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Permalink

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Journal

Topics in Magnetic Resonance Imaging, 29(4)

ISSN

0899-3459

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Publication Date

2020-08-01

DOI

10.1097/rmr.0000000000000247

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Peer reviewed

Practical Considerations for Radiologists in Implementing a Patient-friendly MRI Experience

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Abstract: For many patients, numerous unpleasant features of the magnetic resonance imaging (MRI) experience such as scan duration, auditory noise, spatial confinement, and motion restrictions can lead to premature termination or low diagnostic quality of imaging studies. This article discusses practical, patient-oriented considerations that are helpful for radiologists contemplating ways to improve the MRI experience for patients. Patient friendly scanner properties are discussed, with an emphasis on literature findings of effectiveness in mitigating patient claustrophobia, other anxiety, or motion and on reducing scan incompleteness or need for sedation. As shorter scanning protocols designed to answer specific diagnostic questions may be more practical and tolerable to the patient than a full-length standard-of-care examination, a few select protocol adjustments potentially useful for specific clinical settings are discussed. In addition, adjunctive devices such as audiovisual or other sensory aides that can be useful distractive approaches to reduce patient discomfort are considered. These modifications to the MRI scanning process not only allow for a more pleasant experience for patients, but they may also increase patient compliance and decrease patient movement to allow more efficient acquisition of diagnostic-quality images.

Key Words: abbreviated MRI protocols, claustrophobia, MRI scanner design, patient comfort, patient-friendly MRI

(*Top Magn Reson Imaging* 2020;29:181–186)

Magnetic resonance imaging (MRI) acquisition is a notoriously long process that is difficult for many patients. The patient must lie still for an extended period of time in a scanner with a relatively narrow bore and is subjected to auditory noise that can be as high as 130.7 dB^{1–3} (for comparison, an aircraft produces noise around 120 dB during takeoff).⁴ This makes for an unpleasant experience and can lead to premature termination or low diagnostic quality of imaging studies. Conversely, any innovation that reduces noise or scan time or any scanner design that creates more room for the patient in the scanner has the potential of improving diagnostic quality and patient satisfaction.

A number of physics and engineering advances have resulted in new equipment designs that improve patient comfort during MRI, as discussed in a separate article in this special issue. This article focuses on practical, patient-oriented considerations that will be helpful for radiologists contemplating ways to improve the MRI

experience they offer their patients. Patient-friendly scanner properties are discussed from the perspective of relevant clinical endpoints such as their effects on patient anxiety or motion. Adjunctive devices such as MRI goggles, headphones, and/or videos can be helpful to distract the patient from an otherwise potentially stressful experience and are discussed below. These auxiliary devices are especially important in the pediatric setting as described in more detail by Oztek et al⁵ (Gentle Touch: Non-invasive Approaches to Improve Patient Comfort and Cooperation for Pediatric Imaging) in part 2 of this Special Edition. Shorter imaging protocols (ie, fewer sequences) that can still answer the pertinent clinical question(s) directly reduce scan duration. Finally, other practical points such as patient positioning are also discussed. Notably, the interpersonal skills of the staff interacting with the patient, and the nature and quality of those interactions, can enhance the efficacy of all of these technical improvements. Discussion of these skills are beyond the scope of this article, and are described in more detail by Ajam et al⁶ (Communication and Team Interactions to Improve Patient Experiences, Quality of Care, and Throughput in MRI) in part 1 of this Special Edition.

SCANNER DESIGN FEATURES

A number of scanner design features are available that may improve patient experiences in the MRI scanner, with potential benefits to patient satisfaction, examination throughput, and image quality. Acoustic noise in MRI, predominantly related to gradient activity, is a major source of patient discomfort during MR image acquisition, often with noise levels in the 100 to 115 dB range but occasionally reaching 130.7 dB.^{3,7} Acoustic noise reduction represents one design approach to reduce patient discomfort and can yield up to 81% to 86% sound pressure reduction in clinical settings while maintaining diagnostic image quality.⁸ The feeling of confinement when placed in a long narrow bore of an MRI scanner, combined with the relatively long duration of many acquisition sequences, can lead to claustrophobia, panic attacks, or other anxiety manifestations. Shortened bore length, widened bore diameter, open-bore configurations, or other alterations in scanner architecture are design features that may reduce patient claustrophobia and anxiety-related discomfort. The engineering considerations associated with these modifications are discussed in more detail by Brunnquell et al (Making Magnets More Attractive: Physics and Engineering Contributions to Patient Comfort in MRI)⁹ in part 2 of this Special Edition, while the discussion below is more focused on the patient experience.

Many early MRI scanners were relatively narrow, with a tunnel-like shape and fairly restrictive internal dimensions. Internal bore diameters in the 50 to 60 cm range were typical, a size that can be uncomfortable or infeasible for obese or claustrophobic patients. A limitation of open-bore scanner designs, particularly among older scanners, is their typically lower field strength. The higher magnetic field strengths in cylindrical-bore systems enables better image quality and relatively faster acquisitions compared to their early open-bore counterparts. Although this does not affect diagnostic

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Received for publication April 14, 2020; accepted May 7, 2020.

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The authors declare no conflict of interest.

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DOI: 10.1097/RMR.0000000000000247

utility in many clinical settings, a small decrease in diagnostic accuracy has been reported for brain MRI interpretations when using low-field open-bore magnets.¹⁰ This drawback may be offset by greater patient tolerance due to the ability to see outside the magnet. One study using an interventional 60-cm diameter 0.5 T magnet with a 56-cm gap through which patients can see outside the scanner reported a 94% successful completion rate among claustrophobic patients.¹¹ Although this was a small study of only 50 patients, the study population consisted of high-risk patients who had previously failed conventional MRI attempts or were too claustrophobic to even attempt conventional MRI. Data from patient questionnaires in that study showed lower subjective feelings of claustrophobia in the interventional MRI scanner than during prior experience with conventional scanners.¹¹ In another study, a 1 T open-bore scanner was evaluated in 36 claustrophobic patients, reporting a lower rate of premature termination in the open magnet (8%) compared to 58% in close-bore systems.¹² Subjective intra-acquisition anxiety as assessed using a visual analogue scale was lower in the open magnet than in closed magnets.¹² Both of the above studies were relatively small and did not employ a randomized design and instead compared current open-bore experiences with recollection of past closed-bore scanning experiences.

In a large study of >55,000 consecutive patients, a conventional cylindrical 1 T magnet with length of 225 cm and width of 53 × 60 cm was compared to a newer MR scanner that had a shorter length of 160 cm, a wider conical shaped bore with diameter of 60 cm, and 97% less acoustic noise.¹³ The rate of claustrophobic reactions in this unselected population was 3 times higher in the older system (2.1%) than in the newer system (0.7%).¹³ The newer scanner had half the incompleteness rate (0.4% vs 0.8%) and decreased need for IV sedation (0.3% vs 1.3%).¹³ Despite the large study size, a major limitation of this study was a lack of prospective randomization. A more recent, smaller study examined patients who had claustrophobia-related cancellations or premature terminations on a 60-cm bore 1.5 T MRI and attempted to re-scan them on a 70-cm bore, 125-cm length 1.5 T scanner.¹⁴ The authors reported an 89% successful completion rate for the wider-bore scan attempt, thereby eliminating the need for general anesthesia in the vast majority of these claustrophobic patients.

In the randomized CLAUSTRO trial, 174 subjects unable to tolerate conventional MRI due to claustrophobia were randomized to open-bore or short-bore closed scanners, with the primary endpoint being rate of claustrophobia that precludes successful MRI completion.¹⁵ The open MRI group had a slightly lower rate of claustrophobic events (26%) than the short-bore closed MRI group (39%), but this difference did not quite reach the threshold for statistical significance.¹⁶ The relatively high rate of claustrophobic reactions in this study was likely due to selection of high-risk subjects, because the majority of patients had prior documented history of claustrophobia that prevented completion of prior MRI scan attempts. Of note, the open MRI scans took longer to complete due to longer acquisition times, or, if unsuccessful, took longer to trigger a claustrophobic event compared to the short-bore closed system.¹⁶

Overall, existing literature supports a benefit of wider bore, short bore, or open-view designs, particularly with respect to claustrophobia-related endpoints. Most new MR scanners produced in recent years have bore diameters of at least 70 cm, compared to the former 55 to 60 cm industry standard.¹⁷ Although they are more expensive than smaller-bore systems, the cost of the wide-bore systems is partially offset by benefits related to decreased patient preparation time, fewer claustrophobic events, and capacity to scan larger patients. Other newer approaches in MRI design that circumvent the risk of claustrophobia include the use of dedicated extremity MR scanners¹⁸ or portable point-of-care MR scanners^{19,20} that do not require patients to enter an enclosed space.

IMAGING PROTOCOL OPTIMIZATION

Another important determinant of patient comfort in MRI is the length of the imaging examination. Patient discomfort during a long MRI examination may manifest as increased patient motion and associated imaging artifact.²¹ This often leads technologists to repeat imaging sequences, further increasing the length of the scan. One study found that significant motion artifacts were present on 7.5% of outpatient and 29.4% of inpatient and/or emergency department MR examinations at a large tertiary care center, and that 19.8% of all MRI examinations had sequences which were repeated for motion artifacts.²² The observed higher prevalence of motion artifacts in Emergency department/inpatient settings likely reflects, at least in part, a greater level of discomfort/disorientation for acutely ill patients during the MRI examination.

One strategy for improving comfort and compliance for patients undergoing MRI for emergent indications is to tailor (shorten) the imaging protocol to most efficiently answer the specific clinical question being asked, as well as optimizing imaging parameters and using faster sequences. This has been of particular interest in neuroradiology. Most MRI vendors now offer fast and fully optimized scanning solutions for the brain in 5 to 6 minutes. Institutions can also modify scan parameters, including reducing imaging resolution, reducing signal-to-noise through a reduction in averages, or other measures such as parallel imaging or compressed sensing to accelerate their MRI acquisitions for all scans or for specific targeted applications, including motion reduction, pediatric, or stroke imaging. Physics-based techniques are described in more detail by Brunnquell et al⁹ (Making Magnets More Attractive: Physics and Engineering Contributions to Patient Comfort in MRI) and artificial intelligence by Nguyen et al²³ (Applying Artificial Intelligence to Mitigate Effects of Patient Motion or Other Complicating Factors on Image Quality) in part 2 of this Special Edition.

A number of groups have evaluated the accuracy and workflow improvement of the use of shortened scanning protocols in different patient groups and environments. Trofimova and Kadom²⁴ implemented an optimized 5-minute brain MRI protocol (sagittal T1-weighted, axial T2-weighted, axial T2 Fluid Attenuation Inverted Recovery (FLAIR), axial Diffusion weighted imaging (DWI), and axial T2* gradient-recalled echo sequences) in the clinical context of pediatric primary headache. A total of 31 cases scheduled to be performed with sedation were scanned with the accelerated protocol in patients younger than 8 years of age; of these, 74% were able to be completed without sedation. The accelerated protocol was able to detect abnormalities in 13 of 31 cases, and those who were found to be normal did not require any additional imaging later on. Fagundes et al²⁵ compared the performance of a 10-minute contrast-enhanced brain MRI protocol relative to a standard contrast-enhanced protocol in 53 ICU patients who were scanned without sedation. The comparison was between the following post-contrast sequences performed in random order in each patient: (1) standard T1 spin echo (2 min 30 s) and standard 3D T1 MPRAGE (5 min 20 s) versus (2) accelerated T1 Gradient echo (GRE) (33 s) and accelerated 3D T1 MPRAGE (3 min 3 s). Diagnostic accuracy was compared between the 2 protocols, and there was agreement on the diagnosis in all cases but 1 (61/62 diagnoses), in which a capillary telangiectasia was not initially detected on accelerated sequences but was visible in retrospect. A head-to-head comparison between the sequences was also performed, and the accelerated 2D T1 GRE sequence was felt to have improved image quality ($P < 0.01$) and fewer artifacts ($P < 0.01$) than the corresponding standard spin echo acquisition by the raters, whereas there was no statistically significant difference between the MPRAGE sequences. Nael et al²⁶ evaluated the image quality of a 6-minute MRI protocol that included echo planar FLAIR, T2* GRE, DWI, T2* Dynamic susceptibility contrast perfusion, contrast-enhanced neck

and brain MRA. This imaging protocol was performed in 84 scans on 62 patients, and 90% to 100% of the sequences were of diagnostic image quality per 2 raters. A total of 95% of cases had acute infarction, with inter-rater agreement for findings on FLAIR of $k = 0.78$, mismatch detection on DWI-Tmax of $k = 0.92$, and arterial stenosis on MRA of $k = 0.93$. Thirteen hemorrhages were detected on the gradient recalled echo sequence, with agreement on all cases between raters. These studies show the feasibility of performing accelerated focused imaging protocols that can reduce motion artifacts and the need for sedation, without significant loss in diagnostic value.

Abbreviating or combining protocols can be particularly effective when multiple contiguous body regions are being imaged at the same time for the same indication. For example, patients with an acute neurologic deficit may be referred for urgent MRI of the cervical, thoracic, and lumbar spine to evaluate for spinal cord compression. These 3 MRI examinations performed with routine protocols typically require 90 minutes or more to acquire. An abbreviated protocol consisting of only sagittal images may, however, be sufficient to exclude acute spinal cord compression. One center instituted a screening spine MRI protocol for this indication consisting of noncontrast sagittal T1-WI and sagittal STIR sequences through the entire spine, which reduced scan time by 50% to 70% but preserved diagnostic quality.²⁷ In this study, if acute spinal cord compression was seen on sagittal imaging during the acquisition, the protocol would be converted to a complete study of the affected region with additional axial and postcontrast imaging. Another center described their experience establishing an efficient MRI workflow for a dedicated emergency department scanner with abbreviated neuroimaging protocols designed for making emergent treatment and admit/discharge decisions.²⁸ In this system, emergency department MRI protocols were designed to be completed within 10 minutes, compared to the more comprehensive versions of these protocols which required 30 to 60 minutes of acquisition time. The shortened protocol was sufficient to make disposition decisions in the majority of patients, but some patients who were admitted based upon the findings of the Emergency department triage MRI subsequently underwent a standard comprehensive inpatient MRI.

ADJUNCTIVE DEVICES AND PRACTICAL APPROACHES FOR IMPROVED PATIENT COMFORT

Despite promising evidence for some of the patient-friendly scanner design features, it may not always be practical to replace an existing scanner with one with more advanced features. Other, relatively inexpensive and smaller modifications to the scanner environment can be attempted with some success.

Virtual Reality

The use of virtual reality systems has been shown to distract patients and help with pain,^{29–31} for example, in burn patients as described in more detail by Bermo et al³² (Virtual Reality to Relieve Pain in Burn Patients Undergoing Imaging and Treatment) in part 2 of this Special Edition. Although it has not yet been widely applied to imaging, there are some studies demonstrating it as a potentially useful method to improve patient experience.

Simulating an MRI examination can help patients prepare for the study. By now, the technology is sufficiently advanced that an accurate replica of the real experience can be reliably produced so the patient knows what to expect. More importantly, Virtual reality (VR) has been successfully used for desensitization therapy, making the real experience more tolerable. VR preparation also empowers the patient to start, stop, and restart the experience at any point, giving the patient a sense of control over the whole process, which may be preferable to other desensitization approaches such as use of mock MRI scanners.³³

Clinical studies evaluating the efficacy of VR in the context of MRI are very limited and mostly focused on children. Liszio and Masuch³⁴ tested a prototype VR application for children and concluded that children participating in the study liked it, but decreases in anxiety were not conclusively demonstrated. Children reported reduced anxiety before the MRI, but while there was a trend for decreased anxiety during the actual scan, this was not significantly different from the control group. Nakarada-Kordic et al³⁵ compared VR to mock MRI scans and did not find any difference in patient anxiety between the 2 methods. Eysenbach et al³⁵ developed a VR Smartphone application that enabled children to experience a simulation of the actual scan. The children reported positive responses. Four of the 5 patients who were initially scheduled for an examination under general anesthesia were able to have an awake study, but the lack of a control group makes generalizing the efficacy of their approach difficult. Also, parents reported that the app helped them to reduce their own anxiety by helping them to better understand the procedure and therefore better prepare their child.

VR can be used as a distraction for patients with claustrophobia. Garcia-Palacios et al³⁶ reported a case of a patient with claustrophobia who initially failed a mock MRI scan but was able to successfully complete the mock study with the help of VR. Of note, they performed only a mock scan and not a real study, but their approach may be translatable to actual scanning conditions.

There are some major obstacles to the use of VR during actual MRI scans. The requirement to not move during a scan makes for a less immersive VR experience. MRI-compatible goggles that can use VR have a more limited field-of-view and resolution than, for instance, commercial gaming sets.³⁷ Therefore at this point, without more advanced MR-compatible sets, use of VR seems limited to patient preparation, with an emphasis on children and specific patient groups such as those with high anxiety or claustrophobia.

Audiovisual Systems

Audiovisual (AV) systems such as goggles and headphones can be used to distract patients.³⁸ This lets patients filter out unpleasant parts of the study, such as confinement and noise, and focus on enjoyable aspects, such as entertainment.³⁹ The patient can also choose what to watch or listen to, and this gives them an element of choice, empowering the patient. There are commercial MRI-compatible AV systems that include video goggles and headphones. Cheaper alternatives like mirror-reflected videos can also be used.⁴⁰ Again, these systems have been tested mostly on children, because cooperation during MRI is a larger issue with them. This is described in more detail by Oztek et al⁵ (Gentle Touch: Non-invasive Approaches to Improve Patient Comfort and Cooperation for Pediatric Imaging) in part 2 of this Special Edition, but briefly, AV systems have been shown to reduce sedations by up to 30%, with the greatest impact in the 4- to 10-year-old patient group.^{38–40}

MRI-compatible headphones can be part of an AV system as described above. They are, however, beneficial even without an AV system because they provide hearing protection and facilitate communication between the technologist and the patient.⁴¹ Use of headphones or earplugs, is one of the simplest and least expensive ways of providing acoustic noise protection during MRI.⁷ There have been reports of earphones providing noise reduction of up to 30 dB.⁴¹ They can also allow the patient to better hear what the technologist is saying and thus enable updating the patient on examination progress or giving feedback or warnings before certain sequences that may vary acoustically.

Music

As mentioned above, loud noise is one of the major sources of patient discomfort. An alternate approach to reducing this discomfort

is converting that noise to something more enjoyable. Music as a distraction has been used in various clinical scenarios and has been shown to decrease anxiety in transrectal prostate biopsies⁴² and outpatient urologic procedures,⁴³ in preoperative settings,⁴⁴ and during chemotherapy.⁴⁵

One possibility is simply using headphones to play music. The results, however, related to listening to music in the setting of MRI are not conclusive. Earlier studies showed anxiety levels in patients with earplugs and in patients listening to their preferred music to be no different.⁴⁶ On the contrary, Földes et al⁴⁷ reported better relaxation with music, and Slifer et al⁴⁸ reported decreased anxiety and somatic complaints when patients listened to music during the examination. Another study in which a music therapist played live music matching the tempo to the acoustic noise of the scanner reported decreased anxiety and patient motion compared to patients listening to recorded music of their choice.⁴⁹ Interestingly, in this study not hearing the recorded music well was a common complaint, whereas the live music group did not raise this issue at all. In fact, patients listening to live music could hear the music even when they could not hear the researcher's voice over the magnet's noise. This could be because listening to a piece without prior familiarity may need more active participation on the patient's part and be a better distraction, whereas playing recorded music based on the patient's preference most likely results in familiar pieces being played, making it a more passive and thus less effective measure.

In addition to music, listening to relaxing sounds may also have a calming effect as demonstrated by Stanley et al,⁵⁰ who found that patients reported a subjectively improved experience when they listened to bird noises. Patient motion was, however, not significantly decreased. It is also possible to have sequences that can acquire data and simultaneously play musical sounds using the gradients. This has been reported to be especially suited for localizer scans, where it may reduce the patient's initial anxiety.⁵¹ A different method of image acquisition based on MR fingerprinting, called MR fingerprinting-music, "plays" a short piece of classical music on the gradient coils during the scan; scan volunteers reported significantly improved comfort levels when this technique was employed.⁵²

Radiofrequency Coils

Rigid and bulky coils may be uncomfortable and intimidating for the patient. Beyond discomfort caused by the coil itself, placement of the coil alongside MR-compatible support lines and tubes can exacerbate patient discomfort and increase the door-to-door time of the study.⁵³ Recently, flexible and more comfortable coils systems have been proposed as alternatives to the current standard coils.^{54–57} Winkler et al⁵⁸ evaluated 20 children using 12-channel coil arrays designed by a screen printing process. These coils provided adequate SNR with similar image quality and were preferred by both children and their parents. Vincent and Rispoli⁵⁹ developed a stretchable and flexible coil with SNR similar to flexible, standard Printed circuit board coils. An additional advantage of this is the potential for closer placement of the coil to the skin, therefore, increasing the SNR compared to standard coils. Design efforts of smaller, lighter, and more flexible coils are discussed in more detail by Brunquell et al⁹ (Making Magnets More Attractive: Physics and Engineering Contributions to Patient Comfort in MRI) in part 2 of this Special Edition.

Pressure Relief Systems

The requirement that patients lie still for extended periods of time during MRI is one major source of discomfort and is a potential cause of patient motion. Increasing patient comfort can improve the patient's experience and facilitate completion of studies with less motion artifact. Using pads made from pressure-reducing viscoelastic materials decreased patient motion, resulting in a 56% reduction

in repeat sequences and a 50% reduction in patients needing to repeat the entire study.⁶⁰

Fragrance

Lorig and Schwartz⁶¹ demonstrated reduced anxiety in college students under resting conditions with specific fragrances.⁶² Redd et al applied this idea to patients undergoing MRI, administering heliotropin, which they reported to be a faint, sweet, vanilla-like scent, via nasal cannula. They reported decreased anxiety compared to patients receiving humidified air only and postulated that this is likely due to physiologic effects of the fragrance and distraction caused by associative reactions to it.⁶² Similar to their experience with bird noises, Stanley et al⁵⁰ demonstrated a subjective improvement in patient experience without an objective decrease in patient movement when there was a scented cotton pad placed near the scanner for sensory stimulation.

Patient Positioning

Patient positioning in MRI is almost always supine, with some exceptions such as breast MRI, which can be performed prone. One study, however, reported significantly fewer premature terminations of breast MRI studies compared to other studies and hypothesized that prone positioning might be a major cause of this.⁶³ An older study reported 11 patients who experienced claustrophobia were turned in the prone position and then were able to complete the MRI without further problems.⁶⁴

CONCLUSIONS

In summary, we have described various ways to increase patient comfort during an MRI study, including modifications to the scanner, modifications to the protocol, and other modifications to the scanner suite in the form of auxiliary devices. These not only allow for a more pleasant experience but may also increase patient compliance, decrease patient movement, and/or allow for quicker or better-quality imaging. There is no one-size-fits-all approach, and appropriate use should be determined by considering the patient and the indication for imaging. Combined with interpersonal interaction, appropriate patient education and preparation, and engineering advances toward more patient-friendly scanners, these measures can be effective in reducing patient anxiety and may improve imaging quality and efficiency.

REFERENCES

1. Price DL, De Wilde JP, Papadaki AM, et al. Investigation of acoustic noise on 15 MRI scanners from 0.2 T to 3 T. *J Magn Reson Imaging*. 2001;13:288–293.
2. Radomskij P, Schmidt MA, Heron CW, et al. Effect of MRI noise on cochlear function. *Lancet*. 2002;359:1485.
3. Hattori Y, Fukatsu H, Ishigaki T. Measurement and evaluation of the acoustic noise of a 3 Tesla MR scanner. *Nagoya J Med Sci*. 2007;69:23–28.
4. Münzel T, Schmidt FP, Steven S, et al. Environmental noise and the cardiovascular system. *J Am Coll Cardiol*. 2018;71:688–697.
5. Oztek MA, Noda S, Beauchemin EA, et al. Gentle touch: noninvasive approaches to improve patient comfort and cooperation for pediatric imaging. *Top Magn Reson Imaging*. 2020;29:187–195.
6. Ajam AA, Tahir S, Makary MS, et al. Communication and team interactions to improve patient experiences, quality of care, and throughput in MRI. *Top Magn Reson Imaging*. 2020;29:131–134.
7. McJury M, Shellock FG. Auditory noise associated with MR procedures: a review. *J Magn Reson Imaging*. 2000;12:37–45.
8. Heismann B, Ott M, Grodzki D. Sequence-based acoustic noise reduction of clinical MRI scans. *Magn Reson Med*. 2015;73:1104–1109.
9. Brunquell CL, Hoff MN, Balu N, et al. Making magnets more attractive: physics and Engineering Contributions to Patient Comfort in MRI. *Top Magn Reson Imaging*. 2020;29:167–174.

10. Merl T, Scholz M, Gerhardt P, et al. Results of a prospective multicenter study for evaluation of the diagnostic quality of an open whole-body low-field MRI unit. A comparison with high-field MRI measured by the applicable gold standard. *Eur J Radiol.* 1999;30:43–53.
11. Spouse E, Gedroyc WM. MRI of the claustrophobic patient: interventionally configured magnets. *Br J Radiol.* 2000;73:146–151.
12. Bangard C, Paszek J, Berg F, et al. MR imaging of claustrophobic patients in an open 1.0T scanner: motion artifacts and patient acceptability compared with closed bore magnets. *Eur J Radiol.* 2007;64:152–157.
13. Dewey M, Schink T, Dewey CF. Claustrophobia during magnetic resonance imaging: cohort study in over 55,000 patients. *J Magn Reson Imaging.* 2007;26:1322–1327.
14. Hunt CH, Wood CP, Lane JJ, et al. Wide, short bore magnetic resonance at 1.5 T: reducing the failure rate in claustrophobic patients. *Clin Neuroradiol.* 2011;21:141–144.
15. Enders J, Zimmermann E, Rief M, et al. Reduction of claustrophobia during magnetic resonance imaging: methods and design of the "CLAUSTRO" randomized controlled trial. *BMC Med Imaging.* 2011;11:4. Published 2011 Feb 10. doi:10.1186/1471-2342-11-4.
16. Enders J, Zimmermann E, Rief M, et al. Reduction of claustrophobia with short-bore versus open magnetic resonance imaging: a randomized controlled trial. *PLoS One.* 2011;6:e23494.
17. Nyanue W. Economic Considerations of Wide Bore MR. 2014; 2020. Available at: <https://www.itnonline.com/article/economic-considerations-wide-bore-mri>. Accessed October 3, 2014.
18. Sutter R, Tresch F, Buck FM, et al. Is dedicated extremity 1.5-T MRI equivalent to standard large-bore 1.5-T MRI for foot and knee examinations? *AJR Am J Roentgenol.* 2014;203:1293–1302.
19. Wald LL, McDaniel PC, Witzel T, Stockmann JP, Cooley CZ. Low-cost and portable MRI [published online ahead of print, 2019 Oct 12]. *J Magn Reson Imaging.* 2019;10. 1002/jmri.26942.
20. Cooley CZ, Stockmann JP, Armstrong BD, et al. Two-dimensional imaging in a lightweight portable MRI scanner without gradient coils. *Magn Reson Med.* 2015;73:872–883.
21. Zaitsev M, Maclaren J, Herbst M. Motion artifacts in MRI: a complex problem with many partial solutions: motion artifacts and correction. *J Magn Reson Imaging.* 2015;42:887–901.
22. Andre JB, Bresnahan BW, Mossa-Basha M, et al. Toward quantifying the prevalence, severity, and cost associated with patient motion during clinical MR examinations. *J Am Coll Radiol JACR.* 2015;12:689–695.
23. Nguyen XV, Oztek MA, Nelakurti DD, et al. Applying artificial intelligence to mitigate effects of patient motion or other complicating factors on image quality. *Top Magn Reson Imaging.* 2020;29:175–180.
24. Trofimova A, Kadam N. Added value from abbreviated brain MRI in children with headache. *Am J Roentgenol.* 2019;212:1348–1353.
25. Fagundes J, Longo MG, Huang SY, et al. Diagnostic performance of a 10-minute gadolinium-enhanced brain MRI protocol compared with the standard clinical protocol for detection of intracranial enhancing lesions. *Am J Neuroradiol.* 2017;38:1689–1694.
26. Nael K, Khan R, Choudhary G, et al. Six-minute magnetic resonance imaging protocol for evaluation of acute ischemic stroke: pushing the boundaries. *Stroke.* 2014;45:1985–1991.
27. Potigailo VL, Christoforidis GA, Katzman GL. Acute spinal cord compression: CQI framework increases resource efficiency while promoting delivery of high-quality care. *J Am Coll Radiol.* 2015;12:90–94.
28. Buller M, Karis JP. Introduction of a dedicated emergency department MR imaging scanner at the Barrow Neurological Institute. *AJNR Am J Neuroradiol.* 2017;38:1480–1485.
29. Jones T, Moore T, Choo J. The impact of virtual reality on chronic pain. *PLoS One.* 2016;11:e0167523.
30. Hoffman HG, Patterson DR, Seibel E, et al. Virtual reality pain control during burn wound debridement in the hydrotank. *Clin J Pain.* 2008;24:299–304.
31. Hoffman HG, Chambers GT, Meyer III WJ, et al. Virtual reality as an adjunctive non-pharmacologic analgesic for acute burn pain during medical procedures. *Ann Behav Med.* 2011;41:183–191.
32. Bermo MS, Patterson D, Sharar SR, et al. Virtual reality to relieve pain in burn patients undergoing imaging and treatment. *Top Magn Reson Imaging.* 2020;29:203–208.
33. Nakarada-Kordic I, Reay S, Bennett G, et al. Can virtual reality simulation prepare patients for an MRI experience? [published online ahead of print, 2019 Nov 28]. *Radiography (Lond).* 2019;S1078-8174. 30166-X.
34. Liszio S, Masuch M. Virtual reality MRI: playful reduction of children's anxiety in MRI exams. In: Proceedings of the 2017 Conference on Interaction Design and Children; 2017: 127–136.
35. Eysenbach G, Evans C, Peres N, et al. A free virtual reality experience to prepare pediatric patients for magnetic resonance imaging: cross-sectional questionnaire study. *JMIR Pediatr Parent.* 2019;2:e11684.
36. Garcia-Palacios A, Hoffman HG, Richards TR, et al. Use of virtual reality distraction to reduce claustrophobia symptoms during a mock magnetic resonance imaging brain scan: a case report. *Cyberpsychol Behav.* 2007;10:485–488.
37. Förlim CG, Bittner L, Mostajeran F, et al. Stereoscopic rendering. *Front Hum Neurosci.* 2019;13:365.
38. Lemaire C, Moran GR, Swan H. Impact of audio/visual systems on pediatric sedation in magnetic resonance imaging. *J Magn Reson Imaging.* 2009;30:649–655.
39. Koch BL. Avoiding sedation in pediatric radiology. *Pediatr Radiol.* 2008;38(suppl 2):S225–S226.
40. Harned RK, Strain JD. MRI-compatible audio/visual system: impact on pediatric sedation. *Pediatr Radiol.* 2001;31:247–250.
41. Tellmann L, Herzog H, Boers F, et al. Alternative headphones for patient noise protection and communication in PET-MR studies of the brain. *EJNMMI Res.* 2018;8:106.
42. Chang YH, Oh TH, Lee JW, et al. Listening to music during transrectal ultrasound-guided prostate biopsy decreases anxiety, pain and dissatisfaction in patients: a pilot randomized controlled trial. *Urol Int.* 2015;94:337–341.
43. Kyriakides R, Jones P, Geraghty R, et al. Effect of music on outpatient urological procedures: a systematic review and meta-analysis from the European Association of Urology Section of Uro-Technology. *J Urol.* 2018;199:1319–1327.
44. Uğraş GA, Yıldırım G, Yüksel S, et al. The effect of different types of music on patients' preoperative anxiety: a randomized controlled trial. *Complement Ther Clin Pract.* 2018;31:158–163.
45. Chirico A, Maiorano P, Indovina P, et al. Virtual reality and music therapy as distraction interventions to alleviate anxiety and improve mood states in breast cancer patients during chemotherapy. *J Cell Physiol.* 2020;235:5353–5362.
46. Simpson S. The effects of self-selected music on anxiety levels and movement of patients undergoing magnetic resonance imaging, part II. *Images.* 2000;19:10–16.
47. Földes Z, Ala-Ruona E, Burger B, et al. Anxiety reduction with music and tempo synchronization on magnetic resonance imaging patients. *Psychomusicol Music Mind Brain.* 2017;27:343–349.
48. Slifer KJ, Penn-Jones K, Cataldo MF, et al. Music enhances patients' comfort during MR imaging. *AJR Am J Roentgenol.* 1991;156:403.
49. Walworth DD. Effect of live music therapy for patients undergoing magnetic resonance imaging. *J Music Ther.* 2010;47:335–350.
50. Stanley E, Craddock A, Bisset J, et al. Impact of sensory design interventions on image quality, patient anxiety and overall patient experience at MRI. *Br J Radiol.* 2016;89:20160389.
51. Loeffler R, Hillenbrand C. Anxiety Loss Offered by Harmonic Acquisition (ALOHA). In: Proceedings 10th Scientific Meeting, International Society for Magnetic Resonance in Medicine. 2002; 10.

52. Ma D, Pierre EY, Jiang Y, et al. Music-based magnetic resonance fingerprinting to improve patient comfort during MRI examinations. *Magn Reson Med*. 2016;75:2303–2314.
53. Lamb HJ. Can we convert a comfort blanket to an MRI coil? *Radiology*. 2019;291:186–187.
54. Zhang T, Grafendorfer T, Cheng JY, et al. A semiflexible 64-channel receive-only phased array for pediatric body MRI at 3T. *Magn Reson Med*. 2016;76:1015–1021.
55. Keil B, Alagappan V, Mareyam A, et al. Size-optimized 32-channel brain arrays for 3 T pediatric imaging. *Magn Reson Med*. 2011;66:1777–1787.
56. Lopez Rios N, Foias A, Lodygensky G, et al. Size-adaptable 13-channel receive array for brain MRI in human neonates at 3 T. *NMR Biomed*. 2018;31:e3944.
57. Corea JR, Flynn AM, Lechêne B, et al. Screen-printed flexible MRI receive coils. *Nat Commun*. 2016;7:1–7.
58. Winkler SA, Corea J, Lechêne B, et al. Evaluation of a flexible 12-channel screen-printed pediatric MRI coil. *Radiology*. 2019;291:180–185.
59. Vincent JM, Rispoli JV. Stitching stretchable radiofrequency coils for MRI: a conductive thread and athletic fabric approach. *Conf Proc IEEE Eng Med Biol Soc*. 2019;2019:6798–6801.
60. Park CH, Massey JM, Foury IF, Rothschild PA. Use of pressure relieving viscoelastic MRI pads to reduce patient motion and callbacks. In: Radiological Society of North America (RSNA). *Annual Meeting*. 2006.
61. Lorig TS, Schwartz GE. Brain and odor: I. Alteration of human EEG by odor administration. *Psychobiology*. 1988;16:281–284.
62. Redd WH, Manne SL, Peters B, et al. Fragrance administration to reduce anxiety during MR imaging. *J Magn Reson Imaging*. 1994;4:623–626.
63. Eshed I, Althoff CE, Hamm B, et al. Claustrophobia and premature termination of magnetic resonance imaging examinations. *J Magn Reson Imaging*. 2007;26:401–404.
64. Hricak H, Amparo EG. Body MRI: alleviation of claustrophobia by prone positioning. *Radiology*. 1984;152:819.