Nuclear Medicine and Radiologic Imaging in Sports Injuries

Andor W.J.M. Glaudemans
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ISBN 978-3-662-46490-8 ISBN 978-3-662-46491-5 (eBook)
DOI 10.1007/978-3-662-46491-5

Library of Congress Control Number: 2015938770

Springer Berlin Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer-Verlag GmbH Berlin Heidelberg is part of Springer Science+Business Media (www.springer.com)

Foreword

As President of the International Federation of Sports Medicine (FIMS), I am honoured to write a foreword to this interesting and important initiative: "Nuclear Medicine and Radiologic Imaging in Sports Injuries", edited by Andor Glaudemans (coordinating editor), Rudi Dierckx, Jan Gielen and Hans Zwerver. Personally, I have known Jan Gielen now for many years. He is a current member of the FIMS Scientific Commission.

The textbook is current and concise, and is essential to provide the background information for sports medicine physicians required to practice with confidence in emergency and chronic situations. This volume gives insight in the actual importance of the assessment of injuries with the support of radiologic and nuclear medicine imaging techniques. The chapters written by experts in the field give an overview of actual radiological modalities (computed radiography, CT, ultrasound and MRI) and nuclear medicine imaging techniques (including PET-CT and SPECT-CT) for specific indications, pointing out the specific merits of both. The scope is comprehensive with focus on orthopaedic sports lesions.

The medical society is aware that sports medicine is an integrated multidisciplinary field embracing relevant areas of clinical medicine (sports traumatology, medicine of sports, and sports psychiatry), appropriate allied scientific disciplines (including physiology, psychology, and biomechanics), radiology and nuclear medicine in its natural ally. Sports medicine physicians are increasingly aware that the responsibilities of sports medicine involve not only competitive sports but also recreational sports, and consequently, to this respect, I am proud to recognise over the past years that sports medicine has grown in reliability thanks to its efforts in disseminating the principles of the health aspects of all people engaged in sport and physical activity. In this context, the sport medicine physicians' work has to be dedicated to the protection of the athletes' health, including planning of the medical aspects of sport events and medical treatment, in order to allow them to safely compete in national and international sports events.

Already since the beginning, FIMS promotes the publication of educational books and initiatives enforcing continuous professional development, and this textbook really deserves a special attention.

To my colleague and friend Jan Gielen and to my colleagues Andor Glaudemans, Rudi Dierckx and Hans Zwerver go my sincere congratulations.

Lausanne, Switzerland F. Pigozzi, MD, FIMS President

Preface

A physically active lifestyle is widely promoted since it has numerous positive effects on healthy aging. With this focus on an active lifestyle for everyone, patients and athletes, in all ages, beginners and experts and at a recreational and a professional level, more sports- and exercise-related injuries may be expected. To keep these exercisers "on the move," on the one hand early diagnosis and early therapy decision making are key issues in sports medicine, while on the other hand diagnostic imaging is of increasing importance in successful diagnosis and management of sports injuries, both in recreational and elite athletes.

Sports medicine, as a specialty, has gained much importance in the recent years. Sports and exercise medicine involves the medical care of injury and illness in sports and has a large-scale application in improving the health of the general public and patients with chronic disease, for example, through advice on exercises. However, sports and also "Exercise as a Medicine" may also result in unfavorable side effects on the musculoskeletal system. Optimal management of these injuries requires careful clinical examination, accurate diagnosis, and experience and knowledge of sport-specific movement patterns. The sports medicine specialist treats a wide range of patients from elite sportspersons over recreational people to those who recover from illness and injury. The invaluable importance of this expert area is now increasingly recognized. As an example in 2014, sports and exercise medicine became a new specialty within the Dutch medical community.

Nuclear medicine and radiology are both expanding medical fields, which are potentially able to satisfy the demands of the sports medicine physician by offering precise diagnosis, insights into pathophysiology, monitoring of rehabilitation, and imaging of treatment outcome. Radiologic imaging techniques, such as X-ray, CT, and MRI, already for years play an important role in sports medicine with, for example, growing possibilities in MRI sequences. The development of hybrid imaging systems with better spatial resolution also have led to an increasing use of nuclear medicine techniques. SPECT/CT, PET/CT, and PET/MRI are important developments bringing anatomy and physiology together.

Although there have been some textbooks on imaging sports injuries, the number of these books is limited and mainly focus on radiological techniques. To the best of our knowledge, this is the first comprehensive textbook that combines the perspectives of sports medicine, radiology, and nuclear medicine in one volume. The editors are working in the field of nuclear medicine (Andor Glaudemans and Rudi Dierckx), radiology (Jan Gielen), and sports medicine (Hans Zwerver). In order to obtain a high-quality multi-author textbook, they invited international specialists in all three fields.

The basic chapters describe each specialty, their characteristics, strengths, and weaknesses and provide an overview of all possibilities these specialties may offer. The topographic sections of injuries of the head and face, spine, chest, shoulder, elbow and forearm, wrist and ankle, pelvic region, knee, lower leg, ankle and foot, all exist of three chapters: the first describing the sport-specific injuries, the second describing the radiological perspective with many illustrations, and the third describing the nuclear medicine perspective also with illustrations. After this topographic section, the chapters focus on specific characteristics in adolescents, women, dancers, and musicians. A chapter on equine sports injuries, also to be considered a special athlete, is meant to broaden the scope, as is the case in a special chapter dedicated to the heart as a special muscle in athletes and to the effect of anabolic-androgenic steroids on the heart muscle. The last seven chapters describe the expert views in specific sports (tennis, soccer, cycling, running, and boxing) and the experiences with injuries in Olympic and Paralympic athletes.

We realize that this approach resulted in overlap, albeit from different perspectives. We think this was unavoidable because much integration of the knowledge in radiology, nuclear medicine, and sports medicine is still at its beginning. With this regard, we hope this textbook will prove not only to be useful for those involved in patient care, but also may provide a platform for further common research.

We are happy that our book is produced by one of the premier publishers in the field. This guarantees a high quality of reproduction and allows for the inclusion of many color figures, which is essential in the fields of radiology and nuclear medicine. We would like to thank Dr. Sylvana Freyberg from Springer Verlag for her help and support during the development of this book.

We were also intrigued by the enthusiastic response from contributors from all over the world who made this endeavor successful. Although deadlines sometimes had to be postponed because of the many tasks and roles in the medical field we all play, we appreciated the efforts and enthusiasm of all the authors involved. Hence, our sincere thanks for their contributions. The result to us looks a fine compilation of present evidence, knowledge, and expertise. We hope the interested reader may build on this.

Combining the knowledge of all three specialties involved will hopefully enhance interdisciplinary communication for better patient care and joint research. We sincerely hope that this textbook will become a useful and stimulating reference for sports medicine specialists, radiologists, nuclear medicine specialists, and all professionals working in the field, at the benefit of athletes and patients involved.

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Research Fields

- Imaging of infectious and inflammatory diseases (amyloidosis, fungal infections, vasculitis, endocarditis, patients with bacteremia, vascular graft infections, tuberculosis, atherosclerosis, diabetic foot infections, prosthetic joint infections, osteomyelitis, infections in children)
- Hormonal receptor imaging: estrogen receptor (FES-PET) and androgen receptor (FDHT-PET)
- Imaging of oncological diseases
- Imaging of sports injuries
- Radioisotope therapeutic strategies

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Head of the Medical Imaging Center at the University Medical Center Groningen
Author of more than 500 peer-reviewed publications in international journals, editor of 9 textbooks

Research Fields

Broad interest in nuclear medicine, focus on neuroscience and oncology

- SPECT/conventional nuclear medicine
- PET: research and clinical applications
- Development of novel radiotracers
- Rodent models of human disease
- Medical physics
- Quality, ethics, and economics

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Research Fields

- Radiological imaging and sports medicine
- Gait lab studies in sports and art performers
- Developing skeleton and height prediction
- Imaging and imaging-guided interventions in MSK and sports
- Imaging and imaging-guided interventions of bone and soft tissue tumors

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Research Fields

Broad interest in sports and exercise medicine, focus on musculoskeletal injuries

- Tendinopathy
- Overuse injuries in sports
- Exercise-related injuries in chronic disease
- Exercise and healthy aging

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Part I

Basics

Sports Medicine and Imaging

1

Johannes (Hans) Zwerver

Contents

Abstract

Sports and exercise medicine deals with the medical care of the exercising individual. Strong evidence shows that physical *in*activity increases the risk of many adverse health conditions, including major noncommunicable diseases such as coronary heart disease, type 2 diabetes, and breast and colon cancers and shortens life expectancy. Therefore, exercise is increasingly prescribed by physicians and promoted through government-based health campaigns to prevent the morbidity and mortality caused by inactivity. A side effect is an increasing number of sports- and exercise-related injuries. For optimal management of these conditions, often imaging is necessary to establish a precise diagnosis from the start and to plan the best treatment and rehabilitation strategy.

Dealing with elite athletes, often under time pressure for the next game or an upcoming tournament, poses specific challenges to the medical personnel involved. Good communication between the sports medicine physician and imaging specialist, exchange of relevant information and adequate knowledge of musculoskeletal imaging, and some feeling for what is going on in the athlete are important factors for optimal management.

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A.W.J.M. Glaudemans et al. (eds.), *Nuclear Medicine and Radiologic Imaging in Sports Injuries*, DOI 10.1007/978-3-662-46491-5_1

1.1 Introduction

Sports medicine, or even better sports and exercise medicine, is a rather new specialty that deals with the medical care of the exercising individual. Sports medicine not only involves the delivery of medical care to elite and nonelite athletes, but it also includes prescribing exercise to inactive people at risk for or patients who already suffer from chronic disease (http://www.fsem.co.uk/media/4165/sport_and_exercise_medicine_a_fresh_approach.pdf, Matheson et al. 2011).

1.2 Exercise Is Medicine

Strong evidence shows that physical inactivity increases the risk of many adverse health conditions, including major noncommunicable diseases such as coronary heart disease, type 2 diabetes, and breast and colon cancers and shortens life expectancy (Lee et al. 2012). Physical inactivity is the fourth leading cause of death worldwide (Kohl et al. 2012). It has been estimated that physical inactivity causes 6 % of the burden of disease from coronary heart disease, 7 % of type 2 diabetes, 10 % of breast cancer, and 10 % of colon cancer. Inactivity causes 9 % of premature mortality or more than 5.3 million of the 57 million deaths that occurred worldwide in 2008. If inactivity were decreased by 25 %, more than 1.3 million deaths could be averted every year (Lee et al. 2012). Based on these alarming statistics, many countries have started effective campaigns to stimulate people of all ages to achieve a more physically active lifestyle and to participate in sports (Heath et al. 2012).

Sports physicians and other health care workers also have an important role in prescribing exercise to inactive people and chronic patients in order to prevent the increasing morbidity and mortality associated with inactivity (Matheson et al. 2011, 2013; Sallis 2009).

The American College of Sports Medicine (ACSM) recommends – in order to promote and maintain health – that all healthy adults aged 18–65 years need moderate-intensity aerobic (endurance) physical activity for a minimum of 30 min on 5 days each week or vigorous-intensity aerobic physical activity for a minimum of 20 min on 3 days each week (Haskell et al. 2007). Combinations of moderate- and vigorous-intensity activity can be performed to meet this recommendation. Moderate-intensity aerobic activity, which is generally equivalent to a brisk walk and noticeably accelerates the heart rate, can be accumulated toward the 30-min minimum by performing bouts each lasting 10 or more minutes. Vigorous-intensity activity is exemplified by jogging and causes rapid breathing and a substantial increase in heart rate. In addition, every adult should perform activities that maintain or increase muscular strength and endurance a minimum of 2 days each week. Because of the dose-response relation between physical activity and health, persons who wish to further improve their personal fitness, reduce their risk for chronic diseases and disabilities, or prevent unhealthy weight gain may benefit by exceeding the minimum recommended amounts of physical activity.

Increased physical activity and sports participation inevitably lead to a higher number of specific sports- and exercise-related illnesses and musculoskeletal injuries (Hootman et al. 2002; Shephard 2003). Because of these injuries, novice "athletes" might disappointedly drop out their just started exercise program, and more experienced exercisers might have to reduce their active lifestyle drastically. In this way no health benefits can be expected. Establishing a precise diagnosis from the start and initiating a good treatment rehabilitation program leading to complete recovery are very important for all of them, especially since the greatest risk factor to get an injury is a previous injury. Imaging can play an important role in the effective conservative and surgical management of injuries. It is also helpful to give the athlete visual information that an injury is present (e.g., a stress fracture) and convince him/her that (relative) rest is absolutely necessary.

1.3 Imaging in Sports and Exercise Medicine

As in any other branch of medicine, an appropriate diagnosis can only be established after a thorough history and careful physical examination. Often additional functional tests have to be performed by the injured athlete to obtain valuable information on their movement patterns, strength, and coordination. Both intrinsic and extrinsic sports-related factors (Table 1.1), which might have contributed to the injury, should be taken into account when diagnosing a sports injury and especially in formulating an effective individually tailored treatment and rehabilitation program.

Either on the sideline or in the clinic, an important decision the sports medicine physician has to make is whether an injury needs imaging or not. Obviously this is a subjective decision based on clinical experience and diagnostic examination skills. Due to technological advances like the availability of office and/or even sideline-based ultrasound (US), dedicated magnetic resonance imaging (MRI), and hybrid diagnostic imaging combining 3-dimensional reconstruction computer tomography (CT) and nuclear medicine-based imaging techniques, the clinician now has to choose from a variety of diagnostic options. An extensive description of these imaging modalities is beyond the scope of this chapter but can be found in Chaps. 2 and 3. With these newer imaging techniques, clinical judgment when to order specific testing procedures and how to interpret normal and abnormal findings becomes

Table 1.1 Injury factors

Intrinsic factors	Extrinsic factors
Age	Training program
Sex	Sports technique
Body size and composition	Level of competition
Genetics	Equipment
Current health status	Environmental conditions
Malalignment	Psychological factors
Strength and flexibility	Nutrition
Previous injury	Drugs

even more important. According to Coris et al. (2009), some basic ground rules, which follow "good medical practice," can be set (Coris et al. 2009):

1. Imaging should be undertaken only if it is likely to influence patient management.
2. The dose of ionizing radiation to the patient should be considered.
3. Requesting appropriate imaging method requires an understanding of the pathologic process.
4. Plain X-ray should be the first imaging technique, but in more superficial tendon and muscle injuries, ultrasound (US) may be more appropriate.
5. The cost of the examination to the patient and the community should also be considered.

In order to choose the most appropriate diagnostic procedures, good communication between the sports medicine physician and the imaging specialist is very important. The sports medicine physician should provide the radiologist or nuclear imaging specialist with relevant clinical findings but also with sports-specific information and its impact on the musculoskeletal system. Only in this way, the correct imaging technique can be chosen. Ideally the imaging specialist should have a keen interest in sports and the musculoskeletal system. Even more important, especially when dealing with elite athletes, is an understanding of what is going on and what is at stake in/for the athlete. He/she should be aware of the fact that in a competitive athlete even a minor abnormality, without clinical significance in a nonathlete patient, may hamper the training program or readiness to play.

Besides its role in diagnosis and decision-making, imaging techniques can also help to perform certain therapeutic procedures. For example, ultrasound can be used to guide intra-articular and intralesional therapeutic injections. It has been demonstrated that this increases the accuracy of needle placement and improves clinical outcome compared to non-guided procedures (Raza et al. 2003; Sibbitt et al. 2009).

1.4 Imaging in Elite Sports Medicine

In the "curious" and often demanding world of elite sports, the role of sports medicine and imaging seems to be quite different. Although "good medical practice" has to be followed, and the health of the athlete has the highest priority, the focus is on performance enhancement, competition, and return to play as quickly as possible. Therefore sports medicine physicians often request additional and costly imaging more easily, as they often need a more rapid and accurate diagnosis to guide management. Imaging techniques are also readily used to monitor ongoing pathology and to facilitate return-to-play decisions (McCurdie 2012). Support from sports-minded radiology and nuclear medicine imaging specialists is very helpful in these situations.

One should also realize that imaging results might have an impact on the confidence and performance of the athlete. For example, a minor abnormality on an MRI scan without clinical consequences might disturb the psychological state of the athlete if revealed just before the game. On the other hand, a negative scan can help to boost the athlete's confidence to a great performance. There exists a risk for over-imaging because repeated imaging is asked for to find out whether the injury is improving. One should also realize however that there is not always a clear relationship between symptoms and imaging findings, and this should be clearly explained to the athlete.

An unwanted development but sometimes reality in high-performance sports is that athletes themselves (or the coaching staff or managers) demand a particular scan. As a matter of "first seeing than believing," they can only be convinced to train or compete after a scan has been made. Obviously this approach should be discouraged by ways of building up a good relationship with the athlete and staff and by providing them with relevant and understandable information.

In elite sports settings, imaging is also used for screening and pre-participation assessments (McCurdie 2012). Presigning medical assessments are common in professional sports, and imaging techniques are increasingly used to document damage and sequelae from previous injuries or long-term athletic involvement. This information, which not always reflects clinical condition and readiness to play, may, rightly or wrongly, be used to negotiate the terms of a contract.

Conclusion

Physical activity is important in both prevention and treatment of many common diseases. However, sports injuries can pose serious problems to both the recreational exerciser and the (elite) athlete. The use of imaging can be important for the sports physician to establish an initial precise diagnosis and to set up an appropriate treatment intervention and rehabilitation program. Good interdisciplinary communication, sharing of relevant clinical and sports-related information, knowledge which imaging technique is most suitable for musculoskeletal injuries, and last but not least some feeling of what is going on in the athlete's mind will contribute to optimization of injury management in active people.

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Radiologic Imaging Techniques

2

Jan L.M.A. Gielen and P. Van Dyck

Contents

Abstract

Accurate diagnosis with the use of radiological imaging is often required if clinical findings in sports injuries are nonspecific. The preferred imaging modality is multifactorial. Often an optimal imaging pathway is not available. This chapter reviews the general imaging strategies that can be employed to diagnose and grade sports injuries. Radiographs in two orthogonal perpendicular projections

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A.W.J.M. Glaudemans et al. (eds.), *Nuclear Medicine and Radiologic Imaging in Sports Injuries*, DOI 10.1007/978-3-662-46491-5_2

are generally the first and often the only imaging needed for the evaluation of fractures. In case of clinical suspicion of radiographic occult fracture, MRI is the method of choice. The presence of radiopaque foreign bodies, intra-articular bone fragments, or advanced degenerative joint changes and the results after fixation can be assessed with radiographs.

Major advantages of US are its high spatial resolution for superficial structures, low cost, availability at short notice, ease of examination, short examination times, and lack of radiation exposure. Since approximately 30 % of sports injuries deal with muscle and tendon injuries, ultrasound (US) plays a major role in primary diagnosis of sports traumatology. US palpation, active and passive dynamic US study, and color-power Doppler imaging may be very helpful to the correct diagnosis. In patients with tendinosis, angiogenesis in the tendon may be correlated with clinical symptoms and discriminates early from advanced stages of tendinopathy. Furthermore, US provides image guidance for interventional procedures. For better evaluating deeply located structures, other (cross-sectional) imaging modalities may be required. Other disadvantage of ultrasound includes operator dependency.

CT imaging, by virtue of its excellent multiplanar capability and submillimeter spatial resolution, is a valuable imaging tool for the evaluation of all kinds of sports injuries. It has proved to be an effective method for documenting bone injuries particularly in complex bony structures such as the wrist and pelvis and may often show post-traumatic changes not shown by radiography. It may be helpful for the assessment of comminuted fractures, improving visualization of the fracture's extent and location, shape and position of the fracture fragments, and the condition of articular surfaces. New iterative CT reconstruction algorithms and cone beam computerized tomography (CBCT) techniques are developed to reduce radiation dose with similar or even increased image quality.

The major advantage of CT arthrography (CTA) is the assessment of the cartilage lesions continuous with the articular surface of the cartilage. Limitations of CTA include its invasiveness, possible allergic reaction, use of ionizing radiation, and poor extra-articular soft tissue contrast resolution.

Magnetic resonance imaging is the most complete radiological imaging technique with accurate evaluation of musculoskeletal soft tissue, bone, and joint structures. Its major indication in sports injury is internal derangement of joints, occult bone fractures, stress reaction and fracture of bone, and deeply located muscle and tendon tears. Acute, subacute, and active chronic lesions are demonstrated with high conspicuity due to their increased water content that produces a "light bulb effect" on fat-suppressed sequences with long repetition time (TR); this sequence has become the cornerstone of musculoskeletal imaging.

Equipment and techniques for MRI vary widely; it is generally accepted that high-field-strength magnets provide the highest quality images.

Major indications for MR arthrography (MRA) are labral lesions of the shoulder and hip joint, TFC and intrinsic ligament lesions of the wrist, and grade III osteochondral lesion of the talus.

Abbreviations

CR	Computerized radiography
CT	Computerized tomography
CTA	Computerized tomography with arthrography
DICOM	Digital imaging and communications in medicine
DWI	Diffusion-weighted MR imaging
EFOVS	Extended-field-of-view ultrasonography
e-MRI	Extremity-only small-bore MRI
FAI	Femoroacetabular impingement
FS	Fat suppression
GRE	Gradient echo
LT	Lunotriquetral (intrinsic carpal ligament)
MRA	Magnetic resonance arthrography
MRI	Magnetic resonance imaging
MTJ	Musculotendinous junction
PRP	Platelet-rich plasma injection therapy
SE	Spin echo
SL	Scapholunate (intrinsic carpal ligament)
SNR	Signal-to-noise ratio
SPACE	Sampling perfection with application-optimized contrasts using different flip-angle evolution
STIR	Short-tau inversion recovery
TE	Echo time
TR	Repetition time
TSE	Turbo spin echo

2.1 Introduction

Accurate diagnosis with the use of radiological imaging is often required if clinical findings in sports injuries are nonspecific. Even if symptoms and clinical findings in sports injuries are specific, further imaging investigations may be required for grading purposes to optimize treatment planning (Cook and Purdam 2009).

The preferred imaging modality depends on the diagnostic and grading award balanced against the clinicians' comfort and radiologists' experience with those modalities, the financial costs, and availability and invasiveness of each technique. The optimal imaging pathway is discussed in the specific chapters. Often such a pathway is not available; in these cases, imaging should be tailored to individual cases. This chapter reviews the general imaging strategies that can be employed to diagnose and grade sports injuries. The overall merits of each imaging technique, with its specific advantages and limitations, will be highlighted. The reader will find some overall practical guidelines for the evaluation of sports injuries that, in our opinion, may be useful in daily clinical practice.

2.2 Imaging Modalities

2.2.1 Plain and Computed Radiography and Arthrography

Radiographs in two orthogonal perpendicular projections are generally the first and often the only imaging needed for the evaluation of fractures. Although oblique (¾) views may be helpful, e.g., to demonstrate fractures of the radial head or for detection of bone spurs in anterior and posterior ankle impingement, they are not commonly used in daily clinical practice and have largely been replaced by cross-sectional imaging. In case of clinical suspicion of radiographic occult fracture, it is well known that in ankle distortion about 35 % of the fractures are radiographically occult (Connel et al. 1996). CT is used in complex fractures for complete visualization; MRI is the method of choice for occult fractures and post-traumatic avascular necrosis (Breitenseher 1999) (Fig. 2.1). The lack of soft tissue contrast resolution is a well-recognized limitation of plain radiography; computed radiography (CR) is characterized with improved but still incomplete soft tissue evaluation but has the advantage of its DICOM format with the ease of electronic distribution. When present, soft tissue changes can be used as indirect signs of osseous, articular, and soft tissue pathology. Displacement or blurring of periarticular and intermuscular fat planes in case of acute trauma is related to joint effusion, hemarthrosis, and muscle tear or contusion. Furthermore, the presence of radiopaque foreign bodies, intra-articular bone fragments, or advanced degenerative joint changes can be assessed with radiographs. Stress views may provide indirect evidence of ligament injury. However, recent studies have questioned the value of stress radiographs. For example, in chronic ankle pain, it has been shown that there is significant overlap between stable and unstable ankles, according to the guidelines of the American College of Radiology (ACR 2012). Radiographs are mandatory to confirm the results after internal or external fixation with reduction of dislocations and alignment of displaced fracture fragments, for monitoring the fracture healing with callus formation or detection of soft tissue calcification after severe muscle or ligament trauma (e.g., myositis ossificans and Pellegrini-Stieda disease), and to detect cracks of osteosynthetic material. When complications of the healing process occur, such as loosening, infection, or avascular necrosis, the role of plain radiography may be limited due to its low sensitivity in the early stages, and other techniques, such as scintigraphic imaging and/or MRI, may be useful. For decades, conventional arthrography (after sterile preparation and injection of intra-articular contrast medium) was used for investigating intra-articular pathology. This imaging modality has now largely been replaced by cross-sectional imaging techniques and is only performed as part of CT or MR arthrography.

2.2.2 Ultrasound

Major advantages of US are its high spatial resolution for superficial structures, low cost, availability at short notice, ease of examination, short examination times, and lack of radiation exposure. Since approximately 30 % of sports injuries deal with

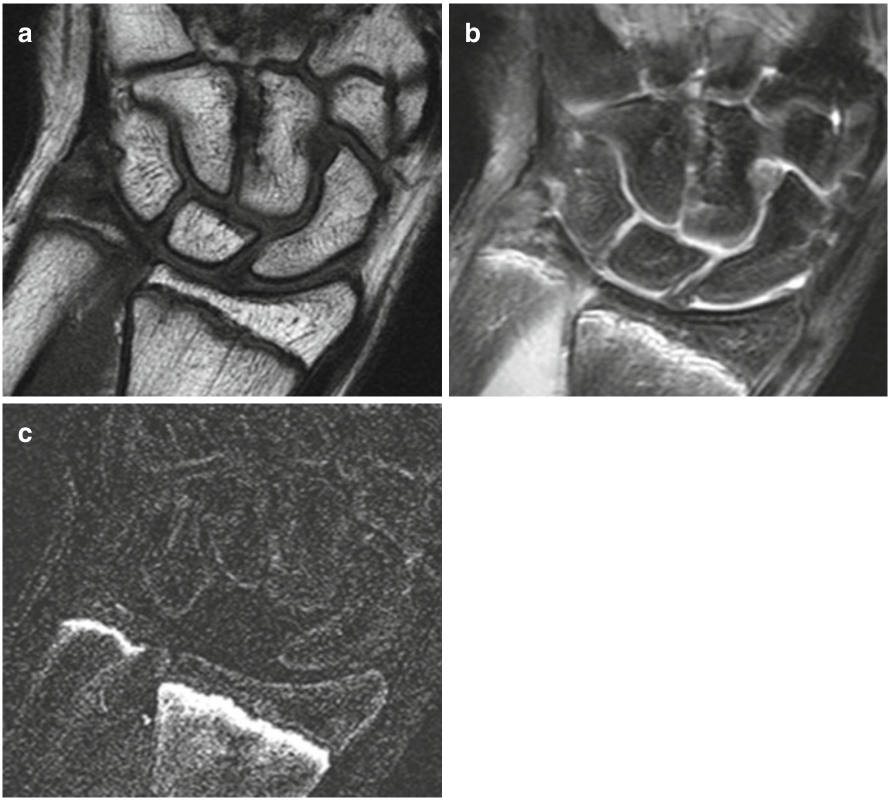

Fig. 2.1 MRI of avascular necrosis of the lunate. Child, 13 years old, with centrally located chronic pain at the dorsal aspect of the wrist. High-level tennis player. No obvious acute trauma. (**a**) Coronal SE T1-WI prior to intravenous gadolinium injection, (**b**) coronal TSE intermediate TE WI, (**c**) Coronal digital subtraction image of T1-WI after and before intravenous gadolinium administration. Normal fat signal on T1-WI (**a**), homogeneous suppression of signal on water-sensitive intermediate TE series, and absence of bone marrow edema at all the carpal bones (**b**). Normal shape of the carpal bones and absence of gadolinium enhancement at the entire lunate (**c**). This case demonstrates the importance of IV gadolinium administration in diagnosis of AVN to prove the lack of vascular perfusion in the absence of other signs of AVN as there are crescent line, demarcation line, and collapse

muscle and tendon injuries, ultrasound (US) plays a major role in sports traumatology, helping the clinician to decide whether the athlete should or should not return to training and competition (Peterson and Renstrom 1986). Due to the excellence of spatial resolution and definition of muscle structure, US keeps its leading edge when dealing with muscle strain and contusion, both in the initial phase for recognition of a lesion, but also for follow-up of lesions and search for healing problems such as fibrosis, muscle cysts, hernias, or myositis ossificans. High-frequency (13 MHz or higher) linear-array probes are used to perform musculoskeletal US examinations; only the deeper-located muscles and tendons are documented at a

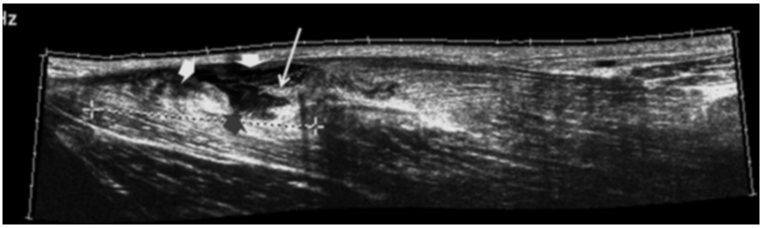

Fig. 2.2 Ultrasound of an adductor longus muscle tear. Longitudinal EFOVS of the proximal half of the right adductor longus in an adult soccer player after sudden snap during ball kicking. Examination performed 2 days after the injury. The EFOVS covers a length of 21 cm including the proximal MTJ and muscle belly of the adductor longus. Disruption of fiber discontinuity with distally retracted tendon (*arrow*) surrounded by a hyporeflective serosanguinous fluid collection with irregular margins (*arrowheads*). The hyporeflective fluid collection accentuates the structural anomaly of the muscle improving lesion conspicuity

lower resolution leading to less sensitivity, e.g., hamstrings muscles and the deep flexor compartment of the lower leg in well-trained sports people with increased muscle mass. The highest accuracy of ultrasound is calculated 24–72 h after the muscle injury; this is related to the easy ultrasound detection of fully developed serosanguinous fluid collections (Fig. 2.2). Because of this drawback, ultrasound evaluation on the sports field is not indicated. Transverse and longitudinal evaluation is mandatory. Lesion detection is most accurate by transverse screening of the involved muscle compartments from origin to insertion. US palpation is a very valuable tool, trying to find the point of maximal tenderness during the examination by a gentle but firm compression of the probe on the skin (Peetrons 2002). Active and passive dynamic US study may be very helpful to the correct diagnosis, e.g., to search for muscle hernia (during muscle contraction), to discriminate grade II (partial) and grade III (complete) muscle or tendon tears, or to evaluate the anterior and lateral snapping hip syndrome (during hip flexion and lateral rotation). To avoid artifacts or pitfalls, comparison with the contralateral side may be necessary. The addition of color-power Doppler imaging to US has allowed for the noninvasive study of blood flow and vascularization within anatomic structures and angiogenesis in lesions (Fig. 2.3). The highest accuracy is reached in the evaluation of angiogenesis in superficial and relaxed structures with gentle probe manipulation. In patients with tendinosis, angiogenesis in the tendon may be correlated with clinical symptoms [Weinberg et al. 1998; Zanetti et al. 2003] and discriminates early (reactive) from advanced (dysrepair or degenerative) stages of tendinopathy (Cook and Purdam 2009). Furthermore, US provides image guidance for interventional procedures such as drainage of fluid collections and cysts (Peetrons 2002), percutaneous tenotomy, and platelet-rich plasma (PRP) injection in chronic tendinopathy. US-guided sclerosis of neovascularity in painful chronic tendinosis has been described as an effective treatment with significant reduction of pain during activity by Öhberg and Alfredson; their accuracy however is until now not reproduced by other centers; in a large RCT only moderate results were obtained with few of the patients cured; the majority still had reduced function and substantial pain after 24

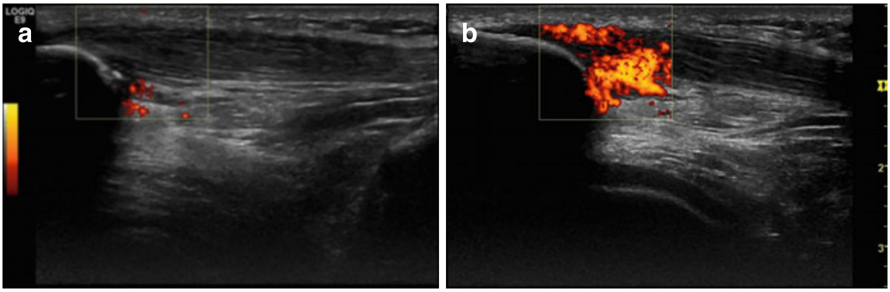

Fig. 2.3 Ultrasound of patellar tendinosis (jumper's knee), advanced stage with angiogenesis. Sagittal US examination in 17-year-old female volleyball player with chronic pain at right the patellar apex. (**a**) Image with stretched quadriceps muscle, (**b**) image with relaxed quadriceps muscle and with gentle probe manipulation. Demonstration of thickening of the patellar tendon at its origin without obvious major structural anomalies and regular lining on the image with stretched quadriceps muscle. (**a**) Demonstrates no angiogenesis and (**b**) demonstrates major angiogenesis at the thickened area of the tendon and at the anterior cranial part of Kager's fat plane

months of follow-up (Öhberg and Alfrendson 2002; Hoksrud et al. 2012). The trade-off for high-frequency, linear, musculoskeletal transducers is their limited depth of penetration and the small, static scan field. This is a disadvantage if the structure to be visualized is large (e.g., large intramuscular hematoma) or deeply located (e.g., hip joint). Extended-field-of-view sonography (EFOVS) overcomes the disadvantage of a small static field by generating a panoramic image. With this technique, during longitudinal probe translation over the skin of the patient, sequential registration of images along a broad examination region and their subsequent combination into an image of larger dimension and format is obtained (Weng et al. 1997). EFOVS does not add much in diagnosis but is, however, easily interpretable by the novice and improves cross-specialty communication. For better evaluating deeply located structures, such as the hip joint, hamstrings, and deep posterior lower leg compartment in an obese or well-trained patient, other (cross-sectional) imaging modalities are often required. Other disadvantages of ultrasound include operator dependency, selective and often incomprehensible documentation, and the inability to penetrate osseous structures. Despite the latter, ultrasound is sensitive to rule out cortical fractures of superficially located bones and is more accurate to detect rib fractures compared to radiographs (Evans and Harris 2012).

2.2.3 Multidetector Spiral CT Scan

2.2.3.1 Technique

CT imaging, by virtue of its excellent multiplanar capability and submillimeter spatial resolution due to the development of the spiral acquisition mode and current multidetector row technology, is a valuable imaging tool for the evaluation of all kinds of sports injuries (Berland and Smith 1998). Very fast image acquisition time of large volumes with submillimeter section thickness has become the norm. It has proved to be an effective method for documenting injuries particularly in complex bony structures such as the wrist and pelvis and may often show post-traumatic changes not shown by radiography. For most musculoskeletal studies, slice thickness is 0.75 mm, reconstructed to 1 mm images with increment of 0.5 mm. The images should be assessed using both bone and soft tissue window settings. From the three-dimensional data set, images can be reformatted in other planes (2-D technique) and be used for volume rendering (3-D technique). The 2-D reformatting of sagittal and coronal images from axial images can highlight longitudinal fracture lines and can make it easier to evaluate horizontal interfaces, such as the acetabular roof. The 3-D rendering allows different displays of the volume data. Surface rendering by thresholding, which, in contrast to volume rendering, incorporates only a portion of the data into the 3-D image, is the most widely used technique. By adding a virtual light source, a shaded surface display (SSD) can be achieved, which enhances the 3-D understanding of the image. However, it may provide an inadequate display of undisplaced and intra-articular fragments, and, in comparison to axial imaging, surface rendering does not increase the detection rate of fractures and should only be supplementary to plain films and axial CT scan in the evaluation of comminuted fractures. Volume rendering, incorporating all the data into the 3-D image, requires more computer manipulation. All reconstruction methods offer a more effective display of complex anatomic and pathologic structures. It may be helpful for the assessment of comminuted fractures, improving visualization of the fracture's extent and location, shape and position of the fracture fragments, and the condition of articular surfaces (Bohndorf et al. 2001). New iterative CT reconstruction algorithms and cone beam computerized tomography (CBCT) techniques are developed to reduce radiation dose with similar or even increased image quality (see Sect. 2.3).

2.2.3.2 CT Arthrography

Intra-articular injection of iodinated contrast material mixed with 1 ml of a 0.1 % solution of epinephrine is performed under fluoroscopic or ultrasonographic observation (Newberg et al. 1985; Jacobson et al. 2012; Berkoff et al. 2012). The volume of contrast medium injected depends on which joint is studied: shoulder, 10–15 ml; wrist, 5 ml; hip, 10 ml; knee, 20 ml; and ankle, 6–12 ml. After injection of contrast material, patients are asked to perform full-range mobilization of the joint with weight bearing and walking a few steps if a joint of the lower limb is involved. Anteroposterior, lateral, and oblique views are routinely obtained to image the entire articular cavity. Subsequently, multidetector CT is performed. The major advantage of CT arthrography (CTA) for the assessment of the cartilage is the excellent conspicuity of focal morphologic cartilage lesions continuous with the articular surface of the cartilage that results from the high spatial resolution and the high attenuation difference between the cartilage substance and the joint contrast filling the lesion (Fig. 2.4). Vande Berg et al. (2002) found, in a study with spiral CTA of cadaver knees, a better correlation for grading articular surfaces between macroscopic examination and spiral CTA than with MR imaging. Other potential advantages of spiral CTA with respect to MR imaging are the short examination time, the availability at

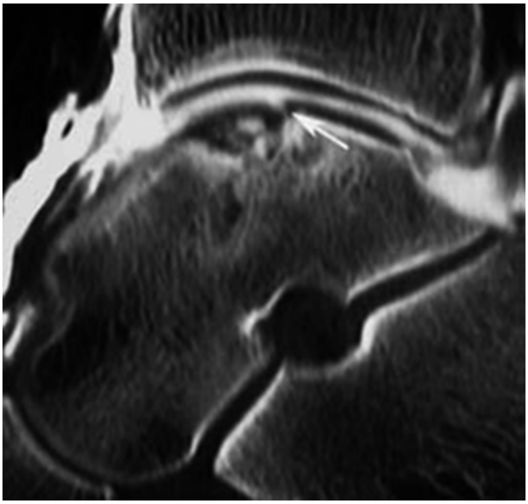

Fig. 2.4 CT arthrography of the ankle. 24-year-old soccer player with chronic ankle pain and history of repetitive ankle distortion. Radiographs demonstrate osteochondral lesion of the talus with in situ fragment (grade 3). CTA is performed to discriminate adherence of the fragment. Sagittal multiplanar reconstruction demonstrates the osteochondral defect with centrally located bone fragment; posterior to the fragment contrainfiltration is documented (*arrow*) that is not surrounding the fragment

short notice (short waiting list), and the low sensitivity for and limited degree of imaging artifacts related to the presence of microscopic metallic debris which may hinder MR imaging studies. Limitations of CTA include its invasiveness, possible allergic reaction, use of ionizing radiation, and poor extra-articular soft tissue contrast resolution. Another major limitation of CTA imaging of the cartilage is its complete insensitivity to alterations of the deep layers of the cartilage.

2.2.4 Magnetic Resonance Imaging

Magnetic resonance imaging is the most complete radiological imaging technique with accurate evaluation of musculoskeletal soft tissues, bony structures, and joints. Its major indication in sports injury is internal derangement of joints, occult bone fractures, stress reaction and fracture of the bone, and deeply located muscle and tendon tears. Acute, subacute, and active chronic lesions are demonstrated with high conspicuity due to their increased water content that produces a "light bulb effect" on fat-suppressed sequences with long repetition time (TR); this sequence has become the cornerstone of musculoskeletal imaging. This light bulb is present in similar areas with high tracer uptake in bone scintigraphy and PET imaging. Specific MRI applications in the musculoskeletal system are addressed in the specific chapters.

2.2.4.1 Technique

Equipment and techniques for MRI vary widely, and although it is generally accepted that high-field-strength magnets provide the highest quality images, there has been considerable advancement in the technology of low-field-strength systems over the past few years, greatly improving their image quality. Open-bore gantry design is available in low- and midfield MRI and has specific musculoskeletal advantages related to off-center positioning and patient comfort with less claustrophobic renouncement. Absence of claustrophobia and low cost are the major advantages of low-cost extremity small-bore design (e-MRI); this is available at low field up to 1.5 T and used for investigation of the peripheral joints only (wrist, elbow, foot and ankle, and knee). Although appropriate selection of imaging planes will depend on the location and desired coverage of the anatomical region to be examined and the pathology to be expected, a complete MR examination of musculoskeletal regions requires that images be obtained or reconstructed in the axial, coronal, and sagittal planes. Of utmost importance is to respect the anatomical orthogonal planes since, with excessive rotation of a limb, inappropriate positioning of imaging planes may result in images which are difficult to interpret. Oblique planes may also be useful, e.g., in the hip in FAI (paracoronal and parasagittal images) and wrist in LT ligament disorders (paraxial images). The number of pulse sequences and combinations ("hybrid techniques") is almost infinitive: in musculoskeletal MR, the most commonly used sequences include conventional spin echo (SE) for T1 weighting, turbo SE (TSE) sequences for intermediate or T2 weighting, and gradient echo (GRE) sequences. SE T1-WI is used for anatomic detail and as an adjunct in the evaluation of the osseous structures. TSE sequence has replaced conventional SE for T2 weighting (due to its relatively long acquisition times). However, because of image blurring, TSE sequences are not recommended for proton density imaging. Blurring can be reduced by increasing TE, decreasing the inter-echo time and echo train length (ETL), and increasing matrix. At higher field strengths (3 T), volume sequences are available with multiplanar reconstruction capacity at high resolution (0.5 mm) in all imaging planes. 3D-SPACE (sampling perfection with application-optimized contrasts using different flip-angle evolution) is recently pushing 2D TSE T2 or intermediate TE to the background (Fig. 2.5). TSE sequences are less susceptible to field inhomogeneity than SE sequences. Therefore, when metallic artifacts are present, such as in postsurgical patients, TSE sequences are preferred over SE and GRE. GRE sequences and TSE sequences with intermediate TE are used for the evaluation of articular cartilage. GRE sequences are used for dynamic contrast-enhanced imaging. They are also used in a limited number of T2 protocols (glenoid labrum, meniscus of the knee). When using short TE in T1-weighted or PD images, one should take the magic angle phenomenon into account, a source of false-positive MR findings. Furthermore, a pulse sequence is always a compromise between acquisition time, contrast, detail, or signal-to-noise ratio (SNR). SNR is highest in TSE and decreases respectively in SE and GRE sequences. Concerning the different fat-suppression (FS) techniques, in our institution, we prefer the spectral FS technique because of its better SNR and spatial resolution compared to inversion recovery fat-suppression techniques (Fleckenstein et al. 1991). Both T2-WI with (spectral) FS and STIR images are most sensitive to bone marrow and soft tissue edema or joint effusion. For good detection of fluid with preservation of anatomical detail and good differentiation between joint fluid and hyaline cartilage, we include an FS TSE intermediate-weighted sequence (TR/TE = 75/30–35 msec) in at least one imaging plane in our standard protocols. Cartilage-specific sequences

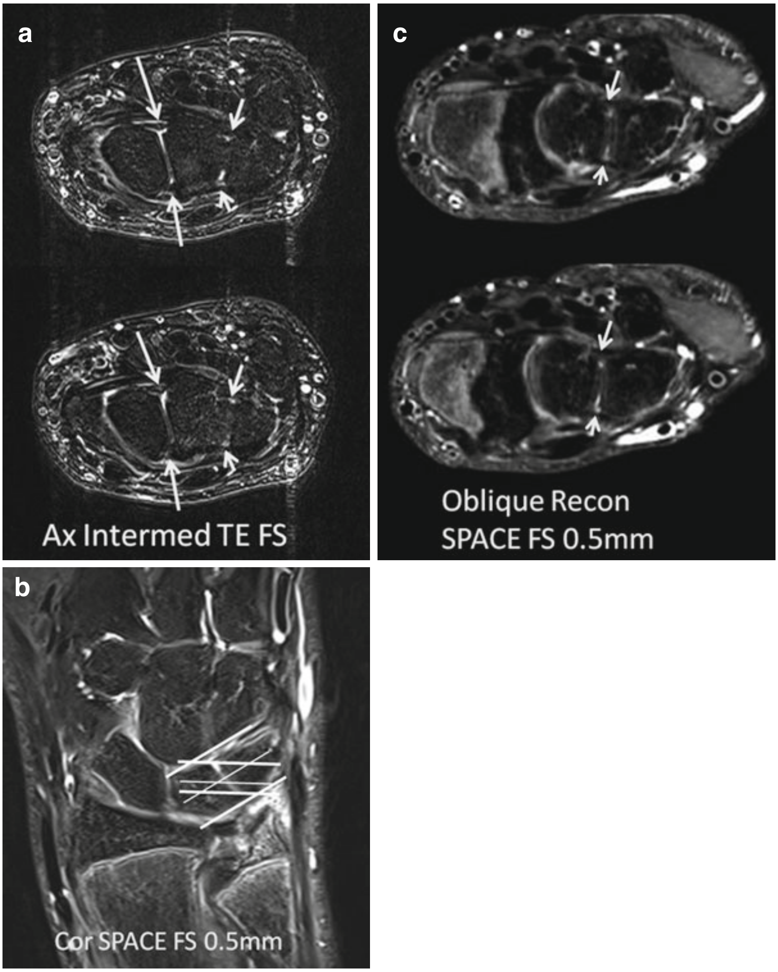

Fig. 2.5 SPACE volume sequence of the wrist in tennis player with chronic ulnar-sided wrist pain. Tennis player, male, 17 years old, with chronic ulnar-sided right wrist pain. (**a**) Axial TSE intermediate TE FS sequence of the right wrist. Easy demonstration of the intrinsic SL ligament at its dorsal and palmar components (*arrows*) but difficult demonstration of the LT ligament (*short arrows*). (**b**) Coronal volume TSE intermediary TE FS (SPACE) demonstrating the axial plane of A and the oblique axial reconstruction plane of (**c**). Easy demonstration of LT ligament (*short arrows*) (**c**). Oblique axial multiplanar reconstructions of series B perpendicular to the lunotriquetral joint space

have been developed (Disler et al. 2000; Ulbrich et al. 2013). The musculoskeletal system, especially in the extremities, is not influenced by motion, and as a consequence, motion artifacts are rare. Infolding artifacts can be avoided by selecting an appropriate imaging matrix, saturating anatomical areas outside the region of interest, and off-center imaging. Artifacts due to distortions of the local magnetic field are attributable to ferromagnetic and, to a lesser degree, nonferromagnetic orthopedic devices. The use of surface multichannel coils will improve the SNR; smaller slice thickness and larger matrices are essential for soft tissue imaging. The choice of small "field of view" (FOV) without changing the matrix size will increase the spatial resolution. Sometimes, imaging of the contralateral side may be useful, requiring a larger FOV and the use of a body coil. Contrast-enhanced MR studies lead to a prolonged examination time and high costs, and therefore, the use of intravenous contrast agents is not indicated when evaluating a sports lesion. It should be reserved for cases in which the results would influence patient care (Kransdorf and Murphey 2000). Application of intravenous gadolinium is indicated when dealing with a tumoral or pseudotumoral mass to detect neovascularization and intralesional necrosis (which is a major parameter for malignancy), in cases of inflammation or as part of indirect arthrography. For detection of subtle areas of contrast enhancement, we use subtraction images (SE T1-WI with FS after minus SE T1-WI with FS before gadolinium) (static MR imaging). After IV administration of gadolinium, STIR-type sequences should not be used, since not only fat but also enhancing tissue will be shown with a reduced signal intensity.

MR arthrography (MRA) with direct, 3 % diluted gadolinium DTPA, injection in the joint or indirect technique with intravenous administration and joint mobilization is used in specific joints and specific indications. Major indications for MRA are labral lesions of the shoulder and hip joint, TFC and intrinsic ligament lesions of the wrist, and grade III osteochondral lesion of the talus. More detailed description of the technique and indications is available in the specific topographic chapter of the book (Chaps. 17, 26, and 35).

Diffusion-weighted (DWI) MR sequences detect Brownian motion in areas with increased water content and allow mapping of the diffusion process of water in tissues. Water molecule diffusion patterns can therefore reveal microscopic details about tissue architecture, either normal or in a diseased state. In areas with restricted diffusion, increased T2 signal is present; in areas with increased water content without diffusion restriction, a low SI is detected. DWI is of practical use in sports-related brain concussion.

Recently, diffusion tensor imaging (DTI) has been used to study muscle architecture and structure. In the future, DTI may become a useful tool for monitoring subtle changes in the skeletal muscle, which may be a consequence of age, atrophy, or disease (Galban et al. 2004). Furthermore, important information about muscle biomechanics, muscle energetics, and joint function may be obtained with unique MRI contrast such as T2 mapping, spectroscopy, blood-oxygenation-level-dependent (BOLD) imaging, and molecular imaging. These new techniques hold the promise for a more complete and functional examination of the musculoskeletal system (Gold 2003). The clinical MR imaging protocol will be greatly influenced by local preferences, time constraints, and MR system available (field strength, local coil). For an in-depth discussion of the different MR imaging protocols, the reader is referred to subsequent chapters. MRI has the disadvantage of not always being well accepted by patients, of being incompatible with dynamic maneuvers, and of not always being possible in emergency conditions. Furthermore, it provides the evaluation of an entire anatomical area – bone structures included – but is only good for the study of a limited part of the skeleton. This is in contrast to scintigraphy, with which the whole skeleton can be evaluated at once. Otherwise, MRI helps to elucidate the true nature of highly nonspecific hotspots on scintigraphy. For a discussion of the value of nuclear medicine techniques used in sports lesions, we refer to the specific chapters.

2.3 Effective Radiation Dose Related to Radiography and CT Compared with Nuclear Imaging

A wide range of radiation absorbed doses is delivered to patients by various diagnostic imaging modalities that use ionizing radiation (radiography, CT, nuclear medicine). The potential for radiation-induced injuries exists. Quantitative proof of risks for radiation-induced cancer in humans can be derived from the life span study at organ cumulative doses above approximately 100 mSv, although significant effects can only be observed above 200 mSv (Little 2003; Heidenreich et al. 1997). The effective radiation dose is regarded as a good indicator for the possible biological effect of radiation; it is a measured unity to compare the stochastic risk of a nonuniform exposure of ionizing radiation with a uniform exposure to the body. Its actual SI unit of measurement is Sv (Sievert); the old unity was rem (radiation equivalent in men), 1 Sv = 100 rem (McCollough and Schueler 2000). The natural background radiation is the natural radiation; it varies by geographic location; the mean level of NBR is 2.5–3 mSv/year. BERT (background equivalent radiation time) is the unit of measurement to compare the effective radiation dose of imaging procedures with the natural background radiation of 1-year time (3 mSv). For example, one thorax radiography is equivalent to 1/52 BERT; 1 CT abdomen is equivalent to 3.3 years BERT. Digital radiography and iterative CT reconstruction or cone beam CT imply less effective radiation dose compared to conventional radiography and classic CT reconstruction, respectively. At the knee multislice computed tomography (MSCT) with iterative reconstruction effective radiation doses range between 0.27 and 0.48 mSv; for CBCT the effective radiation dose was 0.12 mSv, compared to digital radiography of the knee in lateral view of 0.018 mSv and 0.012 mSv for AP view (Koivisto et al. 2013). Table 2.1 gives an overview of typical effective radiation doses in musculoskeletal radiographs, CT, and nuclear imaging techniques (Parry et al. 1999). A series of ten PET or four PET-CT examinations on older equipment may imply a radiation dose with increased cancer risk! Radiologists and specialists in nuclear medicine should be aware of methods by which radiation dose may be minimized with regard to using the lowest possible dose to achieve a diagnosis. Medical alternatives should be taken in consideration for CT and nuclear imaging techniques such as MRI of the whole body. We have to weigh the acute risk for the patient on the one hand and on the other hand the overall low risk of radiation exposure.

Table 2.1 Typical effective radiation doses in adult diagnostic radiological imaging and nuclear medicine

Imaging modality	Body part	Effective dose mSv	BERT equivalent in weeks
Radiography	Skull	0.4–0.7	7–12
	Cervical spine	0.2–0.4	3–6
	Lumbar spine	0.5–1.5	9–26
	Limb	<0.1	<2
Digital radiography	Knee	0.012–0.018	0.07–0.1 (11–17 h BERT)
	Hand	0.001	0.02 (3 h BERT)
MSCT conventional	Head	1–2	17–35
	Pelvis	3–4	52–69
	Cervical spine	2–4	35–69
	Lumbar spine	3–5	52–87
MSCT iterative reconstruction	Knee	0.27–0.48	1.5–2.5
CBCT	Knee	0.12	0.7
Bone scintigraphy SPECT 99 m Tc-diphosphonates[a]		3	52 (1-year BERT)
PET[b]		4	69 (1.5-year BERT)
PET/CT		5.5	96 (2-year BERT)
Cancer risk threshold		100	1,733 (33-year BERT)

[a] ^{99m}Tc-diphosphonates: 0.0057 mSv/MBq. According to EANM bone scintigraphy requirements 2003 and NVNG requirements 2007, adult dose is 500 MBq and the effective dose is 2.85 mSv. With SPECT-CT additional dose of 0.5-1.0 mSv (low-dose CT)

[b] ^{18}F-FDG: 0.019 mSv/MBq. According to EANM requirements 2003 and NVNG requirements 2007, 3 MBq/kg, a person with weight 70 kg = 210 MBq, effective dose is 3.99 mSv. With low-dose CT additional dose of 1.5 mSv

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Nuclear Medicine Imaging Techniques

3

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Contents

Abstract

Nuclear medicine is a rapidly developing field which focuses on the imaging of physiological processes and the evaluation of treatment of specific diseases. It involves the use of radiopharmaceuticals for both purposes. Different radiopharmaceuticals have different kinetics and can therefore be used to image processes in the body, the function of an organ or the presence of a specific cellular target. In sports medicine, bone scintigraphy and leukocyte scintigraphy play important roles. Radiopharmaceuticals in bone scintigraphy are diphosphonate complexes

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A.W.J.M. Glaudemans et al. (eds.), *Nuclear Medicine and Radiologic Imaging in Sports Injuries*, DOI 10.1007/978-3-662-46491-5_3

which are absorbed onto the hydroxyapatite crystal of newly formed bone and therefore represent osteoblast activity. When combined with the radionuclide technetium-99 m (^{99m}Tc), it is very suitable for imaging. Bone scintigraphy, especially combined with additional single-photon emission computed tomography and conventional computed tomography (SPECT/CT), can, e.g. discriminate a (stress) fracture from osteoarthritis. In leukocyte scintigraphy, autologous white blood cells are labelled with ^{99m}Tc and reinjected in the patient. In case of an active infection, the leukocytes accumulate at the location within 24 h after administration. The combination of three-phase bone scintigraphy with leukocyte scintigraphy has the best test characteristics for identifying infectious processes in the peripheral skeleton. The positron emission tomography (PET) radiopharmaceutical fluor-18-labelled fluorodeoxyglucose (^{18}F-FDG) is indicated for infectious processes of the axial skeleton (osteomyelitis and spondylodiscitis). Its uptake mechanism is distinct from that of diphosphonate complexes; it represents the glycolytic activity of cells. ^{18}F sodium fluoride is another PET tracer to image the skeleton. However, at the moment it has no role in sports medicine.

3.1 Introduction

Nuclear medicine is a rapidly developing field which focuses on imaging of physiological processes and the evaluation of treatment of specific diseases. It involves the use of radiopharmaceuticals for both purposes. Different radiopharmaceuticals have different kinetics and can therefore be used to image processes within the body, the function of a specific organ or the presence of a specific cellular target (receptor, enzyme, antibody, etc.). Radiopharmaceuticals are usually administered intravenously. So, images are made from radiation which is emitted from within the patient. These characteristics form the main distinction with radiology, which mainly focuses on tissue anatomy by using external radiation sources.

This book chapter discusses the basic principles of nuclear medicine and the existing camera types. Special focus will be given to the different imaging techniques which are generally available to image sports injuries.

3.2 Principles of Nuclear Medicine

3.2.1 Basics of Nuclear Medicine

In nuclear medicine radiopharmaceuticals are used to image physiological process in the body. Radiopharmaceuticals consist of two compounds: a radioactive element (radionuclide) attached to a chemical compound or pharmaceutical (drug, antibody, etc.). A radionuclide is an unstable atom. To understand the basics of nuclear medicine, knowledge of basic physics is important.

An atom (or nuclide) consists of a nucleus and orbiting electrons. The nucleus is composed of positively charged protons and neutrons (which have no charge). The number of protons within the nucleus of an atom is called the atomic number (Z).

In an electrically neutral atom, the number of protons equals the number of electrons. Each element has a unique atomic number. So, the chemical symbol of each element is synonymous with the atomic number. The number of neutrons in a nucleus is denoted by N. The atomic mass number (A) is the summation of protons and neutrons in a nucleus: $A = Z + N$.

Nuclides with similar characteristics can be grouped into nuclear families. Isotopes are nuclides with the same number of protons (thus, atomic number Z) and therefore nuclides of the same element.

Most nuclei that are present in nature are stable. However, some are not stable and transform themselves to form stable configurations. This transformation can result in emission of either particles or energy (γ-photons) from the nuclei. This transformation, which is spontaneous and occurs at random, is called radioactive decay. So, any nuclide that is unstable is radioactive and is therefore called a radionuclide. The rate at which the atoms decay is measured in disintegrations per second or in Becquerel (Bq). One disintegration per second equals 1 Bq.

Radionuclides are abundant in nature, but can also be produced artificially. Radionuclides that are present in nature are long-living radionuclides and are not suitable for imaging. All of the radionuclides in nuclear medicine are produced by means of bombarding stable nuclei with high-energy particles in a cyclotron (Fig. 3.1), linear accelerator or nuclear reactor.

Fig. 3.1 Image of a cyclotron, a particle accelerator in which charged particles accelerate from the centre outward, along a spiral path. These particles are held within an exact course by static magnetic fields and accelerated by rapidly alternating voltage. When the particles have developed the desired kinetic energy, they hit a target. This creates secondary particles (e.g. fluorine-18), which are guided outside the cyclotron and into instruments for radiopharmaceutical production

3.2.1.1 Decay Processes

There are several types of nuclear decay processes. Two of those are important for imaging purposes in sports medicine. The first one is called 'metastable-state transitions'. A metastable state is an excited state of the nucleus that exists for a measurable lifetime. The atom in metastable state is the same as the atom in ground state, since they have the same Z and N. The only difference is the energy state. The decay of a metastable state towards the ground state occurs through de-excitation by means of γ-emission. An example is the decay of molybdenum-99 (^{99}Mo) through technetium-99 m (^{99m}Tc) towards ^{99}Tc. The prefix 'm' indicates the metastable state. ^{99m}Tc decays by emitting a γ-ray with a characteristic energy of 140 kilo-electronvolt (keV). ^{99}Mo, on its turn, is a radionuclide which is produced by neutron bombardment of a target containing uranium-235. It disintegrates by emitting an electron (β^-). ^{99}Mo is commercially available in technetium-99 m generators, which is used to extract ^{99m}Tc in an on-site setting. Every nuclear medicine department has access to such a generator.

The second type of decay important in sports medicine is 'positron decay'. In this decay process a positron is emitted, because of an excess of protons in the unstable nuclide. The decay process can be described by the conversion of a proton into a neutron, with the emission of a positron with a certain amount of kinetic energy. A positron (β^+) is a positively charged electron. A positron cannot exist at rest in nature. As soon as it loses its kinetic energy, it immediately combines with an electron and undergoes a reaction called annihilation. The masses of the two particles are completely converted into energy: two annihilation γ-ray photons, each with energy of 511 keV, which leave their production site opposite to each other (Fig. 3.2). This is the basics of positron emission tomography (PET). The most important example of a positron emitting radionuclide is fluoride-18 (^{18}F).

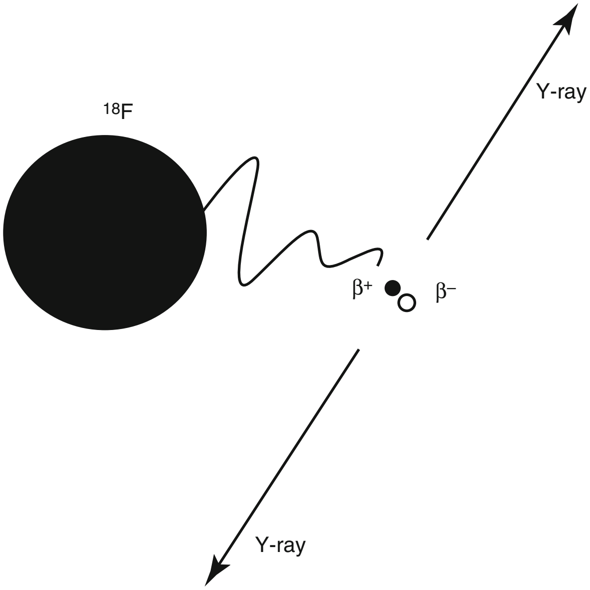

Fig. 3.2 Principle of annihilation. The radionuclide ^{18}F emits a positron (β^+), which finds an electron (β^-) at the end of its course. Both particles annihilate and two γ-rays having 511 keV of energy are produced, 180° apart

3.2.1.2 Physical Half-Life

As mentioned before, the decay of each individual radionuclide is a random and spontaneous process. However, in a large group of the same radionuclides, the decay is rather constant. In fact, each radionuclide has its uniquely defined decay constant (λ). A term which is more commonly used for defining decay is 'physical half-life' ($T_{1/2}$). This is the time required for one-half of a group of radionuclides to decay. The half-lives of the most important radionuclides in sports medicine are 6.01 h for ^{99m}Tc and 1.83 h for ^{18}F.

3.2.2 Camera Systems

Radiopharmaceuticals are usually administered intravenously. Therefore, the patient is the source of radioactivity. The cameras that are used in nuclear medicine to visualize the radiopharmaceuticals are the gamma camera and the PET camera. The detection of γ-rays emitted from the patient and transforming it into an image is the main principle of the camera systems used in nuclear medicine.

3.2.2.1 Gamma Camera

A γ-camera (or Anger scintillation cameras, named after its inventor) consists of the following components: a collimator, a scintillation crystal, a light guide, photomultiplier tubes and a positioning and energy discrimination system. The individual components are discussed in this section.

A collimator is a thick sheet of lead with multiple holes. The individual holes guide the individual γ-ray photons towards the scintillation crystal. Photons which do not travel in the right direction are absorbed in the septa between the holes. Different types of collimators are available, depending on the energy level of the emitted γ-rays from the radionuclide. For γ-ray photons of ^{99m}Tc, the parallel hole collimator is the collimator of choice. Only those photons which pass the collimator in a perpendicular course are transferred. Sometimes a pinhole collimator is used, especially for imaging small structures or organs.

After passing through the collimator holes, the γ-ray photons encounter the scintillation crystal. The individual photons are absorbed in the crystal (usually sodium iodide (NaI)) and converted into a small flash of light. As the energy of the photon increases, the flash of light becomes brighter. This flash of light is transferred through a silicon light guide to minimize the loss of intensity.

Next, the light reaches the photomultiplier tubes (PMTs). In fact, one flash of light is detected by multiple PMTs. The light interacts with photocathodes and is transformed into a photoelectron. This signal is amplified by electrodes or dynodes at increasing voltages in the PMTs, but also in external electronic preamplifiers. These signals are combined in a positioning system, which gives each signal from the individual PMTs different weights to derive the positioning information of γ-ray photons in x- and y-directions.

Finally, the energy pulse is examined (z-direction), to ensure that only photons falling within the photopeak are accepted. Usually, the same pulse as for positioning is used.