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An Overview Of 3T MRI: Current Practices And Future Prospects

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ABSTRACT:

This article delves into the current landscape and future prospects of 3T MRI, offering a thorough examination of its applications, challenges, and advancements. Highlighting its pivotal role in modern medical imaging, we explore the enhanced capabilities afforded by 3T MRI, such as heightened signal-to-noise ratio (SNR) and superior spatial resolution. Despite these advantages, we also confront the obstacles that accompany higher field strengths, including susceptibility artifacts and concerns about radiofrequency power deposition. However, our analysis reveals a promising trajectory fueled by ongoing technological innovations and imaging techniques. By fostering collaboration among researchers, clinicians, and industry stakeholders, we anticipate overcoming these challenges and unlocking the full potential of 3T MRI. Ultimately, this continued evolution holds the promise of transformative advancements in diagnostic imaging, ultimately leading to improved patient outcomes and enhanced healthcare delivery.

Keywords*: 3T MRI, Signal-to-noise ratio (SNR), Medical applications, Advancements.*

INTRODUCTION

Medical imaging has revolutionized healthcare, enabling us to peer inside the human body non-invasively and gain invaluable insights into health and disease. Among these remarkable tools, Magnetic Resonance Imaging[1] (MRI) stands out for its versatility and exceptional detail. MRI is a technique that produces cross-sectional images of a patient's body, using magnetism and radio waves. Unlike X-rays that primarily visualize bones, MRI utilizes the sophisticated interplay of powerful magnetic fields and radio waves to create detailed cross-sectional images of organs, soft tissues, and even functional activity within the brain (What Is an MRI Scan and What Can It Do?, 2011). MRI's applications extend beyond neurological disorders and musculoskeletal injuries, playing a crucial role in diagnosing and monitoring various health conditions across the body. Since its inception in the early 1980s, MRI has evolved significantly, leading to numerous clinical and research uses, which in turn have spurred further technical advancements. Originally hailed for its potential, MRI has now become a primary

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diagnostic tool, renowned for its ability to provide detailed soft tissue contrasts and versatile imaging options such as oblique orientations, 2D, and 3D data (Yousaf et al., 2018).

Utilizing non-ionizing electromagnetic radiation, MRI produces cross-sectional images of internal structures by exploiting the phenomenon of nuclear magnetic resonance. Its ability to capture detailed tissue information, including biochemistry and structural properties, makes it highly adaptable. MRI techniques can be customized to enhance specific features of interest, offering high-resolution images of various structures like white matter tracts, lesions, and arteries (What Is an MRI Scan and What Can It Do?, 2011). While initially focused on anatomical depiction, MRI is increasingly used for functional imaging and localized spectra acquisition, broadening its clinical applications to include neurological, psychiatric, cardiac, abdominal, musculoskeletal, and vascular areas (Yousaf et al., 2018).

MRI machines with a static magnetic field strength (B0) of 1.5 T have been the standard in the field since the mid-1980s. Until the late 1990s, "high field strength" typically denoted machines with a field strength of 1.5 T or even 1.0 T for clinical imaging (Bottomley et al., 1983). However, in the last 5 to 6 years, this term has evolved to mainly refer to systems with field strengths exceeding 2 T, specifically highlighting the widespread adoption of 3-T machines. High field-strength MRI now pertains to imaging or spectroscopy conducted with static magnetic field strengths at or above 3 T (Ladd, 2007). While MRI machines with field strengths higher than 3 T, such as 7 T, exist, 3 T remains the most prevalent and pragmatic option (Ladd, 2007).

This article delves into the diagnostic power of 3T MRI, exploring its diverse applications across various medical specialties. We will explore how 3T MRI aids in the detection, characterization, and staging of a wide range of diseases, from neurological disorders and musculoskeletal injuries to cancer and cardiovascular conditions. We will also discuss the latest advancements in MRI technology, including higher field strengths and functional imaging techniques, further enhancing its diagnostic capabilities. By exploring the fascinating world of MRI, we gain a deeper appreciation for its transformative role in modern medicine and its ongoing potential to revolutionize healthcare diagnosis in our institution and in Saudi Arabia in general.

MECHANISM OF MRI

Within atomic nuclei, each proton possesses a positive charge of +1. When subjected to a magnetic field, these protons undergo a process called precession, akin to the gyrations of a wobbling spinning top, at a frequency determined by the type of atom they belong to (e.g., hydrogen, phosphorus) and the intensity of the local magnetic field, measured in units called Tesla. These precessing protons generate a new current, which is detectable and measurable (Gibby, 2005). MRI machines consist of a transmitting coil that generates a magnetic field and a receiving coil that captures the current. This data is then processed by a computer to create an image based on the signals' location and strength. The resulting image's appearance varies depending on the body tissue; for instance, ligaments and bones typically appear dark, while fat appears bright. This discrepancy arises because substances with higher hydrogen atom content, and thus greater proton density, emit stronger signals than those with fewer hydrogen atoms (e.g., water emits more than bone). Numerous pathologies, such as infection, inflammation, and tumors, increase tissue water content (edema), making MRI useful for distinguishing these tissues from adjacent structures with lower water content. Moreover, grey matter can be discerned from white matter due to its higher water proton content. MRI scans can reveal various pathological features like demyelination, stroke, and subarachnoid hemorrhage
(Gibby, 2005).

Using different coils:

Different coils are used for specific imaging needs; the standard whole-body coil is suitable for large body areas, whereas smaller surface coils placed closer to the body may enhance image quality by improving the signal-to-noise ratio, albeit with a limited field of view. Dedicated coils exist for breast, neck, and pelvic examinations (The Royal College of Radiologists, 2006).

Using different planes:

Doctors often use two standard planes (front-to-back and side-to-side) for organs with consistent position like the prostate. However, for organs that can move around more, like the uterus and cervix, they might need to use angled views to get a better picture (The Royal College of Radiologists, 2006).

Using contrast medium:

For abdominal imaging, oral contrast agents such as cranberry or pineapple juice can be utilized. Additionally, for other organs, intravenous contrast agents (such as iodine-based or gadolinium-based contrast agents)are used to enhance specific structures. Examples include: Liver-specific contrast agents: These increase the sensitivity for detecting and characterizing specific liver lesions. Lymph node-specific agents: These aid in the detection of metastases (cancer spread) within lymph nodes (The Royal College of Radiologists, 2006).

Using higher-field strength (3T or higher):

Increasing the static magnetic field strength of an MRI machine from 1.5 Tesla (T) to 3T, or even higher, primarily involves employing stronger and more sophisticated magnet designs. Here's a breakdown of some key technical aspects:

Magnet design:

Superconducting magnets: These are the mainstay of modern MRI machines and utilize special materials that become highly conductive at extremely low temperatures (near absolute zero). This allows for the creation of powerful magnetic fields with minimal energy consumption.
Higher field strength magnets: To achieve a 3T field, stronger superconducting materials and more complex magnet geometries are required compared to those used in 1.5T machines. This can involve:1. Increased number of windings: More coils can be used to generate a stronger magnetic field, requiring advanced engineering to optimize current distribution and minimize heat generation. 2. Advanced conductor materials: Newer materials like high-temperature superconductors (HTS) are being explored to create even stronger fields, although they still face challenges in terms of cost and practicality (Ladd, 2007).

TYPES OF MRI

MRI utilizes the intricate dance of **powerful magnetic fields and radio waves** to generate detailed cross-sectional images of organs, soft tissues, and even **functional activity within the brain**. Understanding the various types and field strengths of MRI is crucial for appreciating its diverse applications and limitations (NHS Choices, 2009).

Types according techniques:

- Closed MRI: This is the most common type, featuring a cylindrical tunnel-like design that surrounds the patient during the scan. It typically offers higher image quality due to the stronger magnetic field and better signal-to-noise ratio.
- Open MRI: This type features an open design, addressing concerns for claustrophobia experienced by some patients in traditional closed scanners. The open design offers greater comfort, but it may come at the cost of slightly lower image quality compared to closed systems.

- Functional MRI (fMRI): This specialized technique goes beyond anatomical imaging, measuring brain activity by detecting changes in blood flow associated with neuronal activation. fMRI plays a crucial role in investigating brain function and studying cognitive processes like language, memory, and decision-making.
- Diffusion MRI (DWI): This technique measures the diffusion of water molecules in tissues, providing information about the integrity of white matter tracts in the brain and other tissues. DWI is valuable for assessing conditions like stroke, traumatic brain injury, and tumors (NHS Choices, 2009).

Types of MRI according to Field Strengths:

MRI scanners are characterized by their magnetic field strength, measured in Tesla (T). The most common field strengths are:

- 1.5 Tesla (T): This is the standard field strength used in most clinical settings, offering a good balance between image quality, scan time, and patient comfort.
- 3 Tesla (T): offers superior image resolution and signal-to-noise ratio, leading to more detailed and clearer images. However, 3T scanners are often more expensive, louder, and may not be suitable for all patients due to potential safety concerns with certain implants.
- 7 Tesla (T) and higher: These are still under development and primarily used in research settings. They offer even greater detail but are even more expensive and have limitations in patient accessibility and safety considerations (Ladd, 2007).

Beyond these broad categories, various specialized MRI scanners exist, tailored to specific body organs like the blood vessels (magnetic resonance angiography, MRA), the heart (cardiac MRI), joints (musculoskeletal MRI), and the abdomen (abdominal MRI). These specialized scanners often incorporate additional features or techniques optimized for the specific needs of the targeted region (NHS Choices, 2009).

ADVANTAGES AND DISADVANTAGES OF 3T MRI

3T MRI differs from low-field strength imaging in several keyways. Some of these differences are clearly beneficial, while others have drawbacks. However, many characteristics exhibit both advantages and disadvantages, and their overall impact depends on the specific use case. Several factors contribute to better image quality and faster scans in different applications, especially musculoskeletal MRIs, but 3.0 Tesla (T) field strength is currently the most impactful. 3.0 T systems not only improves spatial resolution, contrast, and speed, but they often come with additional features like advanced hardware for faster signal processing and specialized coils for detailed images. These advancements allow for even faster scans and improved image quality through techniques like shorter data acquisition, parallel imaging, and AI-based reconstruction (Fritz et al., 2021). While the initial cost of 3.0 T systems is higher, this can be balanced by the benefits of quicker, higher-quality scans, the ability to use advanced techniques, and shared use with other departments. For facilities with enough patients, the advantages of 3.0 T MRI often outweigh the initial investment (Khodarahmi & Fritz, 2021).

The strongest motivation for transitioning to higher field strengths arises from the improved spin polarization achieved at these levels, leading to increased sensitivity (Sunshine & Durek, 1996). The SNR rises nearly in proportion to the increase in magnetic field strength because of the enhanced polarization of nuclear spins. This advantage can be fully utilized in certain applications like spectroscopy or fat-suppressed imaging. However, for other applications, adjustments to measurement parameters are necessary. These adjustments may include longer repetition time (TR) to accommodate extended T1, longer radiofrequency (RF) pulses to comply with specific absorption rate (SAR) limits, or higher readout bandwidth to address increased chemical shift artifacts and image distortions at higher field strengths. These modifications compromise the extent of increased signal yield to some degree (Schick et al., 2021).

Relaxation time is an important factor that differ with different field strengths. It tends to increase with higher field strengths. For instance, the T1 time of gray brain matter rises from approximately 1000 ms at 1.5 T to 1331 ms at 3 T. On the other hand, T2 relaxation times are less affected by field strength, with reported values for gray matter ranging between 80 and 90 ms at 1.5 T to about 110 ms at 3 T. Theoretical considerations also support an anticipated increase in T1 with field strength and relatively constant T2; however, at very high field strengths (above 3 T), dynamic averaging is expected to cause a rapid decrease in T2 times (Wansapura et al., 1999). Higher field strength permits heightened spectral dispersion between fat and water, which results in more pronounced chemical shift artifacts, that enables most fast saturation techniques to perform more effectively (von Falkenhausen et al., 2006).

Moreover, higher field strengths offer significant advantages for magnetic resonance spectroscopy (MRS). The increased separation between spectral peaks and heightened sensitivity of high-field-strength MRI allow for the detection of more metabolites even in smaller quantities. MRS at 1.5 T has had limited clinical utility. However, the introduction of 3 T MRI may herald a notable shift in how MRS is utilized in clinical practice. Particularly in studying disease processes like neurodegenerative disorders Chen & Zhu, 2005). On the other hand, dielectric or standing wave artifacts manifest as abnormal bright and dark regions caused by B1 field inhomogeneity at higher field strengths. Depending on the dielectric properties, certain body regions can act as radiofrequency resonators, leading to constructive and destructive B1 interferences with a spatial distribution influenced by body geometry and radiofrequency pulse wavelength. At 1.5 T, the radiofrequency pulse wavelength is typically 52 cm, larger than the axial dimensions of the human torso. However, at 3.0 T, the increased Larmor frequency results in higher tissue dielectric constants and a shorter radiofrequency pulse wavelength of 26 cm, approaching the torso's axial dimensions. Consequently, both constructive and destructive areas fall within the imaged region, causing varying signal intensities. However, modern 3.0 T scanner systems are equipped with independent transmit channels and radiofrequency shim capabilities, effectively eliminating this artifact (Chang et al., 2015).

Another issue is the magic angle effect which occurs in tissues with anisotropic structural patterns, such as tendons and cartilage, during short echo time acquisitions. When water molecules align preferentially at a 55-degree angle to the static magnetic field, decreased dipole-dipole interaction leads to T2 prolongation. While this effect is expected to be more pronounced at 3.0 T, it rarely poses a diagnostic challenge beyond what is encountered at 1.5 T. Additionally, magic angle effects can be reduced substantially with TSE pulse sequences using echo times greater than 60 to 70 milliseconds (Kuo et al., 2007). Parallel imaging has emerged as a valuable technique even at 1.5 T, but its effectiveness is further enhanced at higher field strengths. Numerous aspects of parallel imaging and high field strength complement each other, with parallel imaging frequently offering solutions to challenges associated with high field strength. While parallel imaging may lead to a reduction in SNR, the higher field strength can offset this decrease (Wiesinger et al., 2006).

From physiological perspective, workers and patients exposed to high magnetic fields have reported several effects, including dizziness, nausea, light flashes (magnetophosphenes), headache, and a metallic taste. These effects are attributed to the flow of electrically conductive blood through the magnetic field, which also alters the electrocardiogram signal, notably elevating the T wave due to peak aortic flow (Schenck, 2005). Fortunately, these effects have been transient, with no known permanent cellular or metabolic damage. However, severity of these side effects increases with field strength, imposing a practical upper limit on acceptable field strengths for human subjects. In a study at 7 T, around 96% of participants completed the examination, though 64% reported adverse effects likely linked to the static field.

Comparatively, only 32% reported effects during a 1.5 T examination (Theysohn et al., 2008). Despite these challenges, most subjects rated the sensations associated with the high magnetic field as less disturbing than other factors typically encountered during an MRI. These findings suggest that individual sensitivity thresholds vary, but still considered the 3T as the safest high-strength field MRI (Ladd, 2007). At a recent workshop focused on high-field-strength MRI, it was noted that there are much research showing that higher field strength, mainly at 3 T, results in alterations in patient treatment and tangible improvements in patient outcomes, such as length and quality of life (Ladd, 2007).

COST EFFECTIVENESS OF 3T MRI

While 3 T MRI machines are more expensive upfront than older lower- strength field techniques, their advantages can justify the cost. These benefits include faster scans with better image quality, the ability to use more advanced techniques, and the potential for shared use with other departments. For facilities that see a high volume of patients, the advantages of 3 T MRI often outweigh the initial investment. This statement has been approved by many research studies in the last decade. A recent study has investigated the cost-effectiveness of various imaging strategies for diagnosing SLAP tears (shoulder injury). They found that using an unenhanced 3 T MRI was the most cost-effective option, offering the best balance between accuracy and financial burden. This approach was superior to using 1.5 T MRI or other imaging methods like X-rays or ultrasound for diagnosing SLAP tears in patients (Gyftopoulos et al., 2022). Another study has assessed cost-effectiveness of using 3T MRI compared to 1.5T MRI for routine knee imaging in a general radiology setting. They found that utilizing 3T MRI was cost-effective, offering similar diagnostic accuracy to 1.5T MRI while potentially reducing overall healthcare costs. This outcome suggests 3T MRI could be a valuable choice for general knee examinations in high-volume practices (Wiersma et al., 2010).

ESTABLISHED AND POSSIBLE APPLICATIONS

1. Musculoskeletal Imaging

The introduction of 3T MRI has brought significant advancements to musculoskeletal imaging, offering increased SNR and improved spatial resolution, allowing for better delineation of ligaments, tendons, and cartilage. However, despite its potential, most clinical MRI devices sold are still 1.5T scanners, and debates persist regarding image quality compared to 1.5T systems. Challenges such as chemical shift artifacts and susceptibility artifacts have been extensively discussed, along with increased image inhomogeneity due to local dielectric effects at 3T. These challenges can lead to signal loss and artifacts, particularly near tissue-bone and tissue-air interfaces. Additionally, radiofrequency power deposition poses concerns, especially in fast spin-echo sequences. Recent advancements in sequence and surface coil technologies, as well as post-processing techniques, have improved image quality at both 1.5T and 3T. While 3T MRI may offer advantages in certain scenarios, such as assessing cartilage and ligamentous pathology in knee and ankle imaging, the diagnostic accuracy of 1.5T MRI remains comparable in many orthopedic indications. Ultimately, factors beyond magnetic field strength, such as coil technology and image acquisition parameters, play crucial roles in determining image quality in musculoskeletal MRI. Therefore, a magnetic field strength of 1.5T with optimized parameters remains adequate for most musculoskeletal imaging needs (Sormaala et al., 2011, Anderson et al., 2008, Bowers et al., 2008).

2. Abdomin, Liver, and Ascites

With the introduction of high field strength MRI in the mid-2000s, numerous studies have compared the advantages and disadvantages of imaging at 3T versus 1.5T, particularly in abdominal applications such as liver imaging. While there are slight variations in findings, the consensus is that the higher SNR and contrast-to-noise ratio at 3T, along with the potential for higher spatial resolution and/or lower acquisition time, outweigh the drawbacks of increased specific absorption rate and other technical challenges (Springer et al., 2010). Moreover, specific needs such as staging of liver fibrosis or detection of steatosis benefit from the higher field strength (3 T). Determining iron content could be done with low field or higher field strength (Yokoo et al., 2018). However, abdominal MRI faces challenges due to factors like the large field of view which is clearly manifested in conditions such as ascites. The shortened wavelength of the RF field (B1) in water at higher field strengths can lead to standing waves of B1 field interference resulting in shading artifacts in the image. While parallel RF transmission technology can mitigate this to some extent, B1 inhomogeneities still persist at 3T. Therefore, for patients with significant ascites, MRI is preferably performed at 1.5T (Merkle & Dale, 2006).

3. Nervous System

Neuroimaging at 3T typically has improved SNR and enhanced spectral resolution compared to 1.5T. The heightened SNR contributes to better resolution and contrast in images. Moreover, the increased absolute frequency shift between various metabolites is advantageous for techniques like magnetic resonance spectroscopy (MRS). Consequently, 3T MRI serves as a robust neuroimaging tool for evaluating both normal and pathologically altered tissue, offering high spatial and temporal resolution, along with additional insights into metabolic changes. 3T MRI is specifically useful in detecting brain tumors and cancerous tissues (Krautmacher et al., 2005), ischemic strokes (Kuhl et al., 2005), neuroinflammatory/ neurodegenerative diseases such as multiple sclerosis (Bachmann et al., 2005), optic neuritis (Nielsen et al., 2006), and epilepsy (Phal et al., 2008).

4. Oncology

Whole-body MRI (WB-MRI) has become increasingly important in diagnosing, staging, and monitoring oncologic diseases. It offers exceptional soft tissue contrast and high spatial resolution, making it particularly attractive for detecting and following up on pathologies. WB-MRI is especially advantageous for cancer patients who may require repeated imaging due to evolving treatment regimens and improved long-term survival rates (Chien et al., 2015). However, despite its benefits, WB-MRI faces challenges such as limited availability and high operating costs. Artifact issues, particularly concerning certain implants, also pose significant obstacles. Nevertheless, advancements in both hardware and software have led to improvements in WB-MRI, including shorter acquisition times and enhanced image quality (Schaefer et al., 2019). Common WB-MRI protocols typically involve T1-weighted sequences and diffusion-weighted imaging (DWI), which aids in detecting malignant lesions and provides qualitative and quantitative information. WB-MRI can be performed using both 1.5T and 3T scanners, each with its advantages and drawbacks. While 3T imaging offers increased spatial resolution and SNR, it also presents challenges such as higher RF power deposition and susceptibility-induced artifacts. On the other hand, 1.5T imaging may have fewer metal-related artifacts and superior image quality in certain scenarios (Morone et al., 2017).

Overall, boosting the SNR at 3T can serve various purposes: speeding up image acquisition, enhancing spatial resolution, or finding a balance between the two, ultimately reducing examination durations. This improvement facilitates greater scanner throughput, making the diagnostic method more accessible and cost-effective for a wider population, thus enabling its integration into daily clinical practice.

5. Cardiology

While 3T MRI has established applications in cardiology, such as assessing cardiac function and structure, recent developments have opened doors for new and exciting clinical applications:

Myocardial perfusion imaging: 3T MRI is increasingly being used for myocardial perfusion imaging, which assesses blood flow to the heart muscle. This can be crucial for diagnosing coronary artery disease and identifying areas of potential heart attack risk. **Ventricle scarring assessment:** Advanced 3T MRI techniques, like late gadolinium enhancement (LGE), offer even clearer visualization of myocardial scarring caused by previous heart attacks or other injuries. This information aids in risk stratification and planning treatment strategies.

Cardiovascular magnetic resonance spectroscopy (CMRS): This advanced technique, primarily used in research settings at present, provides valuable information about myocardial metabolism and tissue viability, offering potential for early detection of heart damage and monitoring treatment response. Overall, 3T MRI continues to evolve and offers promising new avenues for improved diagnosis and management of various cardiovascular conditions (Shenoy & Bawaskar, 2023, Fluschnik et al., 2022).

6. Personalized Medicine

Functional MRI (fMRI) typically benefits from higher field strength MRI. High field strength MRI, such as 3 Tesla or even higher, provides several advantages for fMRI studies. Many new personalized clinical applications in different areas bases on fMRI. Various functional MRI techniques are utilized to observe biological processes in living organisms. For instance, diffusion-weighted imaging is employed to examine tissue structure, dynamic contrast-enhanced MR imaging evaluates tumor blood flow, and magnetic resonance spectroscopy or dynamic nuclear polarization can analyze tumor metabolites. The primary advantage of functional MRI lies in its ability to perform whole-body imaging, capturing the complete heterogeneity of tumors in vivo and tracking changes over time without invasive procedures. However, future efforts should focus on standardizing these imaging techniques for consistent application and interpretation (Benz et al., 2016).

7. Involving Machine Learning in MRI

Machine learning (ML) in MRI involves the application of computational algorithms and statistical models to analyze imaging data. These algorithms learn from the data to identify patterns, make predictions, and extract meaningful information from MRI scans. A new study aimed to forecast the best deep brain stimulation (DBS) settings for Parkinson’s disease through fMRI and machine learning techniques. They studied 3 T fMRI data from 67 Parkinson's disease patients, comparing optimal and non-optimal DBS settings. Optimal stimulation leads to a specific brain response pattern, emphasizing motor circuit activation. They suggested that fMRI brain responses to DBS stimulation in PD patients might serve as an objective biomarker of clinical response (Boutet et al., 2021). Another study researched ML in breast MRI as rapidly progressing, particularly in areas like lesion detection and predicting response to chemotherapy. However, both supervised and unsupervised ML techniques still require further investigation to achieve clinical applicability (Reig et al., 2019).

CONCLUSION

In conclusion, this article has provided a comprehensive overview of 3T MRI, detailing its current practices and exploring the potential future prospects in the field. We have discussed the advantages of 3T MRI, such as increased SNR and improved spatial resolution, which offer enhanced imaging capabilities across various medical applications. Additionally, we have addressed some of the challenges and limitations associated with 3T MRI, including susceptibility artifacts and radiofrequency power deposition issues.

Despite these challenges, the continued advancements in technology and imaging techniques hold promise for further improving the clinical utility of 3T MRI. From functional MRI to whole-body imaging, the potential applications of 3T MRI are vast and continue to expand. Moreover, with ongoing research and development efforts, we anticipate that 3T MRI will play an increasingly significant role in diagnostic imaging, enabling more accurate disease detection, characterization, and treatment planning.

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