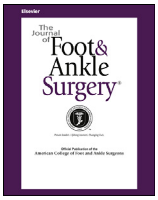
The Journal of Foot & Ankle Surgery 54 (2015) 17–22

Contents lists available at ScienceDirect

The Journal of Foot & Ankle Surgery

journal homepage: www.jfas.org



Mineral Density and Penetration Strength of the Subchondral Bone Plate of the Talar Dome: High Correlation and Specific Distribution Patterns

André Leumann, MD, PhD [1,2], Victor Valderrabano, MD, PhD [2], Sebastian Hoechel, MD [1],
Beat Göpfert, BSc [3], Magdalena Müller-Gerbl, MD [1]

[1] *Institute of Anatomy, University of Basel, Basel, Switzerland*
[2] *Orthopaedic Department, University Hospital of Basel, Basel, Switzerland*
[3] *Laboratory of Biomechanics and Biocalorimetry, Clinical Morphology and Biomedical Engineering, University of Basel, Basel, Switzerland*

ARTICLE INFO

Level of Clinical Evidence: 5

Keywords:
ankle
bone density
cartilage
osteoarthritis
osteochondral lesion
talus
tibia

ABSTRACT

The subchondral bone plate plays an important role in stabilizing the osteochondral joint unit and in the pathomechanism of osteochondral lesions and osteoarthritis. The objective of the present study was to measure the mineral density distribution and subchondral bone plate penetration strength of the talar dome joint facet to display and compare the specific distribution patterns. Ten cadaver specimens were used for computed tomography (CT) scans, from which densitograms were derived using CT-osteoabsorptiometry, and for mechanical indentation testing from which the penetration strength was obtained. Our results showed 2 different distribution patterns for mineral density and penetration strength. Of the 10 specimens, 6 (60%) showed bicentric maxima (anteromedially and anterolaterally), and 4 (40%) showed a monocentric maximum (either anteromedially or anterolaterally). A highly significant correlation ($p < .0001$) for both methods confirmed that the mineral density relied on local load characteristics. In conclusion, the biomechanical properties of the subchondral bone plate of the talar dome joint facet showed specific distribution patterns. CT-osteoabsorptiometry is a reliable method to display the mineral density distribution noninvasively. We recommend CT-osteoabsorptiometry for noninvasive analysis of the biomechanical properties of the subchondral bone plate in osteochondral joint reconstruction and the prevention and treatment of osteoarthritis and osteochondral lesions.

The subchondral bone plate is anatomically located between the calcified cartilage (deepest layer of cartilage) and the subchondral bone. The subchondral bone plate thickness is 0.1 to 1.5 mm and can be seen on computed tomography (CT) scans as a distinct radiodense line separating the articular cartilage and cancellous bone (1,2). Its function is to transfer and modulate the load from the joint to the subchondral cancellous bone and vice versa (3). It was suggested by Mente and Lewis (4) that the subchondral bone plate serves as a transitional zone of intermediate stiffness.

The subchondral bone plate has gathered increasing attention, because it has been found to be involved in joint pathologic entities such as osteoarthritis (OA), osteochondral lesions, osteonecrosis, and osteochondral or intra-articular fractures (1). In animal models of OA, the subchondral bone plate has showed thinning in models of early-stage OA and thickening in late stages of OA (5,6). Subsequent to cartilage degeneration, the load transfer modulation will be altered, leading to greater local peak forces and changes in the biomechanical properties of the subchondral bone plate. In humans, vascular invasion, microcracks, and multiplication of the tidemark were found in OA (7). In treating osteochondral lesions (e.g., the talus), restoration of the subchondral bone plate has become an important factor to seal the subchondral bone and avoid cyst recurrence (8).

Because all musculoskeletal tissues (e.g., bone, cartilage, muscle) adapt to mechanical input such as load or strain, the subchondral bone plate is thought to adapt to the load transfer through the joint, showing the effects of the long-term mechanical load in what is known as "morphology revealed biomechanics." CT-osteoabsorptiometry (CT-OAM) is a noninvasive technique that displays the mineral density distribution in the subchondral bone plate based on conventional CT scans (9). Mineral densitograms have shown consistent patterns for several joints, such as the knee, hip, and shoulder (9–12).

Financial Disclosure: None reported.
Conflict of Interest: None reported.

Address correspondence to: André Leumann, MD, PhD, Orthopaedic Department, University Hospital of Basel, Spitalstrasse 21, Basel 4031 Switzerland.
E-mail address: aleumann@uhbs.ch (A. Leumann).

http://dx.doi.org/10.1053/j.jfas.2014.09.035

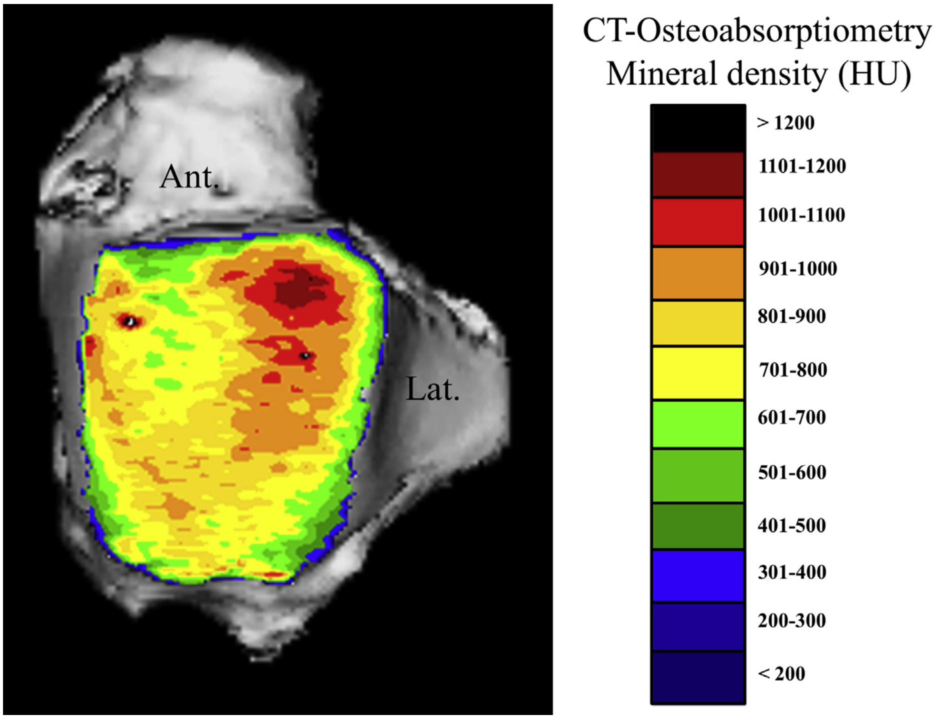


Fig. 1. Computed tomography (CT)-osteoabsorptiometry of a right talus (specimen 2) showing characteristic distribution of subchondral bone plate mineral density. One area of high density is found in the anterior (Ant.) to central parts of the medial curvature and another on the lateral (Lat.) curvature. Color-coded computed tomography-osteoabsorptiometry densitogram is superimposed onto the surface of the total talar body to facilitate anatomic orientation. HU, Hounsfield unit.

The objectives of the present study were to measure and display the mineral density distribution and penetration strength patterns of the subchondral bone plate of the talar dome joint facet of the ankle and to compare the results of the density distribution and penetration strength with each other. The talar dome is a joint facet frequently affected by OA and osteochondral lesions (13,14). The biomechanical properties related to the penetration strength and mineral density can help to elucidate mechanical and anatomic subchondral bone plate properties and to understand pathobiomechanical joint disorders.

Materials and Methods

Specimen

Ten unpaired human cadaver tali were used in the present study. At the time of death, the mean donor age was 85.4 (range, 72 to 91) years, and 6 (60%) were female and 4 (40%) were male. The specimens were fixed in formalin. The exclusion criteria were macroscopic cartilage degeneration according to the International Cartilage Repair Society score ($\geq$1) (15), signs of OA or osteoporosis on the CT scans using the Osteoarthritis Research Society International criteria (16), and a positive patient history of ankle pathologic features. The local ethical committee approved the present study.

CT-Osteoabsorptiometry

Data sets for CT-OAM were acquired using conventional CT scanning (16 row-detector; 1-mm thickness; Somatom Sensation™, Siemens, Erlangen, Germany) and analyzed using a specific image analyzing system (ANALYZE, version 7.4, Biomedical Imaging Resource, Mayo Foundation, Rochester, MN). The CT scans were segmented to isolate the subchondral bone plate. The maximum intensity projection revealed the Hounsfield unit (HU) of each pixel. Threshold values were chosen according to previous studies to be <200 to >1200 HU (17). To display the mineral density distribution, these data were false color coded and superimposed on the identical 3-dimensionally reconstructed talus for anatomic localization (Fig. 1).

Indentation Testing

Indentation testing (IT) was performed using a material testing machine (Synergie 100, MTS Systems, Eden Prairie, MN) at predefined measuring points according to a 15-point grid scheme, measuring the reactive force with a constant speed of penetration (17). Therefore, the specimens were fixed in a custom-made frame on a ball joint that enabled repetitive penetration of the subchondral bone plate perpendicular to the surface (Fig. 2). A custom-made indenter of stainless steel with a conical tip (radius, 1.25 mm; area, 4.91 mm^2) was used. The distance between the IT measurement points was chosen to be 7 mm in accordance with the results of previous studies to minimize interference with the measurements (9,18).

For analysis, the force curve was divided into 3 relevant parts. The first part with reactive force resembled the cartilage indentation (points A to B); the second part, deflection of the subchondral bone plate consisting of a linear slope (points B to C); and the third part was defined as the end point of this slope, depicting failure (fracture) of the subchondral bone plate (point C) (Fig. 3). At point C, the failure load (N) was measured. The penetration strength (MPa) was calculated by dividing the failure load by the indenter size (mm^2). The term “penetration strength” was used throughout our report, because this value was independent of the indenter size.

Comparison of CT-OAM and IT

Resolution of the CT-OAM and the 15 measurement points of IT were largely different. To compare both methods, the CT-OAM values were identified at exactly the same measurement points with the same measurement size (indenter size, 4.91 mm^2) at which the penetration strength was measured. The HUs were scaled in 8-bit. The results of both methods were visualized in schematic diagrams so that visual comparison was possible.

The correlation of mineral density and penetration strength was calculated for the corresponding data set points to elucidate the correlation of the noninvasively measurable densitograms with invasive mechanical strength testing. For statistical analysis, linear regression correlation (Bravais-Pearson correlation coefficient) was calculated using Microsoft® Excel® 2007 (Microsoft Corporation, Redmond, WA), and statistical significance was defined at the 5% ($p \leq .05$) level.

Results

Density Distribution

The mineral density distribution was not homogenous throughout the entire joint facet but followed distinct distribution patterns. Two specific density distribution patterns were identified. In 6 (60%) of the 10 samples, bicentric density maxima were found (Fig. 4C). The absolute maxima were found anteromedially with an extension along