DAMAGE ABOUT NATURAL AND DRILLED HOLES IN BONE

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ABSTRACT

We quantified microarchitecture and microcrack damage near a natural hole – the nutrient foramen - and drilled holes in bone beams subjected to cyclic four point bending. We found smaller osteons more tightly packed and less damage near the foramen. This microarchitecture appears to confer toughness to the foramen.

INTRODUCTION

Our related studies found that static strength in osteonal bone benefited from the microstructural adaptation of the bone matrix about the nutrient foramen located in the palmar aspect of the equine third metacarpal (MC3). These studies revealed the adaptation reduces the stress concentrations near the foramen [4] and increases the structural strength [7]. Subsequently, elastic and strength manifestations of the microstructure were mimicked in the design and fabrication of a plate with a central hole [6]. These plates demonstrated superior performance over a structurally uniform plate with a hole [3]. The current research serves to determine if the foramen is mechanically superior with respect to cyclic loading by subjecting it to a direct comparison with a drilled hole.

METHODS

Two equine MC3 were obtained from skeletally mature animals and stored at –26°C until further preparations. All procedures were approved by our Institutional Animal Care and Use Committee. Beams measuring 110 mm long by 15 mm wide by 2 mm thick were prepared from the palmar aspects (**Figure 1**) [1]. The nutrient foramen served as a reference point for all cuts. A comparative drilled hole (12 mm away from the foramen) and a control drilled hole (40 mm from the foramen) were created. A 75 rpm nitrogen powered drill was used to create the drilled and control holes. Each drilled and control hole was made similar to the foramen by meticulously grinding and polishing to corresponding elliptical shapes using a custom made fixture. Each beam was finely polished prior to testing to remove any surface damage.

The bone beams were tested in four point bending (support span 80 mm, load span 4 mm, roller diameters 3.2 mm). The foramen and the drilled hole endured the same strain level, as they were located in the region of constant moment between the two loading noses. The control hole was located in the overhanging region, outside the support noses and consequently not loaded. One beam was strained to 5,000 με and the other to 8,000 με to induce different levels of damage around the loaded holes. A servohydraulic materials testing machine was used to load the beams in displacement control at a frequency of 2 Hz. The beams were cycled for 60,000 cycles unless failure occurred prematurely. The testing took place in a calcium buffered [3] gentamycin doped saline bath at a temperature of 37°C. After testing, the beams were immediately stained with basic fuchsin [2] to differentiate between microcracks induced by loading and existing and those produced by subsequent sectioning.

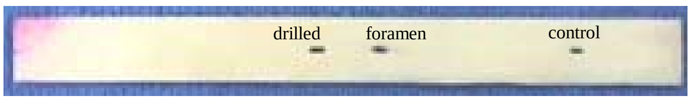

Figure 1. Bone beam with foramen and drilled holes.

Each stained beam was sectioned (100 μm thick) through the foramen, drilled hole, and control hole. The sections were observed with a bright field microscope at a magnification of 150X. All quantification was done by one observer blinded as to the source of the sections. A total of six sections were observed. Microarchitectural (osteon density, osteon diameter, and porosity) and microcrack (crack type, density, and length) parameters were quantified in relation to the proximity to each hole (far and near regions). Osteon density was obtained from the number of Haversian canals of complete osteons. The osteon diameters were measured at higher magnification (300X). Two diagonals (0° and 90°) were measured and averaged for each osteon; therefore, only relatively circular osteons with clear cement lines were chosen. Porosity was comprised of Haversian canals, Volkmann's canals, and resorption spaces. Each section was scanned for microcracks, and two damage types were quantified with respect to their location (**Figure 2**): black wispy microcracks and bundles of microcracks. Both types predominantly appeared in interstitial bone. Black wispy microcracks were defined as longer than 20 µm. Bundles of microcracks were defined as a group of five microcracks each smaller than 20 µm. Crack density (number of cracks/mm^2) and crack length density (mm/mm^2) were quantified in regions near to and far from each hole.

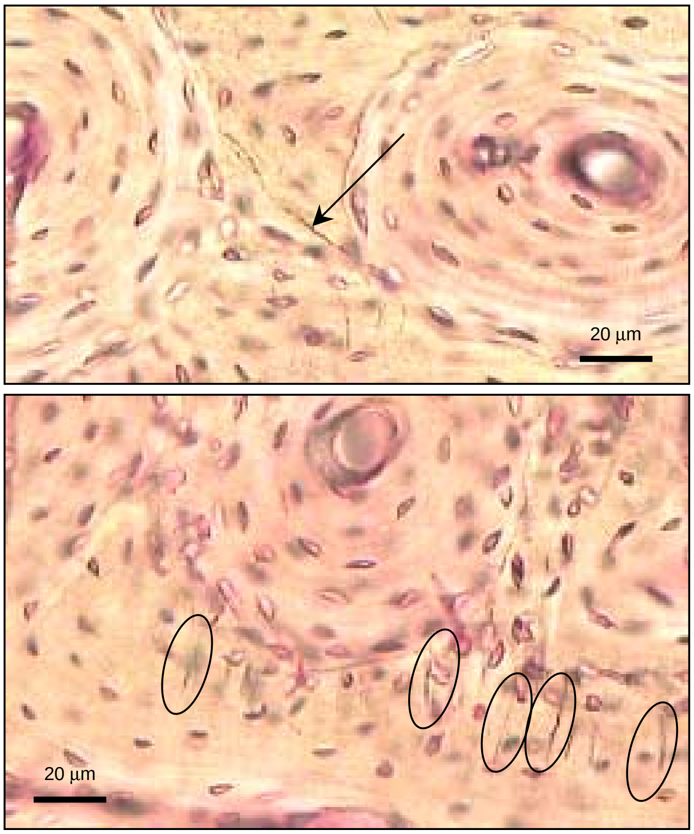

Figure 2. Black wispy microcrack (top, indicated by arrow) and bundle of microcracks (bottom, individual cracks encircled).

RESULTS

We found distinct microarchitectural differences near the foramen and the drilled holes. Osteon density was significantly greater in the region near the foramen compared to regions surrounding the drilled and control holes (**Figure 3**, left). Osteon diameter was least nearest the foramen (**Figure 3**, right). The porosity in the region near the foramen was nearly twice that far from the foramen (mean 9% near vs. 16% far). However, porosity differed by only about 1% about the drilled and control holes.

We found distinct differences in the amount of damage near the foramen and the drilled holes. Crack density was greater about the drilled hole compared to the foramen but less than that found about the control hole (**Figure 4**, left) Crack length density near the drilled hole was about twice that found near the foramen (**Figure 4,** right**)**. Crack density and crack length density was only slightly greater in the region nearest the foramen compared to nearest the control hole.

DISCUSSION

Our current microarchitectural results agree with and compliment our previous work on the MC3 foramen [4], and correlate with the reduced amount of damage we quantified near the foramen. The high porosity near the foramen was primarily due to resorption spaces, and it is unclear if these existed due to recent remodeling or have just remained unfilled. The correlation between highest osteon density and smallest osteon diameter seems obvious, but this higher packing of osteons near the foramen translates into more cement lines for possible crack arrestment and deflection. This seems to be supported by our findings of decreased damage near the foramen. We are currently investigating the effects of different aspects of osteon "construction" (intra osteonal and cement line properties) that result in minimum damage states and creating designs based on these constructions.

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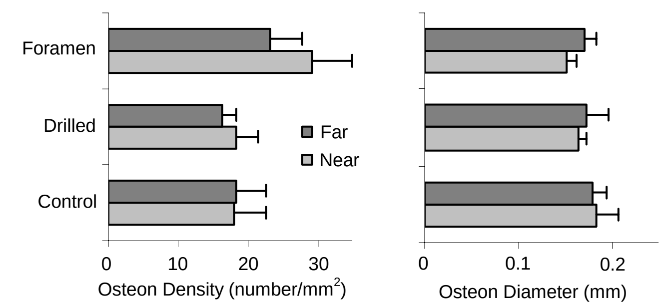

Figure 3. Osteon density (left) and diameter (right) by hole type for far and near regions.

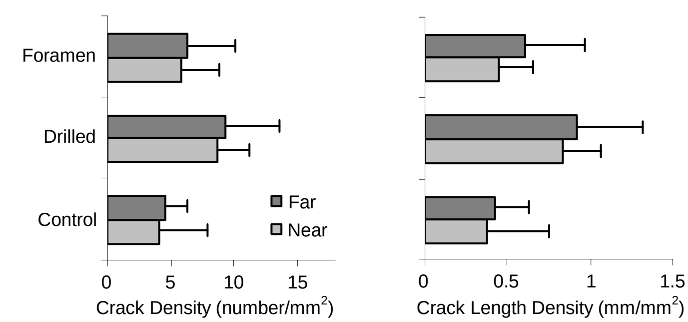

Figure 4. Crack density (left) and length density (right) by hole type for far and near regions.