Radiology

Advances in Musculoskeletal Imaging: Recent Developments and Predictions for the Future

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In this editorial, written for the centennial of *Radiology*, we will discuss recent advances in musculoskeletal imaging and make predictions for the future of our subspecialty. It is important to look back on discoveries that vaulted the field of medical imaging forward. Thus, we must acknowledge Roentgen's discovery of x-rays in 1895. Following this discovery, the value of imaging for detecting abnormalities of the musculoskeletal system was quickly established, with the first monograph on bone radiography published in 1901 (1). We present our predictions for what musculoskeletal imaging might look like by 2050 with trepidation (Table). We are cognizant of Yogi Berra's warning: "It's tough to make predictions, especially about the future" (2). To paraphrase Abraham Lincoln, however, we believe that "the best way to predict the future is to envision it and then create it."

MRI: Past and Recent Advances

For most of the 20th century, musculoskeletal imaging was primarily limited to radiography and the diagnosis of osseous (bone) abnormalities. The introduction of MRI in the 1980s substantially expanded the use of musculoskeletal imaging. This was owing to its excellent soft tissue contrast and ability to acquire both morphologic and quantitative information. Although the use of MRI in extremity imaging increased by 653% from 1993 to 2014 (3), its use remained limited by its slow acquisition times when compared with other modalities such as radiography and CT. Indeed, the relatively long MRI examination times lead to several disadvantages, including motion artifacts degrading image quality, high cost, and decreased accessibility, especially in countries with a limited number of MRI scanners (4). Due to the high cost of an MRI examination, radiography is the recommended first-line imaging modality even for conditions optimally visualized with MRI, such as sports injuries. This is true even in countries with a large number of MRI scanners. Therefore, it is not surprising that increasing the speed of MRI has been a primary objective for musculoskeletal imagers over the past several years.

Rapid Acquisition with Relaxation Enhancement and Parallel Imaging

One of the first major advances in speed was the introduction of rapid acquisition with relaxation enhancement (RARE) imaging (5) in 1986, with fast or turbo spin-echo imaging quickly becoming the dominant technique used in musculoskeletal imaging (6). The next major advance occurred in the late 1990s with the introduction of parallel imaging (7). Parallel imaging allows for undersampling without the introduction of aliasing by taking advantage of the information provided by multichannel coil arrays. Undersampling or decreasing the number of phase-encoding steps acquired allows for faster imaging times because imaging time is directly proportional to the number of phase-encoding steps acquired. Decreasing the number of phase-encoding steps in half will lead to a decrease of imaging time by 50%, producing an acceleration factor of 2. Decreasing the number of phase-encoding steps, however, can lead to aliasing or wrap artifact because the sampling frequency cannot distinguish between objects found at two different locations. Parallel imaging takes advantage of the unique sensitivities of each individual coil within a multichannel array to accurately locate each object and eliminate aliasing. Unfortunately, the signal-to-noise ratio is also decreased when the number of phase-encoding steps is decreased. Decreasing phase-encoding steps by half will cause a decrease in the signal-to-noise ratio by 40%. This decrease generally limits the acceptable acceleration gained by using parallel imaging to a factor of 2–3 for most musculoskeletal imaging examinations. Although a substantial improvement, the gradient time of protocols using a combination of RARE and parallel imaging techniques remains in the 10–20-minute range, with examination times generally in the 30-minute range.

Simultaneous Multislice Imaging

Simultaneous multislice (SMS) imaging is a technique that excites and acquires multiple sections at the same time rather than the traditional method of one section at a time (8). Dedicated reconstruction techniques separate the signals arising from the multiple excited sections. Acquiring multiple sections simultaneously allows for acceleration by either decreasing repetition times, increasing the echo train length, or using fewer concatenations. Compared with parallel imaging, one major advantage of SMS imaging is that the signal-to-noise ratio remains relatively preserved; however, an increase in the specific absorption ratio can pose a challenge—particularly at 3.0 T. The increase in the specific absorption ratio limits the acceptable acceleration to a factor of 2–3. By combining

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See also the editorial by Carrino in this issue.

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Predictions for Musculoskeletal Imaging by 2050

Prediction
Deep learning reconstruction techniques will be the standard for all musculoskeletal MRI examinations, allowing them to be performed in 2–3 minutes
Low-field-strength, inexpensive-to-purchase (<$50 000), easy-to-site, and inexpensive to maintain MRI scanners will allow MRI to become as ubiquitous and affordable as extremity radiography is today
MRI will have replaced radiography for the evaluation of sports injuries
AI tools will be relied upon for "supervised" diagnostic interpretation of all musculoskeletal examinations
Automated opportunistic quantitative tissue compositional assessments will be a standard component of all musculoskeletal cross-sectional imaging studies by 2050
Musculoskeletal imaging examination reports will routinely contain data-based metrics predictive of patient-specific clinical outcomes, including disease progression and responsiveness to therapy
Image-guided musculoskeletal interventions will occur in highly realistic 3D virtual reality environments controlled by robotics with haptic feedback and remote capabilities, aided by AI and telemedicine advancements
The spectrum of percutaneous image–guided musculoskeletal interventions will expand to include minimally invasive osteosynthesis; repair and reconstruction of tendons, ligaments, and menisci; and tissue regeneration through targeted drug delivery
Our discipline will no longer be called *radiology*

Note.—AI = artificial intelligence, 3D = three-dimensional.

SMS and parallel imaging, however, it is possible to achieve acceleration factors ranging from 4 to 6, shortening imaging times to approximately 5 minutes for knee MRI (9).

Deep Learning Reconstruction

The most recent advances in accelerating musculoskeletal MRI use deep learning reconstruction (DLR) techniques. These advances have been facilitated by the release of large-scale publicly available data sets of both raw MRI k-space data and magnitude Digital Imaging and Communications in Medicine, or DICOM, images (10). Two recent studies (11,12) using parallel imaging undersampling and DLR achieved 5-minute examination times for MRI of the knee and demonstrated diagnostic interchangeability between the DLR technique and a standard turbo spin-echo sequence using parallel imaging. We believe that by 2050, DLR will be the standard for all musculoskeletal MRI examinations, allowing them to be performed in 2–3 minutes.

In addition to increasing the speed of MRI examinations, the ability of DLR to improve image quality through artifact reduction, denoising (removing noise), and superresolution (enhancing image resolution from low to high) decreases the need for field homogeneity and allows for lower acceptable field strengths. Low-field-strength (0.2–0.5 T) dedicated extremity magnets have demonstrated good diagnostic accuracy (13), but their clinical acceptance has lagged due to inferior image quality compared with that of high-field-strength MRI scanners. DLR techniques combined with recent improvements in hardware and software have reignited the interest in low-field-strength scanners due to the lower total cost of ownership and easier siting of low-field-strength scanners compared with 1.5- or 3-T scanners (14). These changes, in combination with the now achievable rapid examination times, underscore the promise of substantially decreasing the cost of purchasing, siting, and maintaining MRI scanners. By 2050, low-field-strength, inexpensive to purchase (<$50 000), easy to site, and inexpensive to maintain MRI scanners will allow MRI to become as ubiquitous and affordable as extremity radiography is today.

Shorter MRI examination times, which will be equal to or less than those of other modalities such as radiography or CT, and low-cost, easy-to-site scanners will allow MRI to become the preferred first-line imaging method for sports imaging. On their visit to the emergency department or sports medicine physician, it is likely that an athlete who has a knee or shoulder injury will receive a "walk-in" MRI examination and receive an immediate diagnosis. This is a marked improvement from the current situation of first undergoing radiography and then waiting several days or weeks for authorization before undergoing MRI. By 2050, MRI will have replaced radiography for the evaluation of sports injuries.

Artificial Intelligence

In addition to its role in accelerating MRI acquisition times, artificial intelligence (AI) will have a transformative impact on all facets of musculoskeletal imaging. AI has already demonstrated utility in optimizing workflow, such as ensuring imaging appropriateness and scheduling efficiency, as well as generation of reports (15,16). Perhaps even more important is the usefulness of AI for pattern recognition and image interpretation. Deep learning algorithms, primarily through the use of convolutional neural networks, have demonstrated diagnostic accuracies equivalent to or approaching those of radiologists in the detection of multiple conditions including but not limited to fractures (17), internal derangement of the knee (18), and metastatic lesions in the spine (19).

Interestingly, however, studies have demonstrated that a combination of interpretations both by a radiologist and by AI is better than the interpretation of either alone (20). Thus, we believe that it is unlikely that AI will rapidly replace radiologists for the diagnosis of musculoskeletal disease. Rather, AI algorithms will assist radiologists, improving their accuracy and enhancing their efficiency and productivity. By 2050, we will rely on AI tools for "supervised" diagnostic interpretation of all musculoskeletal examinations. The degree to which future AI technologies will be relied upon as standalone autonomous tools in medical imaging without human physician involvement, however, will ultimately depend on regulatory requirements, legal-liability frameworks, and, perhaps most importantly, the degree of consumer (patient, medical system, insurer) acceptance of autonomous AI technologies in medicine and society in general.

AI also has the potential to improve our ability to derive quantitative information routinely and accurately from our images. Studies have demonstrated that AI can perform routine measurements, further enhancing the radiologist's workflow, thereby allowing radiologists to concentrate on the more challenging tasks of detecting and diagnosing abnormalities (21). AI techniques have also shown promise in performing reliable tissue segmentation, offloading time-consuming manual processes involved with volume segmentation and analysis of musculoskeletal tissues on imaging studies. Opportunities for AI-driven quantitative imaging segmentation include the characterization of fat, skeletal muscle, and other soft tissues such as the articular cartilage (22). Such AI-driven techniques offer the promise of routine imaging analysis including tissue compositional data, thus allowing opportunistic assessments of conditions such as osteoporosis, obesity, frailty, and sarcopenia (23). Automated opportunistic quantitative tissue compositional assessments will be a standard component of all musculoskeletal cross-sectional imaging studies by 2050.

Radiomics

One of the most exciting potentials of AI in musculoskeletal imaging is radiomics, the ability to extract and mine quantitative data elements intrinsic to images but beyond the scope of human visual detection and interpretation. These data include complex quantitative characteristics such as image texture, voxel intensities, and intervoxel relationships. Correlative statistical modeling using such radiomics-derived data elements (radiomic features) can be predictive of features such as tissue microenvironment, biologic behavior, and prospective clinical outcomes (24). The utility of radiomics in musculoskeletal imaging has been most widely studied in the assessment of CT and MRI of musculoskeletal soft tissue and bone tumors. Radiomics has shown promising results in the characterization of tumor biology, differentiation of benign and malignant lesions, prediction of response to adjuvant chemotherapy or radiation therapy, and determination of the risk for the development of systemic lung metastases, as well as patient survival outcomes (25).

An example of the potential impact of radiomics in musculoskeletal oncologic disease is evident in encouraging preliminary results of MRI radiomics studies in the pretreatment prediction of histologic response to chemotherapy, disease relapse, and overall survival in patients with osteosarcoma (26–28). Combining radiomics with other complementary patient-specific data takes us a step closer to predictive personalized precision medicine. Patient-specific information may include data from histologic and biochemical analyses, biomechanics, proteomics, and/or genomics (also known as radiogenomics). While musculoskeletal radiomics is still in its early stages, by 2050 we believe musculoskeletal imaging examination reports will routinely contain data-based metrics predictive of patient-specific clinical outcomes, including disease progression and responsiveness to therapy.

Musculoskeletal Interventions

Interventional procedures are a continuously expanding part of musculoskeletal imaging (29). The use of cross-sectional imaging techniques such as US, CT, and MRI has been instrumental in developing and expanding the use of minimally invasive musculoskeletal interventions (30). High-resolution imaging and fast acquisition speeds have enabled accurate targeting of submillimeter structures and have allowed monitoring under real-time image guidance (31). Soon, we anticipate that a technology-based paradigm shift in musculoskeletal interventions will revolutionize how we approach and treat many musculoskeletal conditions.

The use of robust image fusion technologies using high-resolution images will provide three-dimensional imaging guidance with maximized visibility of anatomic structures for highly accurate and efficient targeting (32). Integrating metabolic data derived from PET and physiologic data provided with diffusion-weighted MRI will permit the selective targeting of biologically active inflammatory, infectious, and neoplastic tissues, rather than biologically inactive necrotic tissues, to improve diagnostic yields (33). Mixed, augmented, and virtual reality technologies have the potential to translate two-dimensional image data into a three-dimensional image from which the interventionalist can plan and simulate procedures. This will help prevent the injury of adjacent structures such as nerves or vessels. In addition, this technology can enhance the interventional training of residents and fellows (34,35).

Musculoskeletal interventions will likely shift from manual to robot-assisted procedures, improving the targeting of anatomic structures and lesions; the precise placement of needles, drills, and probes; the accuracy of tissue sampling; and the positive results of ablations and cement injections (36). Robotic musculoskeletal interventions will further enable a shift toward remote procedure guidance. Like sophisticated gaming environments, it is possible to combine robotic procedure guidance with virtual reality environments and haptic feedback during device placements, biopsies, and injections (37). Such guidance offers several benefits, such as increased accessibility to specialized expertise, reduced risk of exposure to infectious diseases, and improved cost-effectiveness. With advances in technology, remote guidance is becoming increasingly feasible, allowing physicians to perform procedures from a distance with the help of robotic devices. By 2050, image-guided musculoskeletal interventions will occur in highly realistic three-dimensional virtual reality environments controlled by robotics with haptic feedback and remote capabilities, aided by AI and telemedicine advancements.

We predict a substantial expansion in the range of diagnostic and minimally invasive therapeutic procedures based on the technical advances described earlier. Minimally invasive treatments will expand, including injections and thermal ablations for neoplasms and neuropathies (38), back pain (39), and osteoarthritis (40); cement augmentation of bone for stabilization and osseous synthesis (41); percutaneous screw fixation for spinal stabilization (42); and tendon repairs. Novel injectable regenerative medicine strategies, including gene therapies, biomaterials, and scaffolds aiming to regenerate at cellular and molecular levels, will require and benefit from highly accurate and minimally invasive image-guided drug delivery.

Finally, we believe that the many changes described earlier will lead to a shift away from the current practice of standalone interventional musculoskeletal imaging services. In the future, interventional musculoskeletal radiologists will be seamlessly integrated into multidisciplinary teams recruited from multiple surgical, medical, and imaging specialties, providing the most appropriate choice of treatment strategy for each patient. The spectrum of percutaneous image–guided musculoskeletal interventions will expand to include minimally invasive osteosynthesis; repair and reconstruction of tendons, ligaments, and menisci; and tissue regeneration through targeted drug delivery. In this special centennial issue on musculoskeletal imaging, please see the commentary by Carrino (43) and the reviews by Sneag et al (44) on state-of-the-art musculoskeletal MRI and Demehri et al (45) state-of-the-art review on musculoskeletal CT imaging.

Final Prediction

Our final prediction is that by 2050 our discipline will no longer be called *radiology*. Radiology is derived from radio-, a form of radiation, and -ology, a form of science. In short, this word indicates a "scientific study of radiation." As described earlier, our specialty is no longer accurately described as radiology; we are no longer correctly designated radiologists. We are medical imagers and interventionalists, armed with a variety of imaging techniques, many independent of x-rays or radiation. Unfortunately, when consulting a radiologist, some people infer that radiation will be used, which in turn may elicit anxiety and fear. By extension, the name "radiology department" will be changed to "department of medical imaging and intervention," a description already in use at some university hospitals and medical schools.

Conclusion

The last century has witnessed the evolution and growth of musculoskeletal imaging, a specialty once dominated by conventional radiography. The introduction and refinement of other imaging methods, especially MRI, has certainly changed the assessment of musculoskeletal disorders. Most recently, AI and the dramatic expansion of musculoskeletal interventions have further advanced the field. We can only wonder what the next 100 years will bring.

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