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EVIDENCE OF POTENTIAL STRAIN-MODE-SPECIFIC DIFFERENCES IN CORTICAL BONE MICROSTRUCTURE IN A TENSION/COMPRESSION SYSTEM

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INTRODUCTION: A bone's strain (or stress) history is thought to be reflected in its internal cortical structure and external shape (1,2). However, mechanical bone strain is a complex interaction of several related features(2). Nonetheless, several investigators have suggested that cortical bone has the capacity to exhibit differential adaptations to regional differences in habitual strain mode (i.e., tension or compression) (7,8,9). If this is true, it suggests that bone has the capacity to regulate its structural/material organization at a local level.

In vivo strain gauge studies by Lanyon (3), showed that the artiodactyl calcaneus has prevailing compressive strain in the cranial cortex and prevailing tensile strain in the opposite caudal cortex. They also reported a strain magnitude gradient across the cortex, with the greatest strain occurring at the periosteal surface. The purpose of this study is to quantitatively determine if differences exist in osteonal morphology and osteonal reconstruction between tension and compression cortical regions in a simple tension/compression model (artiodactyl calcaneus(4)).

MATERIALS AND METHODS: Ten skeletally mature male mule deer (Odocoileus hemionus hemionus) calcanei were each sectioned transversely at 40, 50 and 70 percent of length (4). Each section was embedded in polymethyl methacrylate and the distal surface of each section was polished and prepared for imaging in the backscattered electron (BSE) mode in a JEOL scanning electron microscope. A total of 540 images, representing almost 650 square millimeters of cortical bone, were recorded on Polaroid 52 film and saved for analysis. The cranial and caudal cortices of each section were subdivided into three regions: subperiosteal (P), middle (M), and endosteal (E) (Fig 1). The subperiosteal region was defined as being immediately adjacent to the periosteal surface, without including any circumferential lamellae. The middle region was defined to be half-way between the periosteum and the border of the endosteal canal. The endosteal region was defined to be adjacent to the medullary canal. One 50x and two 100x images were taken in each region. Care was taken to avoid any overlapping of the 50x images. The 100x images were taken within the bounds of the 50x images. The images were analyzed for number of osteons, fractional area occupied by secondary (osteonal) bone, and porosity. Comparisons between tension and compression regions were made using an ANOVA design and the level of significance was set at $p<0.01$. Since there is a transcortical strain magnitude gradient, comparisons were also made between P, M and E regions within each cortex.

RESULTS: Results are shown in Table 1. There were more osteons in the compression cortex ($38\pm 15/mm^2$) than in the tension cortex ($34 \pm 10/mm^2$) ($p<0.01$). There was also more interstitial bone in the compression cortex (Cranial 1.3 ± 0.4 mm^2/image vs Caudal 0.88 ± 0.3 mm^2/image) ($p<0.01$) . Osteons in the caudal (tension) cortex were observed to be more irregularly shaped than those in the compression cortex. Back-scattered electron (BSE) greylevels showing lower mineral content indicated that the osteons in the tension cortex were younger. The porosity of the caudal (tension) cortex ($8.5 \pm 5.9\%$) was greater than the porosity of the cranial (compression) cortex ($4.7 \pm 2.0\%$) ($p<0.01$). Comparisons between the three regions (Fig. 1B) within the respective cortices showed no differences between the subperiosteal region and the middle region in terms of porosity and all osteon parameters examined (Table 1). However, in the endosteal regions (Fig. 1B) of both strain environments, there were fewer osteons. The osteons were also larger than in either the middle or subperiosteal regions. The degree of porosity in the endosteal regions ($9.05 \pm 6.9\%$) was greater when compared to both subperiosteal ($5.3 \pm 2.1\%$) and middle regions ($5.3 \pm 2.7\%$) ($p<0.01$) in both strain environments. Comparisons between the three regions along the length of the bone in both strain environments showed no differences in any of the parameters examined in this study.

DISCUSSION: Julius Wolff (5) suggested that tension and compression loading are important in directing bone adaptation. Modern experimental evidence suggests that a more complex strain related signal is responsible for observed adaptive phenomena in cortical bone (2). The hypothesis that regions of a bone loaded in compression and regions loaded in tension exhibit mechanically relevant morphological differences, as observed in this study, is supported by the unquantified observation that the greatest density of osteons often appears within the compression cortex (2). Because of the distinct tension and compression regions in the artiodactyl calcaneus, it is compelling to associate the quantitative differences between cranial and caudal osteonal micromorphologies, reported here, with the prevailing strain mode differences. It should be noted that in cortices receiving predominantly compression loads, the strain magnitude is usually greater than in cortices receiving tension (2). However, the lack of differences between the subperiosteal and middle regions in either cortex is important because it suggests that bone is not responding to strain magnitude, at least in terms of the parameters examined in this study. Based on data in chick tibiotarsi, Biewener and Bertram (6) rejected the hypothesis that site-specific morphologic differences exist in cortical bone. However, their model was skeletally immature, therefore these authors conceded it may not be appropriate for examining this issue.

The lower mineral content, larger osteon size, and the irregular shape of the osteons in the tension cortex suggest a more rapid rate of remodeling (renewal) in this region. If this is in fact the case, the increased rate of renewal may be secondary to increased incidence of microdamage or other unknown factors associated with tensile loading. Although the differences seen between the compression and tension cortices are not conclusive proof, they support the hypothesis that some feature associated with tensile loading is inducing an adapative response in this model. Further investigations in simple, skeletally mature models with well defined in vivo loading conditions, is warranted and could help reveal the ultimate mechanisms whereby adult bone adapts to different strain environments. These studies will help in understanding how mechanical stimuli affect skeletal maintenance and repair.

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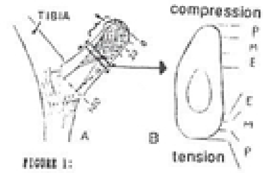
TABLE 1: Osteons refers to number of osteons counted per 1.8mm² image. Area refers to the percent area of secondary bone excluding central canals. Porosity is the percent area of porous spaces. Cr=cranial, Ca=caudal, P=sub-periosteal, M=middle E=endosteal, 50 and 70 refer to percent length.

	OSTEONS		AREA		POROSITY	
	mean	STD	mean	STD	mean	STD
Cr	68.6	27.2	64.8	11.1	4.69	2.03
Ca	61.6	17.3	75.5	8.8	8.45	5.88
P	79.9	14.5	75.9	7.2	5.34	2.14
M	73.8	18.4	73.7	6.9	5.32	2.71
E	41.7	14	60.9	11.8	9.05	6.93
70	68.5	22.8	70.1	12.9	5.82	2.75
50	61.7	22.8	70.2	8.9	7.33	6.1

FIGURE 1:
A. Illustration of the muledeer calcaneus.
B. Transverse section at 50% length. P=subperiosteal region, M=middle region, E=endosteal region



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