Update on optimization of prostate MRI technique and image quality

Tristan Barrett [1 *], Kang-Lung Lee [1,2,3], Maarten de Rooij [4], Francesco Giganti [5,6]

[1] Department of Radiology, Addenbrooke's Hospital and University of Cambridge, Cambridge, UK
[2] Department of Radiology, Taipei Veterans General Hospital, Taipei, Taiwan.
[3] School of Medicine, National Yang Ming Chiao Tung University, Taipei, Taiwan.
[4] Department of Medical Imaging, Radboud University Medical Center, Nijmegen, Netherlands
[5] Department of Radiology, University College London Hospital NHS Foundation Trust, London, UK
[6] Division of Surgery and Interventional Science, University College London, London, UK.

Corresponding author
Tristan Barrett
Department of Radiology, Addenbrooke's Hospital and University of Cambridge, Cambridge, UK
tristan.barrett@nhs.net

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Abstract

Prostate MRI quality has improved dramatically over the past decade, driven by advances in hardware, software, and improved functional imaging technique. MRI now plays a key role in the prostate cancer diagnostic work-up, but outcomes of the MRI pathway are heavily dependent on image quality and optimization. MR sequences can be affected by patient-related degradations which may allow for only partial mitigation, with common artefacts including: rectal spasm, bulk patient motion and susceptibility artefact due to rectal gas or pelvic metalwork. Despite the importance of MR image quality, historically this has been reported in a non-standardized and inconsistent manner. The Prostate Imaging Quality (PI-QUAL) scoring system represents the first attempt to address this, but early clinical application suggests scope for improvement. In this Review, we explore issues relating to the acquisition and interpretation of prostate MRI, mitigation strategies that can be employed at a patient and scanner level, PI-QUAL reporting, and future directions aimed at improving image quality, including artificial intelligence solutions.

Keywords

Prostate MRI Image Quality PI-QUAL Artefacts

Abbreviations

AI, artificial intelligence
bpMRI, biparametric MRI
csPCa, clinically significant prostate cancer
DCE, dynamic contract-enhanced
DLR, deep-learning-based reconstruction
DWI, diffusion-weighted imaging
EPI, echoplanar imaging
ERC, endorectal coil
ESUI, European Association of Urology Section of Urologic Imaging
ESUR, European Society of Urogenital Radiology
FOV, field-of-view
mpMRI, multiparametric MRI
MRI, magnetic resonance imaging
PI-QUAL, Prostate Imaging Quality
PI-RADS, Prostate Imaging – Reporting and Data System
SNR, signal-to-noise ratio
T2WI, T2-weighted images

Introduction

The first magnetic resonance imaging (MRI) study of the prostate gland was performed by Steyn and Smith in 1982[1], however, MRI only became clinically feasible with the introduction of endorectal coils and higher strength imaging at 1.5T in the mid-1990s[2]. Since then, the image quality of prostate MRI has improved dramatically due to advances in MR hardware, including introduction of multi-channel array coils, and consistent high quality diffusion-weighted imaging (DWI), dynamic contract-enhanced (DCE) sequences, with faster imaging acquisitions[3,4]. Higher image quality has resulted in MRI playing a key role in the diagnostic pathway of prostate cancer, enabling a reduction in the number of unnecessary biopsy procedures by 27-49%, with a concurrent reduction in the detection of insignificant disease, whilst maintaining similar detection rates of clinically significant prostate cancer (csPCa)[5-9].

However, the diagnostic ability of prostate MRI is significantly affected by image quality; high-quality prostate MRI is a pre-requisite for accurately identifying lesions[10], while lower image quality is associated with increased uncertainty in MRI decision-making[11]. The Prostate Imaging – Reporting and Data System (PI-RADS) recommendations, last updated in 2019[12], are designed to limit variation in quality by providing minimum technical requirements for the acquisition of prostate MRI sequences. Despite this, prostate MRI quality shows considerable heterogeneity between scanners and centers[13-15], and compliance to the guidelines alone does not guarantee optimal image quality[13,14]. Moreover, patient-related degradations such as from rectal spasm, bulk motion and pelvic metalwork can independently affect image quality with potential for only partial mitigation[4,13,16]. A recent joint European Society of Urogenital Radiology (ESUR) and European Association of Urology Section of Urologic Imaging (ESUI) consensus document recommends that image quality should be routinely reported for all prostate MRI studies[17], with the Prostate Imaging Quality (PI-QUAL) scoring system representing the first attempt to standardize such an approach[18].

In this Review, we explore issues relating to the acquisition and interpretation of prostate MRI, mitigation strategies that can be employed at a patient and scanner level, PI-QUAL reporting, and future directions aimed at improving image quality, including artificial intelligence (AI) solutions.

Quality in the prostate cancer diagnostic pathway

Quality is important throughout the prostate cancer diagnostic pathway, from image acquisition and reporting through to performance of biopsy and pathological interpretation. However, high quality MRI is the first and most crucial step along the pathway and will heavily influence all downstream events[16]. Image quality is determined by several factors, including resolution, signal-to-noise ratio (SNR), contrast, and the presence of artefacts[19]. Quality can be impacted by technical parameters, hardware and software considerations, and patient-related factors. Moreover, image interpretation made by radiologists can also influence clinical decision-making and ultimately impact the quality of the prostate cancer diagnostic pathway[4,16].

Patient-related quality factors

Several patient-related factors may influence prostate MRI quality and interpretation, such as motion artefact due to bulk patient movement or rectal spasm and susceptibility artefact secondary to rectal gas or pelvic metalwork. However, aside from hyperventilation in patients with anxiety or claustrophobia, it is unusual to encounter respiratory motion artefact given the low pelvic location of the prostate, and artefact related to post-biopsy hemorrhage[20] is now rarely seen with the use of MRI prior to biopsy.

Imaging technique-based factors

When optimising MR image quality there is a trade-off between SNR, resolution, and scan time with these three key components collectively known as the "MRI triangle". Improving one component of the triangle may compromise the other two, for instance, increased SNR can be obtained with lower resolution and/or with an increase in scan time (**Figure 1**)[19,21]. SNR is theoretically linearly related to the magnetic field strength, thus 3T provides twice that of 1.5T. The PI-RADS steering committee state a preference for 3T prostate MR imaging where available, however, they state that 1.5T systems if optimised are diagnostically acceptable for prostate MRI. Notably, 1.5T scanning is mandatory if patients have implants or devices considered conditional only for imaging at 1.5T (i.e. prohibited at 3T). In such scenarios, good quality 1.5T prostate MRI can be performed[22]. The choice of receiver coil is between an endorectal coil (ERC) or phased-array surface coil, with studies generally showing that an ERC improves SNR on both T2-weighted images (T2WI) and DWI[23-26]. However, the presence of an ERC may stimulate bowel peristalsis and induce ghosting artefacts in the phase encoding direction, which may be further amplified by poor coil positioning[23] and will also increase the cost, time and associated discomfort of MRI[4]. On balance, the PI-RADS committee recommends that an ERC be reserved for use with older 1.5T MRI systems, or where adequate SNR cannot otherwise be achieved with use of a surface coil[12].

The PI-RADS document proposes minimum technical standards for the acquisition of each individual multiparametric (mp) MRI sequence, including in-plane spatial resolution, repetition time, time-to-echo, and slice thickness and gap on all sequences, along with optimal choices for DWI *b*-values (**Table 1**). Nevertheless, some ambiguity exists. The optimal field-of-view (FOV) is stated for T2WI (12-20 cm) and DWI (16-22 cm), but DCE simply recommends covering the entire prostate and seminal vesicles. In our experience, a larger FOV and lower spatial resolution is required for surface coil imaging at 1.5T[27]. For

DCE, the minimal total observation time should be 2 minutes, however, the start point is not clearly defined as being at the time of contrast medium administration or when contrast arrives in the prostate. It is important to note that full adherence to these recommendations does not guarantee good quality imaging[13,14], and improvements can be achieved with (slight) parameter deviations in particular situations[28,29].

There is an ongoing debate as to the added value of Gadolinium contrast in mpMRI and whether a non-contrast biparametric (bp) MRI approach is sufficient[30,31]. Prospective multicentre trials addressing this question are currently recruiting[32,33], however, it should be noted that there is a benefit of DCE as a "safety net" for both lesion detection and for overall image quality (**Figure 2**). DCE is a more robust sequence than echo-planar DWI, with a lower degree of susceptibility artefacts[34] and can remain diagnostic when T2WI or DWI are compromised. Notably, a PI-RADS committee update states that bpMRI should only be used if high-quality imaging, expert interpretation, and availability of patient recall or on-table monitoring have all been established[35].

Radiologist-based factors

The wide application of the PI-RADS scoring system has aided standardization, however, there remains a moderate degree of inter-reader variability with reported κ values ranging from 0.42 to 0.92[36-40], and with significant variation in the positive predictive value of MRI, even among established centres[41]. Certification for interpretation is a potential quality control method for reducing inter-reader variability and enhancing outcomes, but requires a multifaceted approach incorporating peer-learning, accrual of continuing medical education credits, multi-disciplinary meeting participation, and radiology-pathology feedback mechanisms[16,42]. The American College of Radiology recommends reporting a minimum of 150 prostate MRIs unassisted or 100 under direct supervision before reporting independently[43], however, real-world data suggest reading of 200-300 cases is required to overcome the initial reporting learning curve[44,45]. Recent UK and European consensus documents have outlined proposals for certification[46,47], however, a German process initiated in 2018 offers the only currently available qualification for prostate MRI interpretation[48].

Common artefacts affecting prostate MRI

Movement during image acquisition, including bulk patient motion, small bowel peristalsis, or rectal spasm can resuClt in a phase shift in k-space, leading to the creation of motion artefact on images. If the motion is periodic, there may be the appearance of more discrete "ghosting" artefacts. Several strategies can be employed to reduce motion artefact, including physical stabilization and employing sequences that are more resilient to motion due to their use of parallel and/or partial Fourier imaging for reduced scan time[49,50] (**Table 2**). Additionally, changing the phase- and frequency-encoding directions can act to shift the direction of artefact away from areas of diagnostic interest[51].

Rectal distension is known to negatively correlate with image quality[52], with secondary spasm causing motion artefact predominantly on T2WI and DCE and, if air is present at the recto-prostatic interface, susceptibility artefact on DWI (**Figure 3**). Clearly an empty rectum will mitigate against both types of artefacts and PI-RADS recommends that patients should evacuate the rectum just prior to MR imaging[12]. More invasive preparation methods have also been assessed including: dietary restrictions, enema, rectal gel, catheter decompression, and anti-spasmodic agents[53-58]. However, the current evidence is inconclusive, and the published literature has rarely evaluated the potential impact on eventual prostate cancer diagnosis[59]. PI-RADS therefore does not recommend additional preparation steps, noting further potential disadvantages such as increased costs, enema-induced peristalsis, and contra-indications or drug reactions with anti-spasmodic agents[60].

Susceptibility artefact occurs due to variations in the magnetic properties between different tissues in the body, with resultant magnetic field inhomogeneities distorting the MR signal. Metallic objects including hip protheses are a common cause of magnetic susceptibility causing signal loss, a "halo" effect, or distortion in the surrounding tissues. The severity of metalwork-related susceptibility artefact depends on the size, location, and composition of the prosthesis[4] and may be reduced by scanning at the lower field strength of 1.5T[61] (**Figure 4**), however, evidence on this matter is conflicting [Ref]. Specific metal-reduction sequences can also be employed, for instance techniques that over-sample the central portion of k-space, enabling artefacts to be corrected in the reconstruction process, reducing the susceptibility artefact seen on echo-planar (EPI) DWI or the motion artefact on turbo-spin echo T2 sequences[62-64]. T2-mapping has also shown promise as a more robust alternative to EPI-DWI derived ADC maps for providing quantitative imaging data in patients with hip replacements[65]. Air-tissue interfaces also induce susceptibility artefact and are particularly problematic on EPI DWI sequences in the presence of rectal gas. The severity can vary from mild signal pile-up at the posterior midline of the prostate, to moderate inhomogeneity causing anteroposterior displacement of the prostate gland, through to more severe inhomogeneity producing a "warping" of the prostatic outline (**Figure 5**)[50,66-68]. Air-related susceptibility artefact can be mitigated by scanning patients in a supine position, displacing the air away from the recto-prostatic interface, however, to date improvements have not been objectively demonstrated in the literature and, in clinical practice. Scheduling restrictions may be a limiting factor given the additional time needed to perform such sequences. Blooming artefact is a type of susceptibility artefact due to presence of paramagnetic substances encountered on MRI sequences such as gradient echo DCE; small metallic implants in the prostate such a brachytherapy seeds or fiducial markers can demonstrate similar effects.

Acquiring DCE sequences without fat-suppression is generally required when there is severe metal artefact in the pelvis; however, can also make interpretation more challenging, due to reduced conspicuity of enhancement and presence of chemical shift artefact[50]. The chemical shift phenomenon is observed when water and lipid protons are present in the same voxel, as the protons in fat are shielded to a greater extent to those in water, resulting in a noticeable difference in their resonant frequencies. Using fat suppression techniques or increasing receiver bandwidth can mitigate against this artefact (**Figure 6**). When fat suppression fails due to pelvic metal hardware, acquiring a subtraction series from the non-fat suppressed DCE series can be beneficial if images are adequately co-registered.

Standardized reporting of image quality: PI-QUAL

The Prostate Imaging Quality (PI-QUAL) scoring system was developed from imaging acquired as part of the multicentre PRECISION trial[6] and represents the first attempt to standardize reporting of prostate MRI quality. The PI-QUAL score is based on a 1-to-5 scale that indicates the adequacy of the diagnostic quality of prostate MRI and mandates a multiparametric examination (**Table 3**). PI-QUAL scores of 1 or 2 indicate that two or all sequences [i.e. T2WI, DWI and DCE] are below the minimum standard of diagnostic quality and clinically significant lesions cannot be ruled in and out. A PI-QUAL score of 3 implies that the scan is of sufficient diagnostic quality, but it is only possible to rule in all clinically significant lesions. PI-QUAL scores of 4 or 5 mean that all three sequences are of sufficient diagnostic quality to both rule in and rule out clinically significant lesions. The original PI-QUAL document also includes a dedicated scoring sheet that allows the evaluation of the technical parameters for each single MR sequence. A total of 20 technical parameters are evaluated across the three sequences, with visual assessment including clear delineation of prostatic and periprostatic structures on T2WI, identification of vessels on DCE, adequacy of ADC maps, and the absence of artefacts on all three sequences[69]. Growing evidence is being published on the role of the PI-QUAL score in different clinical settings and cohorts and suggests that higher PI-QUAL scores may improve the efficiency of diagnostic pathway of prostate cancer by reducing false-positive MRI calls and unnecessary biopsies.

Brembilla and colleagues investigated the impact PI-QUAL scores on the diagnostic performance in a targeted biopsy cohort of 300 patients[70]. They observed a higher proportion of PI-RADS 3 lesions in scans with suboptimal (51%) compared to those with optimal (PI-QUAL 4-5) quality (33%). For suboptimal scans, the positive predictive value was lower compared to PI-QUAL ≥ 4 (35% vs 48%; p 0.090), as was the detection rate of clinically significant prostate cancer (≥Grade Group 2) in both PI-RADS 3 and PI-RADS 4-5 lesions (15% vs 23% and 56 vs 63%, respectively). The Authors also observed that overall MRI quality increased over time and concluded that scan quality affects the diagnostic performance of prostate MRI, as scans of suboptimal quality were associated with lower positive predictive values for clinically significant prostate cancer.

Windisch et al. compared upstaging of localised disease on mpMRI to locally invasive disease in radical prostatectomy specimens (≥pT3a) in relation to PI-QUAL in a multicentre setting[71]. The Authors found that scans scoring PI-QUAL ≥ 3 were associated with a lower rate of upstaging (19% vs 35%; p = 0.02), greater detection of T3a and T3b disease on mpMRI (17% vs 2.5%; p = 0.016), a higher rate of PI-RADS 5 lesions (47% vs 27.5%; p = 0.002), and a higher number of PI-RADS ≥ 3 lesions (34.7% vs 15%; p = 0.012) when compared to scans scoring PI-QUAL 1 and 2. On multivariate analysis, PI-QUAL 1 and 2 scans were associated with more frequent upstaging at radical prostatectomy (odds ratio 3.4; p = 0.01). They concluded that PI-QUAL 1 and 2 scans were significantly associated with a higher rate of upstaging from organ-confined disease on MRI to locally advanced disease on pathology, lower detection rates for PI-RADS 5 lesions and extraprostatic extension, and a lower number of suspicious lesions.

Hötker and colleagues evaluated PI-QUAL to assess factors that limit the diagnostic accuracy of prostate MRI[72]. The study included four readers with different levels of experience who independently reviewed 295 scans and assigned scores for subjective image quality (1-5; 1: poor, 5: excellent), the PI-QUAL score and the prostate signal intensity homogeneity score (PSHS) scoring system. Both PI-QUAL and the PSHS scoring system showed good results in assessing the effect of image quality on detection rates of csPCa and the authors concluded that both scoring systems should be included in the prostate MR reports as they focus on different aspects of image quality.

The first inter-reader assessment of PI-QUAL between two experts in prostate MR showed a strong agreement for each single PI-QUAL score (κ = 0.85, with percent agreement = 84%)[73]. Notably, the agreement for diagnostic quality for each sequence was highest for T2-WI (89%), followed by DCE (91%) and DWI (78%) sequences. However, subsequent studies demonstrated only moderate agreement between two independent readers, with Cohen's kappa coefficients ranging between 0.42 and 0.55[11,74,75]. This suggests that defining scan quality can be subjective in nature, and readers are likely to disagree on what entails optimal prostate MR image quality.

PI-QUAL Version 2

The current version of PI-QUAL serves as a starting point for the standardized evaluation of prostate MRI image quality. However, PI-QUAL can only fulfil its purpose if the scoring system has an impact on the diagnostic MRI-driven pathway. Like the PI-RADS guidelines, PI-QUAL is envisioned to be a "living document" that evolves with increasing clinical experience and scientific data[76]. An international working group with representatives from the European Society of Urogenital Radiology (ESUR) and EAU Section of Urologic Imaging (ESUI), among others, is working on an updated version of PI-QUAL to address its current limitations. There are three main concerns related to the first version of PI-QUAL.

The first limitation is the clinical implication that is automatically derived from the observed PI-QUAL score. A PI-QUAL score of 4 or 5 implicates that image quality is good enough to rule in and rule out all significant lesions, while this is not possible when an examination is assessed as PIQUAL ≤ 2. However, a large tumour suspicious lesion can be detected even on a PI-QUAL 1 or 2 study (**Figure 7**), while a small clinically significant tumour can be missed even with good-quality imaging (PI-QUAL 4-5), which a known limitation of MRI[77,78]. Although it is important to give recommendations on the clinical implication, these examples show that deriving these automatically from the observed PI-QUAL score may not be helpful in all clinical scenarios. A two-step approach seems to be more appropriate; the first step should involve an assessment that evaluates image quality as objectively as possible, independent from the diagnostic findings. The second step determines the clinical impact of the observed image quality, taking into consideration the diagnostic findings, the clinical context, and the patient history. This two-step approach should ideally be taken by the reporting radiologist and, if necessary, should also involve the opinion of the other members of the multidisciplinary team. The potential outcome of this (multidisciplinary) decision could for instance be to repeat (a part of) the examination, or proceed straight to biopsy.

The second limitation that will be addressed in future iterations of PI-QUAL refers to the technical recommendations derived from the PI-RADS v2.1 guidelines. Adoption of PI-QUAL v1 may be hindered due to the complexity of the 20 technical parameters it contains. Conformity will not necessarily guarantee good quality and acquiring T2WI with an in-plane resolution of 0.7x0.5 mm rather than 0.7 x 0.4 mm will have minimal effect on quality, particularly in comparison to the presence significant motion artefact at visual assessment. For widespread adoption, PI-QUAL needs to be as straightforward as possible. Therefore, in future iterations of PI-QUAL, sub-optimal image quality should be identified if non-compliant with only basic rather than detailed technical PI-RADS parameters.

The final factor to consider is that in future versions of PI-QUAL one should be able to apply the scoring system on bpMRI. The current version of PI-QUAL applies to mpMRI only, but due to rising interest in bpMRI, especially in low prevalence (screening) situations, the PI-QUAL system should be amended to allow for both bpMRI and mpMRI quality scoring.

After addressing these limitations, PI-QUAL will strengthen its role as a reliable quality assessment tool and safeguard the quality of MRI at the start of the diagnostic pathway. Future reproducibility and generalizability studies are required to evaluate its inter- and intra-reader agreement, in order to establish PI-QUAL as the international standard for assessment of prostate MR image quality.

Future improvements in MR image quality

Future improvements in magnet hardware and coil design alongside novel sequence development and software updates, including artificial intelligence (AI) solutions would be expected to improve image quality.

According to the current PI-RADS guidelines, high *b*-value ($b \geq 1{,}400$ sec/mm^2) DWI can be obtained either as an acquired or calculated sequence. Calculated *b*-values offer higher SNR by avoiding the noise penalty of acquiring DWI at higher *b*-values with longer echo times, and clearly save on scanning time, thus breaking the "MRI triangle". Several articles have suggested that utilizing calculated high *b*-value DWI can result in higher image quality and improved image contrast[79-82]. Single-shot echo-planar imaging (EPI) has been widely used in acquiring clinical DWI due to its rapid acquisition capabilities. However, it is important to acknowledge some of the limitations associated with single-shot EPI, which include vulnerability to susceptibility artifacts, ghosting artifacts from poor fat suppression on the anterior abdominal wall, relatively low SNR, and blurring. Novel DWI techniques can potentially improve the image quality of DWI. One such technique involves utilizing reverse polarity gradient (RPG) methods, where images at $b = 0$ s/mm^2 are acquired using both forward and reverse phase encode trajectories. By calculating a deformation field map, the entire diffusion data set can be corrected for distortion[83-85]. Additionally, multi-shot EPI has been proposed as an alternative to single-shot EPI, aiming to enhance the quality of acquired images. Several segmented techniques have been devised for multi-shot EPI, such as MUSE™ by GE Healthcare and RESOLVE™ by Siemens and can achieve improved SNR, reduced susceptibility artifacts, and minimized blurring within an acceptable scanning time[86]. DWI sequences with reduced field-of-view (FOV) are more routinely available in clinical practice and have been shown to improve image distortion at the recto-prostatic interface by allowing for higher spatial resolution and a shorter echo-train length in the phase-encoding direction[87,88].

Deep-learning based reconstruction (DLR) is a commercially available AI technique that has shown promise in maintaining / enhancing image quality while substantially reducing acquisition time[89-94]. DLR is a post-processing step that applies a "de-noising" algorithm, therefore allowing for deliberate acquisition of "noisy" images, which can either enable quicker scans times or sequences with reduced slice thickness. The reduction in scan time offered by DLR can enhance accessibility to prostate MRI, improve patient comfort, and mitigate against motion artefacts[4,95]. However, it is worth noting that DLR software typically provides differing levels of denoising, and applying higher levels may risk "over smoothing" images which and lead to false positive results, particularly in the TZ (**Figure 8**). Therefore, effective implementation of DLR into clinical practice requires evaluation of the optimal scanning parameters in conjunction with the optimal DLR denoising level.

AI applications may also have a future role in the assessment of MR image quality. Manually verifying the Digital Imaging and Communications in Medicine (DICOM) headers of prostate MRI studies for compliance with PI-RADS technical parameters is arduous, ideally suited to a software tool that can perform this quickly and automatically. Likewise, PI-QUAL scoring is time-consuming, although semi-automated workflows to reduce the time have been proposed, and remains objective with only moderate inter-reader agreement[96]. There is a clear need for a software solution that can evaluate prostate MR image quality in a simpler and more objective way. Cipollari et al developed a convolutional neural network-based analysis tool that could accurately classify prostate MRI quality into a binary category of "low" or "high" quality compared to expert radiologist opinion[97]. However, more complex software that can evaluated multi-category PI-QUAL scoring is yet to be developed. An AI-based tool to assess image quality offers several advantages including time savings and standardization. Future iterations may enable integration into the MRI system with automatic assessments of image quality, flagging any sequences that require repeat acquisition and potentially suggesting appropriate parameter changes. Advise on the need for contrast injection may also be feasible to decide if DCE acquisition is necessary for lesion detection or as a safety net for overall quality of the study. Such an application may minimize the need for patient recalls, a decision often made at a much later time point, when reporting.

Conclusion

Prostate MRI is now integral to the prostate cancer diagnostic pathway, driven by hardware and software developments improving image quality, with all downstream aspects of the diagnostic work-up being reliant on the first step of MRI acquisition. PI-RADS provides a menu of minimal technical parameters, however, adherence alone does not guarantee high-quality imaging and will not account for patient-related factors. AI solutions can currently be applied as a post-processing step for increasing SNR, and future developments may enable on-table monitoring of image quality and identification of sequences that require repeating or parameter adjustments. The PI-QUAL system represents the first attempt to provide an objective assessment of image quality and PI-QUAL version 2 will aim to further improve on this process, however, further validation is required to ensure its clinical effectiveness.

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