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Imaging techniques for the assessment of fracture repair

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ABSTRACT

Imaging of a healing fracture provides a non-invasive and often instructive reproduction of the fracture repair progress and the healing status of bone. However, the interpretation of this reproduction is often qualitative and provides only an indirect and surrogate measure of the mechanical stability of the healing fracture. Refinements of the available imaging techniques have been suggested to more accurately determine the healing status of bone. Plain radiographs provide the ability to determine the degree of bridging of the fracture gap and to quantify the amount of periosteal callus formation. Absorptiometric measures including dual X-ray absorptiometry and computed tomography provide quantitative information on the amount and the density of newly formed bone around the site of the fracture. To include the effect of spatial distribution of newly formed bone, finite element models of healing fracture can be employed to estimate its load bearing capacity. Ultrasound technology not only avoids radiation doses to the patients but also provides the ability to additionally measure vascularity in the surrounding soft tissue of the fracture and in the fracture itself.

Introduction

While mechanical tests constitute the gold-standard for the assessment of fracture healing, sequential assessment of the healing process or clinical assessment of healing require non-invasive methods. It is important to note that most non-invasive assessments are indirect, rather than direct, measurements which provide a surrogate measure of the functional state of repair. One of the aims of assessment of healing is the judgement of the weight-bearing capacity of the healed bone. However, few non-invasive diagnostics for monitoring healing assess callus strength or toughness rather than stiffness. While stiffness may provide valuable information about the healing process, it does not measure the bone's weight bearing capacity. Fortunately, mechanical stiffness and mechanical strength are reasonably correlated during callus formation, thus the surrogate measure for stiffness provides a reasonable estimate for strength.

The notion of *endpoint* vs. *process* is important to consider in terms of the utility of non-invasive diagnostics of bone fracture healing. Ideally, a diagnostic method enables clear judgement on whether the functional endpoint of healing process has been reached, i.e. whether a fracture has healed or not. In addition, the value of a diagnostic method is also its ability to provide an assessment of how well healing is progressing, for the purpose of estimating the likelihood that non-union will occur and the likelihood that intervention is needed. Thus, while accurate estimates of callus strength are not yet possible via non-invasive methods, many such methods either are, or have high potential to be, very successful at revealing whether the structure and composition of the callus suggest that the healing process is on track. Employing non-invasive diagnostics in this context can be beneficial in the research setting—such as when screening candidate therapies and identifying targets for enhancing healing—as well as in the clinic. Most imaging modalities use X-ray radiation such as standard radiographs, X-ray absorptiometry or computed tomography (CT) for assessing fracture repair [1,2]. However, various ultrasound technologies have emerged providing access

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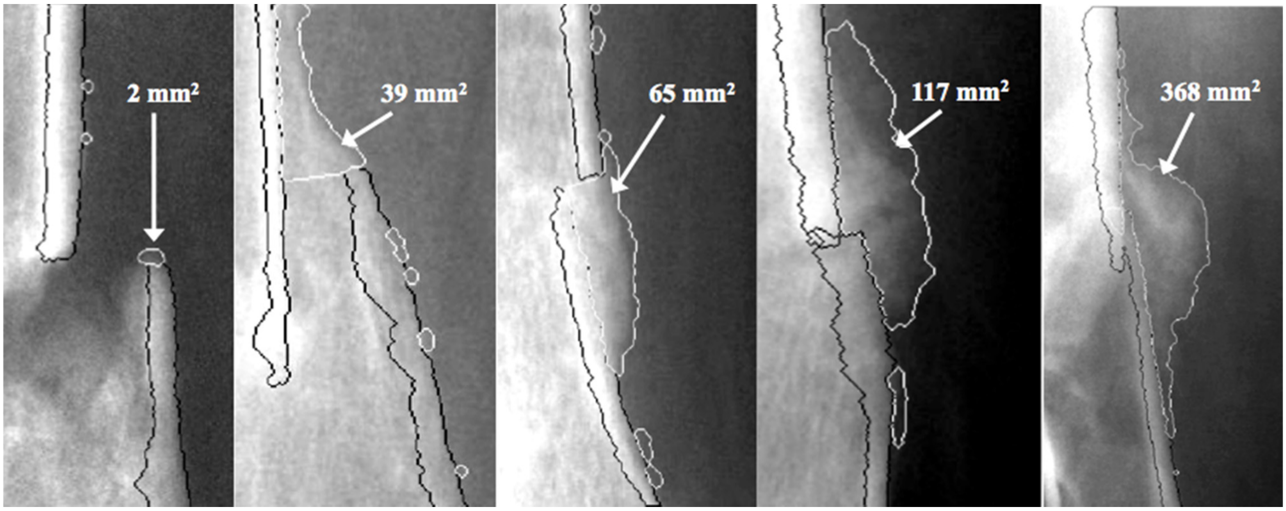

Fig. 1. Periosteal callus measured by the computer algorithm. The algorithm outlines the cortex (black line) and callus (white line). These five cases were part of a radiographic series used to validate the algorithm by comparing callus outlined by the computer algorithm vs. callus outlined by clinicians.

to mechanical and biological properties of a healing fracture [3,4] and are also included in this review.

Radiography

The attenuation of X-rays in bone tissue strongly depends on the amount of mineral that has to be penetrated by the X-ray beam. The increasing calcification of the fracture callus and the fracture gap during the progress of healing can therefore be observed by an increase in X-ray attenuation.

If radiographs are produced in a standardized manner, they can be used for quantitative measurements. The amount of bone tissue formed at the site of fracture determines the appearance of the fracture gap and the fracture callus. The most straightforward way of quantifying the healing process is by scoring the appearance of the fracture area. The Radiographic Union Score for Tibial fractures (RUST) assigns a score to a given set of anteroposterior and lateral radiographs based on the assessment of healing at each of the four cortices visible on these projections. Each cortex receives a score of 1 point, if it is deemed to have a fracture line with no callus; 2 points, if there is callus present but a fracture line is still visible; and 3 points, if there is bridging callus with no evidence of a fracture line. The individual cortical scores are added to give a total for the set of films with 4 being the minimum score indicating that the fracture is definitely not healed and 12 being the maximum score indicating that the fracture is definitely healed [5].

If healing of the fracture is dominated by periosteal callus formation, changes in the amount of the fracture callus indicate the progress of healing. The formation of fracture callus is visible on standard radiographs and has relevance to the fracture's mechanical environment [6–8]. However, user-interactive techniques for measuring fracture callus in radiographs are time-intensive and subjective, with inter-physician variability of 20–25% [9,10]. These deficiencies have implicitly hindered application of these techniques to the evaluation of fracture healing. Automated computerized algorithms analyzing fracture callus in digital radiographs with minimal user interaction may overcome these barriers. In an automatic algorithm presented by Lujan et al. [11], user interaction to detect periosteal callus is limited to the definition of the external cortical fragment outline (Fig. 1). After definition of the external cortical outline, the algorithm identifies the inner cortex based on intensity magnitudes (grey values). Also the callus outline is automatically detected (Fig. 2) using a combination of image processing operations and a custom threshold to define the callus edge. Finally, the number of outlined callus pixels is converted to a metric area by using a hardware feature as a length standard.

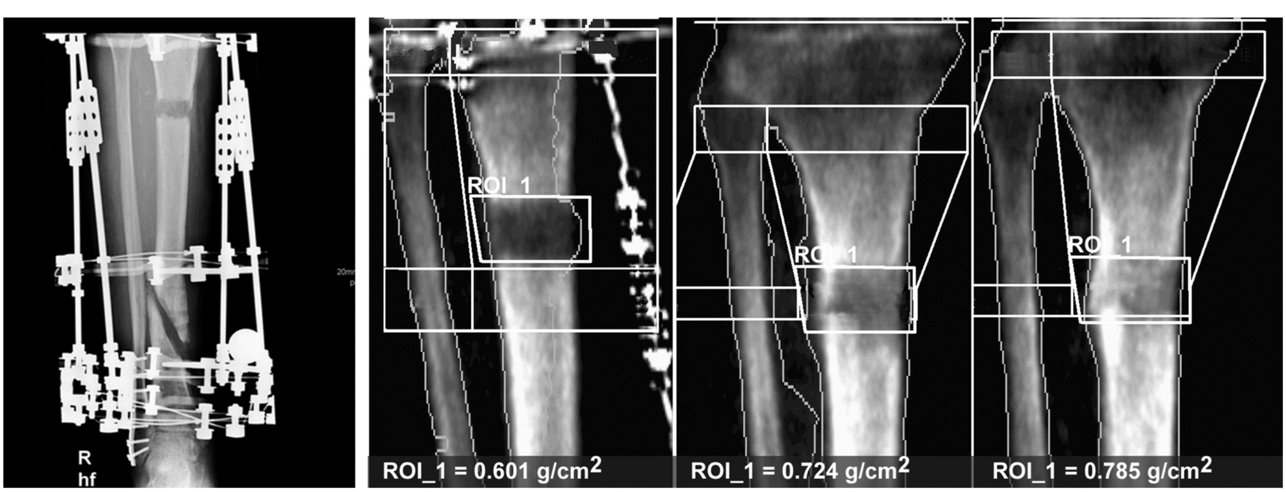

Fig. 2. Quantitative assessment of bone mineral during segmental transport. DXA measurements were performed at the end of segment transport and 4 and 7 weeks thereafter. Areal bone mineral density in mg/cm^2 was determined in the area of the defect (ROI_1).