact with the imaging subject must be cleaned between subjects. This includes coils, battery packs, sensors such as pulse oximeters, patient positioning belts and padding material, the scanner table, and the bore. External facing portions of the scanner that are contacted routinely by imaging personnel should also be cleaned between patients. Air circulation in the room should be continuously monitored. As airflow varies between different construction configurations, it is suggested to measure air turnover in the room and wait a sufficient length of time between subjects at high risk for aerosolization of particles to allow air in the room to turn over seven times. For patients without the risk of having an aerosolization event in the room, no wait period is required between patients.

For all MR imaging center zones a noncorrosive cleaner is suggested that has been verified to eradicate the pathogen in question. It is important to follow the label instructions and ensure an appropriate wet surface time. Care should be applied when using cleaning agents on screens as the screen coating may be damaged by certain agents. Monitor screens do not need to be cleaned between patients; however, touch screens must be sanitized between imaging subjects and personnel shifts. MR scanner field strength does not impact the cleaning strategy required. Ultraviolet-C (UV-C) light energy is an effective technology to clean surfaces.[13,14] Systems utilizing UV-C technology have been shown to be effective and efficient for sterilizing computed tomography (CT) scanner equipment.[15] Several UV-C light energy systems are MR compatible and have been optimized for sterilization of the MR scanner bore in as little as 2–3 minutes. These are time-efficient solutions to sterilize the MR scanner bore between imaging subjects.

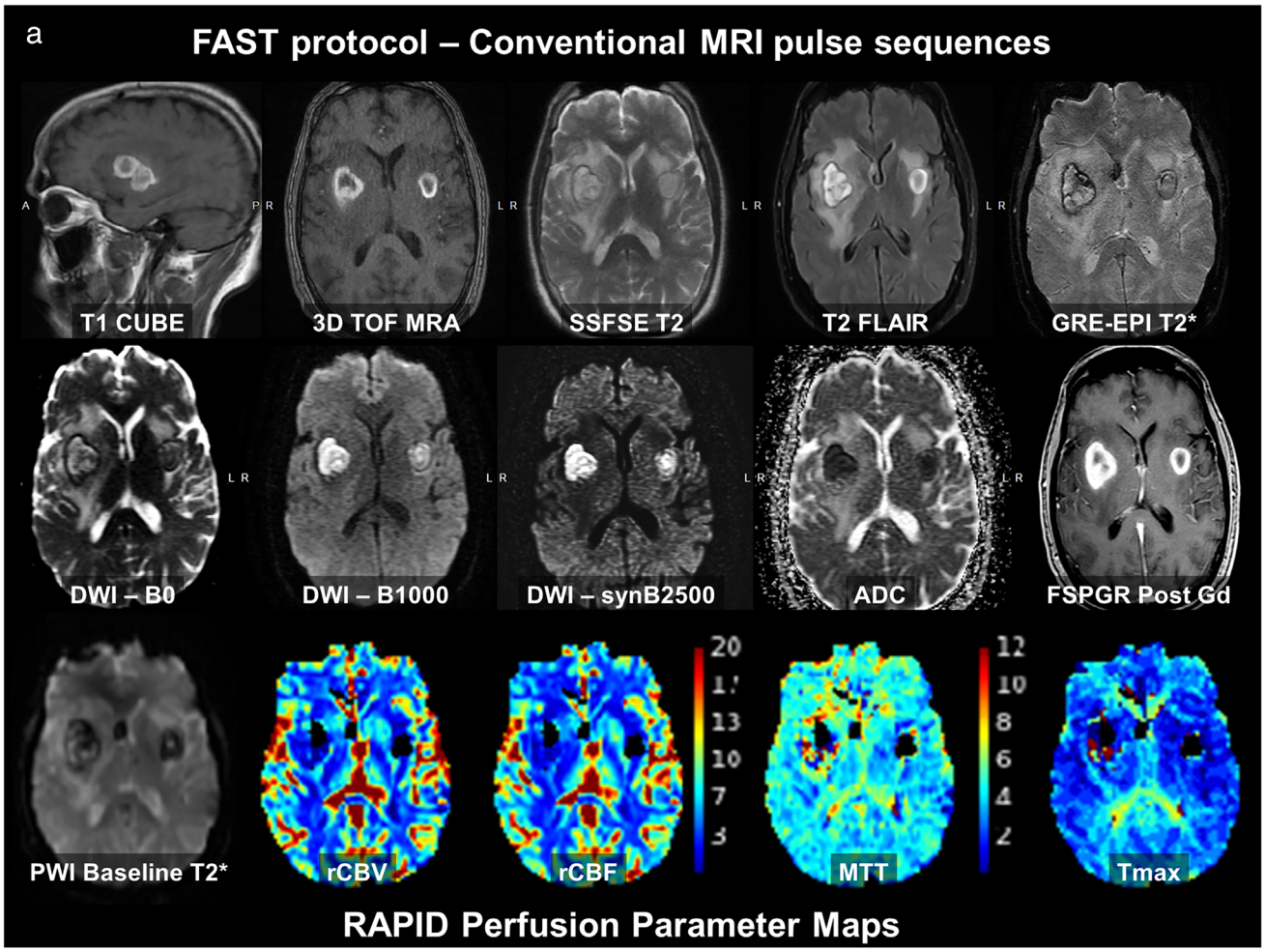
Special Considerations

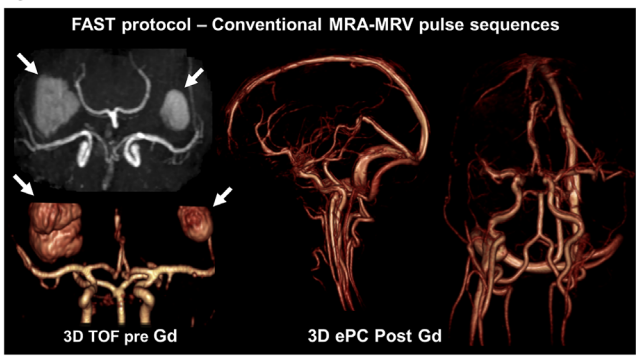
The MR environment poses several specific challenges over other imaging modalities in terms of PPE, ferrous screening, imaging time, device safety issues, and responding to an imaging subject emergency in Zone IV.

Ferrous Screening and PPE

In a pandemic just as is required for normal MR operations, imaging subjects must be screened for ferrous objects on their person and in their bodies. Standard MR safety questionnaires should be used to accomplish this standard screening process. However, in a pandemic, patients will report to the MR imaging area with personal PPE. It is unreliable to rely on patients to provide personal PPE manufacturer information. Therefore, although investigating the safety of such equipment for the MRI environment is time intensive, it may be appropriate if PPE stockpiles are strained.

A particular PPE challenge in the MR environment is the variable composition of material in the nose bridge of many N95 respirators and disposable masks. In addition, masks made with copper and silver nanoparticles infused into the material are very difficult to discern from a regular cloth masks. Therefore replacing these with a disposable mask without a rigid nose bridge is recommended in the MR environment. Details about different types of masks are provided in Table 2. If the safety of personal PPE for the MR environment cannot be confirmed, they should be treated as MR unsafe and imaging subjects should be instructed to replace personal PPE with supplied PPE safe for use in the MR imaging environment. Powered air purifying respirators (PAPRs) should not be brought into Zone IV due to the potential risk of adverse interactions between the ferromagnetic components of the system with the magnetic field.





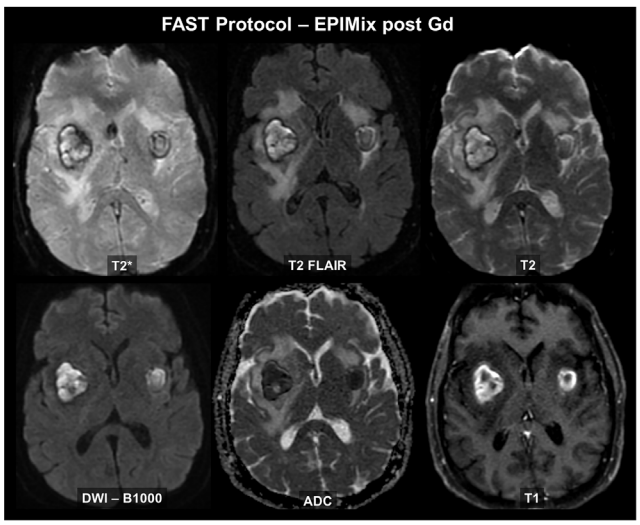


FIGURE 7: Focused, fast abbreviated survey technique (FAST) stroke protocol. (a) This ventilator-dependent man with COVID pneumonia developed encephalopathy and decreased responsiveness. There are subacute bilateral basal ganglia hemorrhages with surrounding vasogenic edema, attributed to COVID vasculopathy. By using parallel acceleration techniques, reduced matrices, compressed sensing, and other modifications, all images shown here required less than 15 minutes to acquire, and allowed complete characterization of lesions. (b) Single-slab 3D time-of-flight (TOF) MRA acquired with hypersense required 57 seconds, and 3D phase contrast MRA-MRV with velocity encoding of 50 cm/sec required 2 minutes, 10 seconds. These are complementary vascular sequences, with arterial emphasis on 3D TOF, but degraded by T1 methemoglobin shine through artifact; phase contrast shows all major arteries and veins and eliminates T1 shine through. (c) In this moving and delirious patient, six high-quality tissue contrasts were obtained in a total of 75 seconds using EPIMix, here done post gadolinium. (EPIMix pulse sequence courtesy of Stefan Skare, PhD, Karolinska University, Sweden).

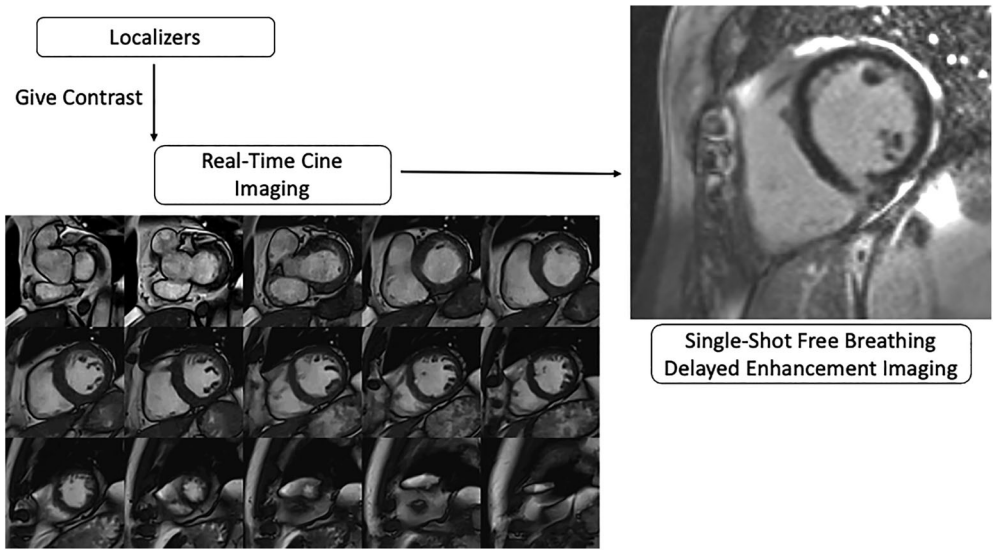


FIGURE 8: Rapid Cardiac MR imaging protocol for scar evaluation. Contrast is administered after confirming patient centering. Conventional breath-held segmented cine imaging is replaced with real-time cine sequences performed under either suspended respiration or free breathing. Myocardial delayed enhancement can be performed with single shot imaging techniques under suspended respiration or free breathing. The entire study can be completed in 15 minutes with excellent image quality in dyspnea and arrhythmia.

Role of Focused, Rapid MR Imaging Protocols

Access to MR imaging is important to maintain during a pandemic. There are additional strains put on MR access related to personnel staffing, the additional time necessary to sterilize Zones III and IV, and inefficiencies related to the intentionally slowed movement of patients through the imaging environment. Shortening the time for imaging also reduces the potential for patient and personnel exposure. A solution to improve MR scanner availability is the use of abbreviated or rapid protocols, which rely on more efficient rapid imaging sequences and/or a shortened imaging protocol focused to answer the clinical question posed. Accelerated scans also reduce the likelihood of safety and image-quality related effects of coughing and involuntary patient motion. Where possible radiologists should consider implementing focused, rapid protocols for use in a pandemic to shorten the overall imaging time. Although the specifics of such protocols are out of scope for this white paper, an example of such a protocol for neuroradiology is provided in Fig. 7 and for cardiac MR in Fig. 8. Examples for abdominal MRI are found in the literature.[16,17]

Implanted Device Safety Issues in the MR Environment

The prevalence of devices in patients has led to resources to clarify the safety of imaging patients with implanted devices in the MR environment. Given the prevalence of implanted devices and the broad utility of MR imaging in diagnosis, assessing treatment effect, and preprocedural planning there is a need for continued access to the MR environment for these patients. Imaging subject safety issues related to the need for additional personnel in the MR environment for monitoring should also be taken into account. Additionally, certain implantable devices require ancillary procedures (CT or X-ray imaging, cardiac implantable electronic device (CIED) interrogation before/after the scan) impacting personnel workflows in the MR environment. Adverse events related to devices in the MR environment are generally managed as they would outside of the constraints of a pandemic: removing the patient as quickly and safely as possible from Zone IV to either Zone III or Zone II for further assessment or resuscitation.

Responding to an Emergency in the MRI Environment

Personnel and emergency responders must first ensure their own safety when responding to an emergency in the MR environment. An automated cardioverter-defibrillator and medications appropriate to respond to a contrast reaction or life-threatening emergency should be immediately available in the MR area. MR personnel must initially remove the patient from Zone IV to Zone II or III. Resuscitation efforts begin by ensuring appropriate PPE for all individuals responding to the emergency situation. Although specific guidance will ultimately be determined by local hospital leadership, personnel should wear contact precaution PPE when attaching defibrillator pads (at a minimum gown, gloves, and surgical mask). When performing cardiopulmonary resuscitation personnel should wear PPE protecting against small droplets and contact precautions (at a minimum gown, gloves, N-95 respirator, eye protection, hair covering).

MR Imaging Research During a Pandemic

Many factors need to be considered when determining how to manage a MR imaging research enterprise during a

pandemic. Although guidance should preferably be provided by the institution's local Institutional Review Board (IRB) or affiliated university, this section can serve as a guide to radiology departments with active research programs balancing research personnel and study subject safety across the range of MR imaging settings. Radiology should engage the institutional IRB regarding studies under review or new research studies during a pandemic as standard workflows may be impacted by institutionally mandated staffing changes.

Staffing Concerns

Designated research magnets may not be accredited to perform clinical scans; however, the personnel working in a designated research area may be reassigned by the hospital's disaster management team to the pools of clinical MR technologists or clinical MR nurse personnel to augment staffing to allow for a pod-based staffing model. Staff may also be reassigned to other non-MR imaging related essential roles. The resultant limitations around available staff may require temporary closure of the MR imaging research center until the temporary staffing model is relaxed. In this setting research subjects should be imaged on clinical MR systems.

Ethical Considerations for MR Imaging Research

Radiology departments should consult with the local IRB or institution regarding continuing MR imaging research during a pandemic. In the absence of such direction, this section provides general guidance when performing MR imaging during a pandemic. It is important to recognize that imaging research covers the gamut from phantom studies to imaging endpoints directing changes in therapy as part of a clinical trial. The initial response should mirror the ramp down of clinical imaging at the institution which will likely amount to limiting MR imaging research to those protocols associated with ongoing clinical activities deemed urgent or emergent. MR imaging research studies that are performed as part of a clinical trial, where the imaging time points are necessary to direct patient care should be classified as urgent. When staffing considerations limit the ability to keep a MR imaging research facility open, research subjects on protocols deemed urgent should be scheduled as per urgent clinical cases on clinical magnets as access to technology allows (software version, pulse sequences, vendor, scanner field strength, etc.). Special consideration should be given for nonhuman subject research studies when the MR research facilities are available as these studies pose the least risks to personnel. Radiology research leadership should discuss the specifics of any changes to MR imaging protocols with the study principal investigator.

During the ramp-up of clinical MR imaging activities, MR research leadership should look to institutional leadership for guidance about restarting all MR imaging research studies. During the ramp-up it may not be feasible to staff the MR imaging research magnets, and access for research patients may be limited to clinical magnets. Decisions regarding restarting research imaging protocols should be made in the context of multiple factors including the prevalence of disease in the community, the availability of vaccinations, prioritization of research staff for vaccination programs, PPE stockpiles, clinical MR imaging volumes, and protocol-specific risks. A suggested research prioritization schema is provided in Fig. 9; this is intended as a starting point for institution-specific prioritization discussions.

Study participant and research personnel safety should mirror the practices put into place for clinical MR imaging. However, it is important that MR imaging research groups

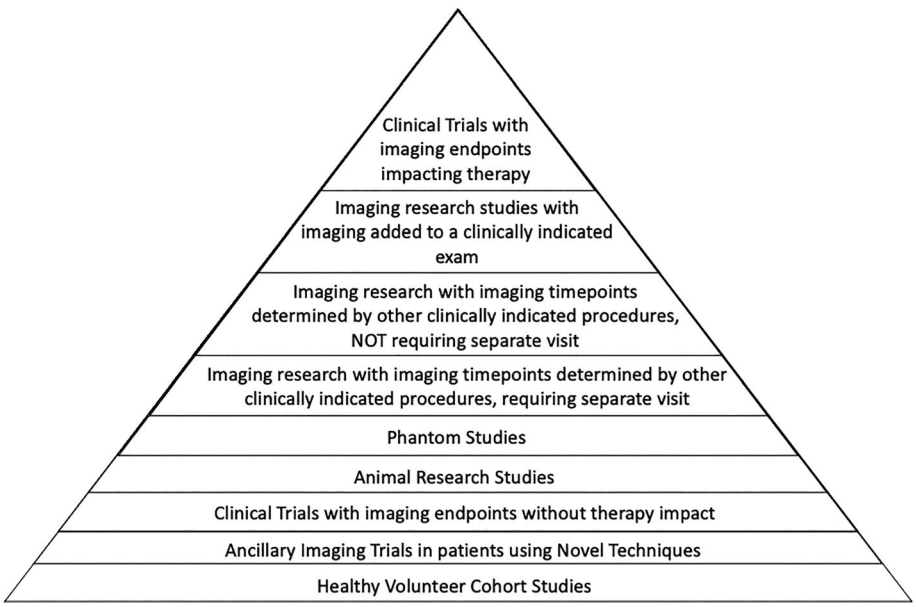


FIGURE 9: Prioritization of research studies: suggested research prioritization pyramid ordering types of human subject and nonhuman subject studies with those with lower direct participant benefit on the bottom.

maximize study participant safety for healthy cohort studies, as participants have limited ancillary benefit from participation.

Study-specific considerations include custom hardware (coils, device), protocols that lengthen the subject's time in the MR environment, and those protocols associated with higher specific energy deposition likely to raise participant body temperature. Cleaning practices described above for the clinical workflow should be adapted to custom hardware. Longer MR imaging protocols increase the length of time a volunteer is in the MR scanner, reduce access for other research studies, and may pose a greater risk to human subjects than shorter protocols. Finally, MR imaging research associated with greater specific energy deposition poses a greater risk to participants who may be febrile; it is important to implement appropriate screening for these research protocols and encourage protocol modifications where possible.

Parallels With Safety in Other Imaging Environments

There is synergy between processes needed to safely perform MR imaging and other diagnostic imaging modalities. The guidance provided in this white paper is applicable to all other diagnostic imaging modalities. In general, restrictions for MR imaging are more significant than for computed tomography, ultrasound, or radiography due to working in the presence of a strong magnetic field, the need for surface coils, and the overall length of time required for imaging. All imaging modalities require interaction between frontline radiology technologists and patients. Concerns regarding limiting and the re-establishing full access to imaging appointments are identical. Access to all imaging modalities is essential to the timely provision of urgent and emergent patient care. When deciding between imaging modalities in making a diagnosis for a particular patient, referring clinicians and radiologists should be free to choose the imaging test most likely to result in actionable information, limiting imaging tests to a single modality where possible. Modality choice should also consider risks to the frontline staff when diagnostic equipoise is present as different imaging modalities are associated with varied direct patient exposure and the ability to image an in-patient in their room rather than transport to an imaging suite (ultrasound, radiography). Radiologists should partner with their clinical colleagues to play an active role in maintaining access to imaging modalities during a pandemic.

Conclusion

MR imaging is an essential imaging modality in healthcare and the need for timely access to MR imaging continues during a pandemic. Early in a pandemic it is appropriate to limit MR imaging to those indications that are urgent or emergent, in the estimation of the referring clinician in consultation with the radiologist. The timing for expansion of MR imaging access beyond emergent and urgent indications should be considered in the context of the prevalence of disease in the local population, availability of effective PPE strategies, and prioritization of vaccine access to healthcare workers including research allied health staff. MR imaging research should also continue during a pandemic with prioritization to studies involving patients in clinical trials with imaging endpoints directing therapies. Radiology departments should have a comprehensive plan in advance for diagnostic imaging in general and MR imaging in particular to address challenges associated with maintaining access to imaging for both clinical purposes and research.

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[Correction added on 16 January 2022, after first online publication: Author names in references 7 and 10 have been corrected.]

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