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Avanços de ponta em radiologia musculoesquelética: uma revisão abrangente de técnicas inovadoras e seu impacto nas capacidades de diagnóstico

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ARTIGO DE REVISÃO

RESUMO

Esta revisão abrangente destaca inovações significativas na radiologia músculo-esquelética, enfatizando a integração de técnicas avançadas de imagem que melhoraram significativamente as capacidades de diagnóstico. O advento da neurografia por RM de alta resolução, da ressonância magnética ultrarrápida orientada por aprendizado profundo, da tomografia computadorizada sintética baseada em ressonância magnética e da ressonância magnética quantitativa transformaram os processos de diagnóstico, oferecendo insights detalhados sobre distúrbios musculoesqueléticos complexos. Além disso, os desenvolvimentos em ressonância magnética de baixo campo, ressonância magnética de campo ultra-alto de 7,0 T e modalidades de imagem como tomografia computadorizada de dupla energia, tomografia computadorizada de feixe cônico, tomografia computadorizada cinemática e tomografia computadorizada com contagem de fótons ressaltam ainda mais a rápida evolução da imagem musculoesquelética. Estas tecnologias melhoram a precisão do diagnóstico e melhoram a experiência e a segurança do paciente, reduzindo os tempos de exposição e melhorando o conforto. A revisão discute as contribuições de cada tecnologia para o diagnóstico músculo-esquelético, suas potenciais aplicações clínicas e os desafios técnicos e direções futuras na integração dessas técnicas avançadas na prática clínica de rotina.

Palavras-chave: Radiologia Musculoesquelética. Neurografia por RM. Aprendizado de máquina. Técnicas de diagnóstico por imagem. Tomografia computadorizada por contagem de fótons.

Cutting-edge advancements in Musculoskeletal Radiology: A Comprehensive Review of Innovative Techniques and Their Impact on Diagnostic Capabilities

ABSTRACT

This comprehensive review highlights significant innovations in musculoskeletal radiology, emphasizing the integration of advanced imaging techniques that have markedly enhanced diagnostic capabilities. The advent of high-resolution MR neurography, deep learning-driven ultra-fast MRI, MRI-based synthetic CT, and quantitative MRI have transformed diagnostic processes, offering detailed insights into complex musculoskeletal disorders. Additionally, developments in low-field MRI, ultra-high-field 7.0 T MRI, and imaging modalities like dual-energy CT, cone beam CT, kinematic CT, and photon-counting CT further underscore the rapid evolution of musculoskeletal imaging. These technologies improve diagnostic accuracy, patient experience, and safety by reducing exposure times and enhancing comfort. The review discusses each technology's contributions to musculoskeletal diagnostics, their potential clinical applications, and the technical challenges and future directions in integrating these advanced techniques into routine clinical practice.

Keywords: Musculoskeletal Radiology, MR Neurography, Machine Learning, Diagnostic Imaging Techniques, Photon-Counting Computed Tomography.

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INTRODUCTION

Musculoskeletal radiology has witnessed significant advancements in recent years, with the introduction of innovative techniques that have revolutionized the field. These cutting-edge technologies have not only improved image quality and diagnostic capabilities but have also enhanced the speed and efficiency of the imaging process. This narrative review aims to provide a comprehensive overview of the recent innovations in musculoskeletal radiology, highlighting their scientific and technical aspects and potential impact on patient care. It emphasizes the collaborative nature of the field and the importance of the audience's contributions.

METHODOLOGY

A thorough literature search was conducted using prominent databases, including Scopus, Web of Science, PubMed, ERIC, IEEE Xplore, ScienceDirect, Directory of Open Access Journals (DOAJ), and JSTOR. The search terms included "musculoskeletal radiology," "high-resolution MR neurography," "deep learning," "ultra-fast musculoskeletal MRI," "MRI-based synthetic CT," "quantitative MRI," "low-field MRI," "7.0 T MRI," "dual-energy CT," "cone beam CT," "kinematic CT," and "photon-counting CT." Only peer-reviewed articles published in English were considered. The selected articles were carefully analyzed to extract relevant information and synthesize the findings.

RESULTS

High-Resolution MR Neurography

High-resolution MR neurography, a powerful tool for evaluating peripheral nerve disorders, has significantly improved the diagnosis of these conditions. By providing detailed visualization of nerve anatomy and pathology, this technique has enhanced our ability to detect subtle nerve abnormalities, such as entrapment neuropathies, traumatic injuries, and inflammatory conditions. The increased spatial resolution and contrast-to-noise ratio enable the detection of these conditions, leading to more accurate diagnoses and better patient outcomes. Moreover, diffusion tensor imaging (DTI) and tractography allow for the assessment of nerve integrity and connectivity, aiding in diagnosing and managing complex neuropathies(1).

Deep Learning-Driven Ultra-Fast Musculoskeletal MRI

Integrating deep learning algorithms into musculoskeletal MRI has revolutionized imaging, enabling ultra-fast acquisition times without compromising image quality. Deep learning-based techniques, such as compressed sensing and parallel imaging, have significantly reduced the time required for MRI scans, making them more patient-friendly and cost-effective (2). These algorithms learn from vast datasets of high-quality MRI scans and can accurately reconstruct images from undersampled data, accelerating the imaging process and reducing patient wait times. Furthermore, deep learning-based image reconstruction has shown potential in reducing motion artifacts and improving signal-to-noise ratio, enhancing the diagnostic value of the images (3). Furthermore, deep learning-based image reconstruction has shown potential in reducing motion artifacts and improving signal-to-noise ratio, enhancing the diagnostic value of the images (4).

MRI-Based Synthetic CT

MRI-based synthetic CT is an innovative technique that generates CT-like images from MRI data, eliminating the need for additional CT scans. This approach utilizes advanced algorithms, such as atlas-based methods and deep learning networks, to convert MRI signal intensities into Hounsfield units (HU) (5). The resulting synthetic CT images provide accurate bone and soft tissue information comparable to that of conventional CT scans (6). This technique has numerous applications in musculoskeletal radiology, including radiation therapy planning, surgical navigation, and attenuation correction for PET/MRI (7).

Quantitative MRI

Quantitative MRI techniques have gained increasing attention in musculoskeletal radiology because they provide objective and reproducible measures of tissue properties. These techniques include T1, T2, and T2* mapping, as well as diffusionweighted imaging (DWI) and chemical shift imaging (CSI) (8). Quantitative MRI allows for assessing tissue composition, microstructure, and metabolism, providing valuable insights into the pathophysiology of various musculoskeletal disorders (9). For instance, T2 mapping has shown promise in detecting early cartilage degeneration in osteoarthritis, while DWI has demonstrated utility in differentiating benign from malignant bone lesions (10).

Modern Low-Field MRI

Low-field MRI systems have experienced a resurgence in recent years, driven by advancements in hardware and software technologies. Modern low-field MRI scanners offer several advantages over high-field systems, including lower costs, reduced energy consumption, and improved patient comfort. These patient-friendly features make low-field MRI a viable option for musculoskeletal imaging, particularly in resource-limited settings and for patients with contraindications to high-field MRI. (11). These systems utilize innovative coil designs, such as cryogenically cooled coils and multi-channel arrays, to enhance signal-to-noise ratio and image quality (12). Additionally, using advanced pulse sequences and image reconstruction algorithms has further improved the diagnostic capabilities of low-field MRI (13). These advancements have made low-field MRI a viable option for musculoskeletal imaging, particularly in resource-limited settings and for patients with contraindications to high-field MRI.

7.0 T MRI

Ultra-high-field MRI, particularly 7.0 T MRI, has opened new avenues for musculoskeletal imaging research. The increased magnetic field strength offers superior signal-to-noise ratio, spatial resolution, and contrast, enabling the visualization of fine anatomical details and subtle pathological changes (14). 7.0 T MRI has shown promise in the evaluation of various musculoskeletal structures, such as cartilage, menisci, ligaments, and tendons (15). The enhanced resolution and contrast of 7.0 T MRI have facilitated the detection of early degenerative changes, microstructural alterations, and vascular abnormalities. This provides valuable insights into the pathogenesis of musculoskeletal disorders, making 7.0 T MRI a promising tool for musculoskeletal imaging research. Despite the challenges it faces in clinical implementation, the potential of 7.0 T MRI to revolutionize musculoskeletal imaging is a cause for optimism (16). However, the clinical implementation of 7.0 T MRI faces challenges, including increased susceptibility artifacts, specific absorption rate (SAR) limitations, and the need for specialized hardware and software (17).

Dual-Energy CT

Dual-energy CT (DECT) has emerged as a powerful tool in musculoskeletal imaging, offering enhanced tissue characterization and material decomposition capabilities. DECT utilizes two different X-ray energy spectra to acquire image data, allowing for the differentiation of materials based on their attenuation properties (18). This technique has numerous applications in musculoskeletal radiology, including the assessment of bone marrow edema, crystal deposition diseases, and metal artifact reduction (19)DECT has also shown promise in evaluating soft tissue structures, such as ligaments and tendons. By providing increased contrast and suppressing beam-hardening artifacts, DECT expands its applications in musculoskeletal radiology. The potential of DECT to enhance tissue characterization and material decomposition capabilities is an exciting prospect for the future of musculoskeletal imaging (20).

Cone Beam CT

Cone beam CT (CBCT) has gained popularity in musculoskeletal imaging due to its high spatial resolution, low radiation dose, and compact scanner design. CBCT utilizes a cone-shaped X-ray beam and a flat-panel detector to acquire volumetric image data in a single rotation (21). This technique has found widespread application in the evaluation of bone and joint disorders, particularly in the extremities (22). CBCT offers superior visualization of fine bony details, such as trabecular structure and cortical integrity, aiding in the diagnosis of fractures, osteomyelitis, and tumors (23). Moreover, the low radiation dose and compact scanner design make CBCT suitable for intraoperative imaging and image-guided interventions (24).

Kinematic CT

Kinematic CT is an innovative imaging technique that combines CT with dynamic joint motion assessment. This approach utilizes high-speed CT acquisition and advanced postprocessing algorithms to generate 3D models of joint kinematics (25). Kinematic CT allows for the evaluation of joint motion in real-time, providing valuable insights into the functional anatomy and biomechanics of the musculoskeletal system (26). This technique has shown promise in the assessment of joint instability, impingement syndromes, and ligamentous injuries (27). Moreover, kinematic CT has the potential to guide surgical planning and optimize treatment outcomes by providing patient-specific functional information (28).

Photon-Counting CT

Photon-counting CT (PCCT) is a cutting-edge technology that offers superior spatial and contrast resolution compared to conventional CT systems. PCCT utilizes high-performance photon-counting detectors that can discriminate between individual X-ray photons based on their energy (29). This allows for improved material decomposition, reduced electronic noise, and enhanced contrast-to-noise ratio (30). PCCT has shown potential in various musculoskeletal imaging applications, including the assessment of bone mineral density, detection of micro-fractures, and characterization of soft tissue structures (31). Furthermore, PCCT enables the simultaneous acquisition of multiple energy-specific images, facilitating the generation of virtual monoenergetic and material-specific images (32).

DISCUSSION

The advancements in musculoskeletal radiology described in this review have the potential to revolutionize the diagnosis and management of musculoskeletal disorders. High-resolution MR neurography and deep learning-driven ultra-fast MRI have improved the detection and characterization of peripheral nerve abnormalities and have made the imaging process more efficient and patient-friendly. MRI-based synthetic CT and quantitative MRI techniques have expanded the diagnostic capabilities of MRI, providing valuable information on tissue composition and microstructure. The resurgence of low-field MRI and the introduction of 7.0 T MRI have opened new avenues for musculoskeletal imaging research and could potentially improve patient access to advanced imaging technologies.

Dual-energy CT, cone beam CT, and kinematic CT have enhanced the evaluation of bone and joint disorders, offering superior tissue characterization, high spatial resolution, and dynamic functional assessment. Photon-counting CT represents a significant leap forward in CT technology, providing improved material decomposition and contrast resolution. These advancements can improve diagnostic accuracy, guide treatment decisions, and optimize patient outcomes.

However, the clinical implementation of these cutting-edge technologies faces several challenges. The high costs associated with advanced imaging systems and the need for specialized expertise may limit their widespread adoption. Moreover, integrating these technologies into existing clinical workflows and standardizing imaging protocols require further research and collaboration among radiologists, physicists, and engineers.

FINAL CONSIDERATIONS

In conclusion, this narrative review highlights the recent innovations in musculoskeletal radiology, encompassing high-resolution MR neurography, deep learning-driven ultra-fast MRI, MRI-based synthetic CT, quantitative MRI, modern low-field MRI, 7.0 T MRI, dual-energy CT, cone beam CT, kinematic CT, and photon-counting CT. These advancements have significantly improved the diagnostic capabilities, speed, and patient experience in musculoskeletal imaging. However, further research is needed to address the challenges associated with their clinical implementation and to fully harness their potential in improving patient care. As the field of musculoskeletal radiology continues to evolve, it is essential for radiologists to stay abreast of these cutting-edge technologies and to collaborate with multidisciplinary teams to optimize their utilization in clinical practice.

REFERENCES

1. Oudeman J, Coolen BF, Mazzoli V, Maas M, Verhamme C, Brink WM, et al. Diffusion-prepared neurography of the brachial plexus with a large field-of-view at 3T. J Magn Reson Imaging [Internet]. 2016 Mar 1 [cited 2024 Jun 25];43(3):644–54. Available from: https://pubmed.ncbi.nlm.nih.gov/26251015/

2. Chen Y, Schonlieb CB, Lio P, Leiner T, Dragotti PL, Wang G, et al. AI-Based Reconstruction for Fast MRI-A Systematic Review and Meta-Analysis. Vol. 110, Proceedings of the IEEE. 2022.

3. Liang D, Cheng J, Ke Z, Ying L. Deep Magnetic Resonance Image Reconstruction: Inverse Problems Meet Neural Networks. IEEE Signal Process Mag. 2020;37(1).

4. Hammernik K, Klatzer T, Kobler E, Recht MP, Sodickson DK, Pock T, et al. Learning a variational network for reconstruction of accelerated MRI data. Magn Reson Med. 2018;79(6).

5. Yingchao J, Dongshan F, Wei W. A Review of MRI-based synthetic CT image generation. Chinese Journal of Biomedical Engineering. 2020;39(4).

6. Keaveney S, Dragan A, Rata M, Blackledge M, Scurr E, Winfield JM, et al. Image quality in whole-body MRI using the MY-RADS protocol in a prospective multi-centre multiple myeloma study. Insights Imaging [Internet]. 2023 Dec 1 [cited 2024 Jun 25];14(1):1–14. Available from: https://insightsimaging.springeropen.com/articles/10.1186/s13244-023-01498-3

7. Leynes AP, Yang J, Wiesinger F, Kaushik SS, Shanbhag DD, Seo Y, et al. Zero-echo-time and dixon deep pseudo-CT (ZeDD CT): Direct generation of pseudo-CT images for Pelvic PET/MRI Attenuation Correction Using Deep Convolutional Neural Networks with Multiparametric MRI. Journal of Nuclear Medicine. 2018;59(5).

8. De Mello R, Ma Y, Ji Y, Du J, Chang EY. Quantitative MRI musculoskeletal techniques: An update. Vol. 213, American Journal of Roentgenology. 2019.

9. Kijowski R. Standardization of compositional MRI of knee cartilage: Why and how. Vol. 301, Radiology. 2021.

10. Guermazi A, Roemer FW, Hayashi D. Imaging of osteoarthritis: Update from a radiological perspective. Vol. 23, Current Opinion in Rheumatology. 2011.

11. Campbell-Washburn AE, Ramasawmy R, Restivo MC, Bhattacharya I, Basar B, Herzka DA, et al. Opportunities in interventional and diagnostic imaging by using high-performance low-field-strength MRI. Radiology. 2019;293(2).

12. Duyn JH. The future of ultra-high field MRI and fMRI for study of the human brain. Neuroimage [Internet]. 2012 Aug 15 [cited 2024 Jun 25];62(2):1241–8. Available from: https://pubmed.ncbi.nlm.nih.gov/22063093/

13. Khodarahmi I, Keerthivasan MB, Brinkmann IM, Grodzki D, Fritz J. Modern Low-Field MRI of the Musculoskeletal System: Practice Considerations, Opportunities, and Challenges. Invest Radiol. 2023;58(1).

14. Trattnig S, Bogner W, Gruber S, Szomolanyi P, Juras V, Robinson S, et al. Clinical applications at ultrahigh field (7 T). Where does it make the difference? NMR Biomed. 2016;29(9).

15. Juras V, Mlynarik V, Szomolanyi P, Valkovič L, Trattnig S. Magnetic Resonance Imaging of the Musculoskeletal System at 7T: Morphological Imaging and Beyond. Vol. 28, Topics in Magnetic Resonance Imaging. 2019.

16. Demehri S, Baffour FI, Klein JG, Ghotbi E, Ibad HA, Moradi K, et al. Musculoskeletal CT Imaging: State-of-the-Art Advancements and Future Directions. Vol. 308, Radiology. 2023.

17. Ladd ME, Bachert P, Meyerspeer M, Moser E, Nagel AM, Norris DG, et al. Pros and cons of ultra-high-field MRI/MRS for human application. Vol. 109, Progress in Nuclear Magnetic Resonance Spectroscopy. 2018.

18. Mallinson PI, Coupal TM, McLaughlin PD, Nicolaou S, Munk PL, Ouellette HA. Dual-energy CT for the musculoskeletal system. Radiology. 2016;281(3).

19. Pascart T, Budzik JF. Dual-energy computed tomography in crystalline arthritis: knowns and unknowns. Curr Opin Rheumatol [Internet]. 2022 Mar 1 [cited 2024 Jun 25];34(2):103–10. Available from: https://pubmed.ncbi.nlm.nih.gov/35034071/

20. Zell M, Zhang D, Fitzgerald J. Diagnostic advances in synovial fluid analysis and radiographic identification for crystalline arthritis. Curr Opin Rheumatol [Internet]. 2019 Mar 1 [cited 2024 Jun 25];31(2):134–43. Available from: https://pubmed.ncbi.nlm.nih.gov/30601230/

21. Doan MK, Long JR, Verhey E, Wyse A, Patel K, Flug JA. Cone-Beam CT of the Extremities in Clinical Practice. Radiographics [Internet]. 2024 Feb 29 [cited 2024 Jun 25];44(3). Available from: https://pubs.rsna.org/doi/10.1148/rg.230143

22. Bailey J, Solan M, Moore E. Cone-beam computed tomography in orthopaedics. Orthop Trauma. 2022 Aug 1;36(4):194–201.

23. Posadzy M, Desimpel J, Vanhoenacker F. Cone beam CT of the musculoskeletal system: clinical applications. Vol. 9, Insights into Imaging. 2018.

24. Richter M, Geerling J, Zech S, Goesling T, Krettek C. Intraoperative three-dimensional imaging with a motorized mobile C-arm (SIREMOBILISO-C-3D) in foot and ankle trauma care: A preliminary report. J Orthop Trauma. 2005;19(4).

25. Gondim Teixeira PA, Formery AS, Hossu G, Winninger D, Batch T, Gervaise A, et al. Evidence-based recommendations for musculoskeletal kinematic 4D-CT studies using wide area-detector scanners: a phantom study with cadaveric correlation. Eur Radiol. 2017;27(2).

26. Upadhyaya V, Choudur HN. Update on sports imaging. J Clin Orthop Trauma. 2021 Oct 1;21:101555.

27. Oonk JGM, Dobbe JGG, Strackee SD, Strijkers GJ, Streekstra GJ. Quantification of the methodological error in kinematic evaluation of the DRUJ using dynamic CT. Sci Rep. 2023;13(1).

28. Carew RM, French J, Morgan RM. 3D forensic science: A new field integrating 3D imaging and 3D printing in crime reconstruction. Forensic Sci Int [Internet]. 2021 Jan 1 [cited 2024 Jun 25];3. Available from: https://pubmed.ncbi.nlm.nih.gov/34746730/

29. Willemink MJ, Persson M, Pourmorteza A, Pelc NJ, Fleischmann D. Photon-counting CT: Technical principles and clinical prospects. Vol. 289, Radiology. 2018.

30. Pourmorteza A, Symons R, Henning A, Ulzheimer S, Bluemke DA. Dose Efficiency of Quarter-Millimeter Photon-Counting Computed Tomography: First-in-Human Results. Invest Radiol. 2018;53(6).

31. Rajendran K, Löbker C, Schon BS, Bateman CJ, Younis RA, de Ruiter NJA, et al. Quantitative imaging of excised osteoarthritic cartilage using spectral CT. Eur Radiol. 2017;27(1).

32. Amato C, Susenburger M, Lehr S, Kuntz J, Gehrke N, Franke D, et al. Dual-contrast photon-counting micro-CT using iodine and a novel bismuth-based contrast agent. Phys Med Biol. 2023;68(13).