Comparative study of bone micro-architecture of some mammalian bones

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ABSTRACT

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In the present study, a comparison has been made on the size of osteon and Haversian canal from bone specimen of seven mammalian species (rat, rabbit, cat, dog, monkey, adult man and cow) with two extinct specimens from primitive land animals (*Diadectes* and *Iguanodon*). Furthermore, relationship between size or weight of animal with respect to the size of its osteon and Haversian canal has been explored by applying allometric scaling laws to the micro architecture data. The results indicate that in general, osteon and Haversian canal size increases with increasing body weight however, the relative size of the osteon and Haversian canal decreases per unit body weight, i.e. rat osteons are larger relative to human and dinosaurian osteon. Interestingly, the ratio of osteon to Haversian canal diameters were in the range of 4 to 6 for all the animals (excluding rat) investigated in the present study including the dinosaurs. This suggests firstly, a close resemblance of extinct bone micro-architecture to mammals and secondly that osteon and Haversian canal sizes were optimised for efficient transport of nutrients and metabolites from the animal body to the bone cells. It may be explained by the concept that outside the optimum range an increase in osteon diameter actually reduces the efficiency of transportation of nutrients and waste products.

Key-words—Osteon, Haversian canal, Osteocytes, Evolution.

कुछ स्तनी का अस्थि सूक्ष्म-स्थापत्य का तुलनात्मक अध्ययन

संजय मिश्र और मेलीस्सा नॉथ टैट

सारांश

वर्तमान अध्ययन में, आदिम स्थलीय प्राणियों (*डायोडेक्टीज* और *इग्वेनोडॉन*) से प्राप्त दो विलुप्त नमूनों सहित चूहा, खरगोश, बिल्ली, कुत्ता, बंदर, वयस्क व्यक्ति तथा गाय के अस्थि नमूने से प्राप्त ऑस्टियॉन एवं हैवर्सियन कैनॉल के आकार के बारे में तुलना की गई है। इसके अतिरिक्त, प्राणि के आकार या भार में संबंधता इसके ऑस्टियॉन एवं हैवर्सियन कैनॉल के आकार के दृष्टिगत सूक्ष्म स्थापत्य, आँकड़ा को सापेक्षमितीय मापन नियमों को लागू करते हुए अन्वेषित की गई है। परिणाम दर्शाते हैं कि सामान्यतः बढ़ते शरीर भार सहित में ऑस्टियॉन एवं हैवर्सियन कैनॉल का आकार बढ़ता है फिर भी ऑस्टियॉन एवं हैवर्सियन कैनॉल का सापेक्षिक आकार शरीर भार प्रति इकाई घटता है अर्थात चूहे की ऑस्टियॉन मानव एवं डायनोसॉरी ऑस्टिऑन धिकतम संबंधी हैं। दिलचस्पपूर्वक, वर्तमान अध्ययन में डायनोसॉर सहित समस्त प्राणियों (चूहा छोड़कर) पर किए गए अन्वेषण में ऑस्टियॉन एवं हैवर्सियन कैनॉल व्यासों का अनुपात 4 से 6 तक फैला था। प्रथमतः यह स्तनधारियों के विलुप्त अस्थि सूक्ष्म स्थापत्य की नजदीकी समरुपता तथा दूसरा कि पोषक के कुशल अभिगमन के लिए ऑस्टियॉन एवं हैवर्सियन कैनॉल आकार तथा अस्थि कोशिकओं से प्राणि शरीर से प्राप्त उपापचयज आशावादी सुझावित करता है। संकल्पना से व्याख्या की जा सकती है कि जटिल आकार के अलावा ऑस्टियॉन व्यास में वृद्धि वास्तव में पोषकों व व्यर्थ उत्पादों के अभिगमन की कुशलता न्यून कर देता है।

संकेत-शब्द—ऑस्टियॉन, हैवर्सियन कैनॉल, अस्थ्यणु, विकास।

INTRODUCTION

ALLOMETRIC scaling laws describe mathematical relationships between complex biological variables, e.g. the relationship between length (L) or diameter (D) and body volume (V) or mass (M) can be described by the equation

$$(L, D) \propto V^{SE} \tag{1}$$

whereby SE is referred to as the scaling exponent.

If one assumes that all species share a common density (Swartz & Biewener, 1992), then this relationship can be described in terms of body mass or weight,

$$[(L,D) \propto M^{SE}] \tag{2}$$

The scaling exponent is defined such that SE = 1/3 for interspecies *isometry*, SE > 1/3 for *positive allometry*, and SE < 1/3 for *negative allometry*.

Although scaling laws have been applied to investigate biomechanical relationships in cancellous bone (Swartz *et al.*, 1998), they have not been applied previously to explore the basic structural unit of cortical bone, i.e. the osteon. Bone micro architecture primarily consists of osteon, Haversian canal and lacuna (Fig. 1). Studies in palaeobiology have described the morphology of primitive and animal bones at osteon level. Recent data suggest that bone microarchitecture is optimized for efficient transport, e.g. through the vascular and lacunocanalicular systems (Mishra & Knothe Tate, 2003). Hence, the aim of this study was to explore quantitatively the empirical relationship between osteon and Haversian canal size and body weight in seven mammalian species and to investigate evolutionary changes in the microarchitectural morphology of cortical bone.

MATERIALS AND METHODS

Data including body weight, osteon and Haversian canal size were collected from published morphometric data (Jowsey, 1966; Tarach & Czaja, 1973) for mammalian species with different weights (10^2 to 10^6 grams). Data including weight, os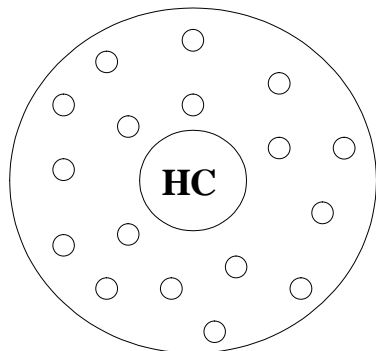teon diameter and Haversian canal perimeter for rat, rabbit, cat, dog, rhesus monkey, man, cow, *Diadectes* and *Iguanodon* were available from Jowsey's 1966 study. Osteon and Haversian canal diameter data for man, monkey, horse and pig were reported by Tarach and Czaja in 1973. Tarach did not report weights of animals in this study, so human and monkey weights were assumed to be similar to the values reported by Jowsey (1966) and an average weight was calculated for the pig and horse. Haversian canal diameter was calculated from canal perimeter measurements (Jowsey, 1966) assuming canals to be of circular cross section. The mean diameters of osteon and Haversian canal, respectively, were calculated from the corresponding maximal and minimal diameters reported by Tarach and Czaja (1973). Osteon and Haversian canal diameters were plotted against body weight for each species. A linear regression line was calculated for each resulting scatter plot. Finally, the ratio osteon : Haversian canal diameter was calculated for each animal species studied.

RESULTS AND DISCUSSION

In general, osteon and Haversian canal size increases in proportion to body weight of the animal (Figs 2, 3). Based on the slope of the linear regression curve, the scaling coefficients for osteon and Haversian canal diameters are 0.12 and 0.17, respectively, indicative of negative allometry. Taking into account the positive allometric relationship between body weight (W) and skeletal weight (W_s), as defined by Prange *et al.* (1979),

$$W_s \propto W^{1.09} \tag{3}$$

And the negative allometric relationship between osteon and Haversian canal diameter, larger animals tend to have relatively more skeletal mass but smaller osteon and Haversian canal size.

Normalizing for body weight, the allometric equations shown in Fig. 2 are divided by the body weight to get the specific osteon and Haversian canal diameter (y'), i.e.

$$(y/x)_{osteon} = 47.79x^{0.12} / x \implies y'_{osteon} = 47.79x^{-0.88} \tag{4}$$

$$(y/x)_{Haversian\ canal} = 6.44x^{0.17} / x \implies y'_{Haversian\ canal} = 6.44x^{-0.83} \tag{5}$$

Fig. 1—Schematic diagram showing the geometry of an idealised osteon. The central Haversian Canal (HC) is surrounded by numerous lucuna.
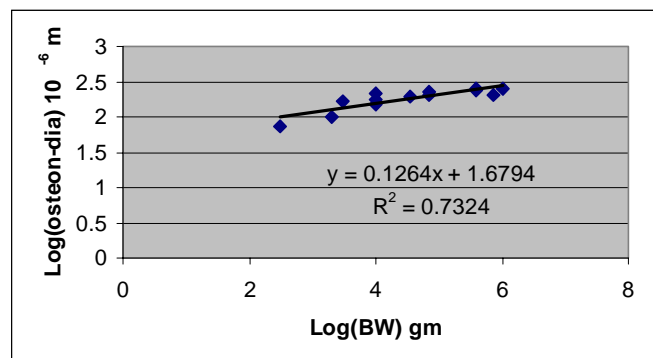

Fig. 2—Log-log plot of osteon diameter vs. body weight for increasing body mass (left to right, animals listed in Fig. 4).
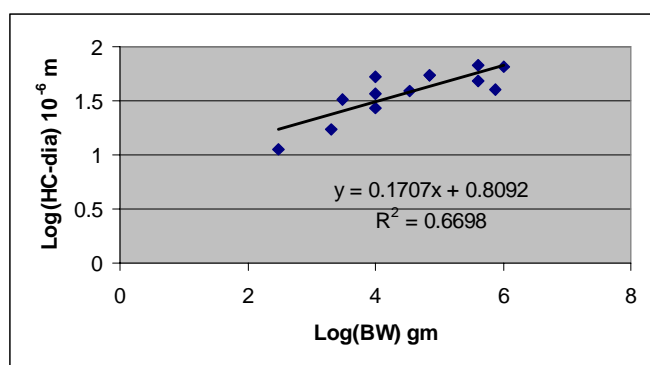
Fig. 3—Log-log plot of Haversian canal diameter vs. body weight for the animals listed in Fig. 4.

Fig. 4—Ratio between osteon diameter and Haversian canal diameter for the different animals considered in this study, [1]rat, [2]rabbit, [3]cat, [4]dog, [5]rhesus monkey, [6]monkey, [7]pig, [8]man, [9]man, [10]cow, [11]*Diadectes*, [12]horse, [13]*Iguanodon*. The data points 1,2,3,4,5,8,10,11 and 13 were after Jowsey (1966) and the data points 6,7,9 and 12 were after Tarach (1973).

resulting in a scaling exponent of –0.88 and –0.83, respectively. The negative SE for both allometric equations shows a decreasing specific osteon and Haversian canal size (i.e. per unit body weight) for increasing animal size or weight. Hence, osteons and Haversian canals in human and cow bone are relatively smaller than those in rat and cat bone with reference to their respective weights. Plotting the specific osteon and specific Haversian canal diameters against body weight on log-log axis, the resulting regression lines have negative slopes equal to the scaling exponents for each case (-0.88 and -0.83).

The evolutionary advantage for allometry for osteon and Haversian canal size may relate to optimizing efficiency of nutrient and metabolite transport in the lacunocanalicular network. It has been shown that beyond a critical size, an increase in osteon diameter actually reduces the efficiency of nutrient transportation in the lacunocanalicular network (Mishra & Knothe Tate, 2003). Due to the differences in SE (Figs 2, 3), animals with lower weights tend to have a relatively higher ratio of osteon diameter to Haversian canal diameter (Fig. 4); this may be advantageous for survival. On the other hand, heavier skeletons tend to have a constant ratio (4 to 6) between osteon and Haversian canal diameter, suggesting an optimum value to satisfy the conflicting requirements for lower hydraulic resistance in lacunocanalicular network and increased nutritional demand due to increase in the size of osteon. Mechanical factors such as optimal fibre size for maximal composite strength may have influenced this evolutionary trend as well.

The comparison of absolute size of the osteon and Haversian canal of *Diadectes* (Permian Period, 299-251 Ma) and *Iguanaodon* (Jurassic Period, 199-145 Ma), we find a relatively large increase in the size of Haversian canal (from 47 to 64 mm; 36%) and a small increase in the size of the osteon (236 to 246 mm; 4%). The morphological data of *Iguanaodon*, a dinosaur (osteon diameter 246 mm and Haversian canal diameter 64 mm) are similar to recent mammals such as the cow (osteon diameter 250 mm and Haversian canal diameter 68 mm)
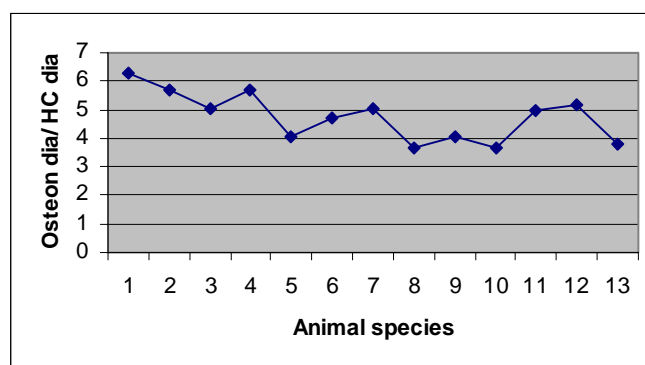
than *Diadectes*. If it is believed, that bone micro architecture is related to its function than the present results indicate that Jurassic dinosaur bones were functionally similar to modern mammals. However, other biomechanical variables needs to be explored to support this finding.

Based on the study of five-mammalian trabecular bone, Mullender *et al.* (1996) suggested that the thickness of trabeculae is limited by the size of domain that can be regulated by the osteocyte. Similarly, the present study support the hypothesis that one of the factors that determines osteon size is the size of corresponding Haversian canal, which can supply and transport metabolites to the osteocytes within a given osteon. Based on this theory, our results indicate that osteon domain that can be nourished efficiently by its Haversian canal is approximately 4 to 6 times of the size of Haversian canal, irrespective of the animal species (Fig. 4). Therefore, the relative area (volume) of the nutrient reservoir in Haversian canal to the supply area (volume) in an osteon is similar regardless of species. Only the morphometric data from the rat shows a higher ratio (>6) between osteonal diameter and Haversian canal diameter, which may be due to non-closure of growth plates and a different mechanical environment imbued in the rat femur as described by Mullender *et al.* (1996).

There are limitations in this study. Firstly, the weight of *Diadectes* and *Iguanodon* were estimated. Secondly, morphometric measurements in the study of Tarach and Czaja (1973) did not account for weight of animals, and minimum and maximum diameters of osteon and Haversian canal were measured instead of mean ± SD as reported by Jowsey (1966). The methodology used by the two previous studies to measure the dimensions of the osteon and Haversian canal may not be similar. Therefore, estimates applied in this analysis may deviate from actual values for the man, monkey, pig and horse specimens reported by Tarach and Czaja (1973). Hence, combining these two sets of morphometric data to calculate

allometric equations may have introduced a degree of error. Furthermore, limited data sets from secondary sources, undue weighting for some species coupled with application of linear regression lines may not appropriate to make conclusions. Nonetheless, this artifact is not expected to alter the trend demonstrated with the allometric equations and qualitative findings. Despite these limitations, this work represents the first application of allometric scaling laws to investigate micro-architecture of cortical bone. Our results indicate that the size of the osteon and the corresponding Haversian canal appears to remain constant for a variety of species. Further studies with large sample size of primary data with stereological methods will be required to further refine this preliminary study.

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