Selection of an Animal Model for Implant Fixation Studies: Anatomical Aspects

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A number of different animal models have been employed by investigators to study the biology of the bone-cement interface as it relates to the problem of hip implant loosening in humans. This study compares to the human three species (baboon, dog, and sheep) currently under use as experimental animal models from an anatomical point of view. A number of parameters, important for the dimensional design of a femoral prosthesis, loads at the hip joint and its subsequent performance, were used for comparing external and internal femoral anatomy. The baboon and dog femora were found to be most similar to the human femur in their external anatomy. The quantification of cancellous bone distribution within the medullary canal revealed that, of the species studied, the sheep femur provided the least support to the prosthesis. The results suggest that the dog and baboon are anatomically appropriate for studying hip implant biomechanics experimentally. Thus, from an anatomical point of view, the current extensive use of the dog as an experimental animal appears appropriate.

INTRODUCTION

Aseptic mechanical loosening in total joint replacement is a significant and well-recognized problem [1,2,3,4]. Its natural history is the result of a complex interaction of biological and mechanical factors relating to the manner in which cyclic loads are distributed within the prosthetic implant, transferred to methylmethacrylate, and then to bone. A number of factors have been implicated in this process. These include the relative stiffness of the metallic implant, its design and orientation in relation to the long axis of the femur [5], the material and structural properties of polymethylmethacrylate (PMMA) [6,7,8,9], and techniques of its application [10,11,12,13]. The principal area affected ultimately appears to be the bone-cement interface.

Several investigators in the past have studied the mechanical properties of the bone-cement interface using fresh frozen human cadaver bones [14,15]. Such in vitro studies, although helpful, are unable to provide sufficient insight into the behavior of the fixation system within a changing biological environment over time. Similarly, studies undertaken on specimens with prosthesis in situ (obtained at the time of autopsy) view this interaction at only one point in time. Moreover, such specimens are difficult to procure. Alternatively, an animal model may be con-
sidered. While this involves a departure from human conditions, the discrepancies may be minimized by the selection of an appropriate animal for use. The great advantage of such a model is that variable control and case numbers may be maximized. Provided caution is exercised in the extrapolation of results to the human, much can be learned about the behavior of this biological system as a function of time.

The following study analyzes the selection of such an animal model for human total hip replacement from the point of view of external and internal femoral anatomy.

METHODS

Ten adult human, three baboon, ten sheep, and ten canine femora were studied. An L-shaped plexiglass frame was constructed (Fig. 1). Each bone was secured to the frame with the posterior surface of the femoral condyles lying flat against plate A, to define the coronal plane. Plate B was attached at right angles to plate A to define the sagittal plane. Two steel balls were placed on plate A at a distance of 30 mm from each other for scaling purposes. Each femur was photographed in the frontal and transverse (from above) planes and then divided coronally with a band saw in such a way as to produce two equal halves. The distribution of the cancellous bone was recorded photographically from the cut surface of each coronal section in the study.

In selecting anatomical parameters for comparison appropriate to implant fixation, studies previously conducted [16,17] were consulted. In keeping with their methods, our own selection included femoral head diameter, neck-shaft angle, anteversion angle, and trochanteric location relative to femoral head center. In addition, because of its importance in the medullary fixation of implants utilizing methacrylate cement, the relative distribution of femoral cancellous bone was studied. The following is a list of all variables and their abbreviations:

*Parameters, External Anatomy (Fig. 2A)*

| Abbreviation | Description |
|--------------|-------------|
| \(D_h\)      | Head diameter |
| \(D_n\)      | Neck diameter |
| \(HL_v\)     | Distance from center of head to lesser trochanter, vertical (superior-inferior) |
| \(HG_h\)     | Distance from center of head to proximal tip of greater trochanter, horizontal (medio-lateral) |
| \(HG_v\)     | Head to proximal tip of greater trochanter distance, vertical (superior-inferior distance) |

FIG. 1. Apparatus used to obtain orthogonal photographs of all femora.
FIG. 2. Parameters used for the comparison of different species. (A) External anatomic parameters. (B) Internal anatomic parameters. Line A-B defines the midshaft axis. Line C-D, drawn at an angle of 45° to A-B and passing through the trochanteric notch, defines the lower boundary of the greater trochanteric region. The line C-H, joining the trochanteric tips is used for the demarcation of head and neck regions. (C) The prosthesis-cement-bone composite in a femur. The length EF is supported by the cortical-cancellous-cement composite. The remaining length (FG) is surrounded by cement which has no interlocking with cortical bone in the absence of true cancellous bone.

L  Femoral length (defined as the distance from the center of the femoral head to the center of the intercondylar notch)
L1 Isthmus location from intercondylar notch measured along a line connecting proximal tip of greater trochanter to intercondylar notch (trochanteric-condylar notch axis)
LG Intertrochanteric distance
| MB  | Medial bow (distance of subperiosteal surface of medial cortex to the line [L] at the isthmus) |
|-----|---------------------------------------------------------------------------------------------|
| $W_1$ | Subperiosteal breadth of femur at isthmus                                                   |
| $\alpha$ | Angle formed by trochanteric-condylar notch axis and neck axis in the frontal plane          |
| $\beta$ | Neck anteverversion angle                                                                     |

**Parameters, Internal Anatomy**

The internal structure of each bone was studied by quantifying the distribution of proximal cancellous bone within the cavity. A number of regions pertinent to medullary implant fixation were described (Fig. 2B):

- $A_1$: Total area above isthmus, defined by the outer boundary of cortical bone (total subperiosteal area)
- $A_2$: Area, above isthmus, defined by the inner boundary of cortical bone (total medullary area)
- $A_3$: Cancellous bone area in the greater trochanter, above a line (D-C) drawn at 45° to the mid-shaft intersecting the transverse neck axis (C-H) at its superior end, mid-shaft axis was marked on each photograph
- $A_4$: Cancellous bone area in the head and neck region, above a line (C-H) connecting the medial borders of the greater and lesser trochanters
- $A_5$: Cancellous bone in the proximal fixation region
- $A_6$: Total cancellous bone area ($A_3 + A_4 + A_5$)
- $E$: Point corresponding to the center of the cross-section of reamed medullary canal along line C-H
- $F$: Point on the distal end of the cancellous bone in the proximal region
- $G$: Point in the medullary canal representing the location of the tip of femoral stem after insertion
- $R$: Fraction of stem length supported by the cancellous-cement composite ($EF/EG$, Fig. 2C)

Points $E$, $F$, $G$ and their relationship to a prosthesis are shown in Fig. 2C. The length $EG$ signifies the stem length of a prosthesis. For an average size human femur, femoral length ($L$) of 410 mm, this was taken as 110 mm. Thus a ratio of 0.27 (prosthesis stem length/femoral length) was taken to calculate the length $EG$ for different bone sizes in the present study. The length $EF$, a function of cancellous bone distribution in the proximal region, was obtained from the photographs of the cut halves.

These parameters were obtained from the photographs with a Talos digitizing tablet. The resolution of the digitizer is 0.025 mm and the measured dimensions were found to be accurate to within ±0.1 mm. Computer programs were developed for the acquisition, storage, and further processing of the raw data into parameters of concern, using Tektronics 4052 Computer. The first step in data manipulation was to transform the digitized data to a coordinate system located on the bone. The origin of this coordinate system was arbitrarily located at the center of the head with the x axis parallel to the line tangential to the articulating contours of the condyles (Fig. 2A). Thereafter, linear parameters were calculated as distances between the relevant points. Similarly, area parameters were computed from the corresponding boundaries. The means and variances of the parameters for each species were also computed. The differences between the species in comparison to humans were evaluated statistically using the student ‘t’ test. However, it should be noted that for
the baboon femora the sample size is very small and thus no statistical comparisons were undertaken. All the external anatomic parameters were non-dimensionalized with regard to parameter \( L \) and area parameters with regard to the total area. All linear dimensions were expressed in mm, angles in degrees, and areas in \( \text{mm}^2 \).

RESULTS

External Anatomy

Figure 3 provides a visual representation of the differences between species studied with regard to external femoral parameters. These were scaled with respect to the parameter \( L \) for the human. The visual comparison of the actual bones is shown in Fig. 3A. In Fig. 3B a computer plot obtained from digitized data is shown. The means and standard deviations (shown within brackets) of all the non-dimensionalized parameters are given in Table 1. The ratio \( H_{\text{H}}/L \) is given in a negative value in the table due to the definition of the axis system chosen for this paper. It can be seen both visually and numerically that, in terms of external parameters, the baboon and the dog show the greatest similarity to the human of the three laboratory animals studied. The baboon had the greatest resemblance to the
TABLE 1
External Anatomic Parameters Used for Comparison of the Four Species. The average and standard deviation (within parentheses) are given. (See text for symbols.)

| Parameters | Human    | Dog      | Baboon   | Sheep    |
|------------|----------|----------|----------|----------|
| L, mm      | 423.5 (33.7) | 188.4 (6.9) | 211.4 (20.5) | 158.7 (8.5) |
| α, deg.    | 127.7 (3.2)  | 121.8 (5.5)  | 105.8 (4.4)  | 116.0 (8.7)  |
| β, deg.    | 14.3 (7.3)   | 21.7 (12.1)   | 19.5 (4.3)   | 5.3 (2.1)   |
| HGₜ/L      | -0.10 (0.01) | -0.13 (0.01) | -0.10 (0.01) | -0.22 (0.02) |
| HGₛ/L      | 0.01 (0.01)  | 0.05 (0.02)  | 0.08 (0.01)  | 0.09 (0.02)  |
| Dₐ/L       | 0.07 (0.01)  | 0.10 (0.01)  | 0.07 (0.01)  | 0.15 (0.01)  |
| Dₑ/L       | 0.10 (0.01)  | 0.11 (0.01)  | 0.11 (0.01)  | 0.15 (0.01)  |
| HLₜ/L      | -0.12 (0.01) | -0.13 (0.01) | -0.13 (0.01) | -0.16 (0.01) |
| LG/L       | 0.16 (0.02)  | 0.22 (0.03)  | 0.22 (0.01)  | 0.31 (0.02)  |
| MB/L       | 0.42 (0.07)  | 0.61 (0.02)  | 0.64 (0.07)  | 0.59 (0.02)  |
| Wₓ/L       | 0.00 (0.00)  | 0.02 (0.01)  | 0.03 (0.01)  | 0.01 (0.01)  |

human, followed by the dog. The baboon and human were most nearly alike in anteverision angle, horizontal head to greater trochanteric distance (HGₜ) and neck diameter (Dₑ), while the dog was closer with respect to angle α and vertical head to greater trochanteric distance (HGₛ). In all other parameters, except isthmus location, both animals were found to be similar to the human. For the sheep, the greatest differences were in anteverision angle (the sheep being almost neutral), horizontal and vertical head-trochanteric distances, neck diameter, intertrochanteric distance, and canal width. The differences or alikeness for the sheep and dog, in comparison to human femora, were statistically significant ($p < 0.05$).

**Internal Anatomy**

A visual comparison of the cancellous bone distribution among the four species is shown in Fig. 4. Here each representative section has been standardized by magnification to the human, using again the parameter L as a scaling factor. The distal ends of the femora have been omitted for the sake of clarity. It may be noted that the medullary canal of the sheep exhibits a very smooth surface and is relatively wider in comparison to the other three species. Table 2 indicates the computed mean cancellous bone areas in different regions, with standard deviations given in paren-

![FIG. 4. Comparison of cancellous bone distribution. All bones have been scaled with respect to the human.](image-url)
TABLE 2
Average Distribution of Cancellous Bone in Different Regions Obtained from Cut Halves of the Bones. Standard deviation appears within parentheses.

| Species | Cortical Boundary | Total Cancellous Bone Area, $A_c$ (mm²) | Greater Trochanter Region, $A_T/A_c$ | Head and Neck Regions, $A_N/A_c$ | Proximal Region, $1 - (A_T + A_N)/A_c$ |
|---------|------------------|----------------------------------------|----------------------------------|---------------------------------|----------------------------------|
|         | Outer, $A_1$ | Inner, $A_2/A_1$ |                                    |                                 |                                  |
| Human   | 7791.9(1280.0) | 0.732(0.075) | 4005.0(510.6) | 0.112(0.040) | 0.510(0.032) | 0.378(0.034) |
| Dog     | 3134.5(527.1)  | 0.840(0.037) | 1450.9(350.0) | 0.169(0.052) | 0.329(0.055) | 0.503(0.059) |
| Baboon  | 3195.5(36.1)   | 0.695(0.047) | 1536.0(158.4) | 0.211(0.109) | 0.332(0.047) | 0.458(0.149) |
| Sheep   | 2069.4(221.3)  | 0.865(0.018) | 1146.8(136.3) | 0.233(0.046) | 0.375(0.043) | 0.392(0.060) |
thesis. The ratios of the proximal cancellous bone area available below the head and greater trochanter \((A_3)\) to the total cancellous area \((A_6)\) were 0.378, 0.503, 0.458, and 0.392, respectively, for the human, dog, baboon, and sheep femora. Thus, the amount of cancellous bone in the proximal femur of the sheep, expressed by the ratio \((A_3/A_6)\) appears most similar to the human of all the species studied. The average values for the ratio \((R)\), defining the relative extent of cancellous bone along the length of a standard femoral stem, from the human, dog, baboon, and sheep femora were 0.43, 0.77, 0.70, and 0.25, respectively. The areas \(A_1\) and \(A_2\), although not used in the present analysis, are also documented in Table 2 for completeness.

**DISCUSSION**

In order to optimize an animal model for human total hip replacement, several criteria appear appropriate for animal selection. These include: \((1)\) femoral anatomy (external and internal) similar to the human; \((2)\) femoral size appropriate for reproducible total hip reconstruction techniques similar to those used in human practice, and large enough for later mechanical testing; \((3)\) vascular anatomy similar to the human; \((4)\) and the use of an animal active enough to stress the implant, docile enough to handle, and available for purchase and maintenance at a reasonable cost. Similarity of hip joint kinematics to the human would be ideal but impossible, since man is the only functionally bipedal primate. Thus, an appropriate nonhuman quadruped appears the necessary alternative. The animals included in this study were selected because they best fit the stated criteria.

This paper deals only with the femoral anatomy of different species relevant to hip joint replacements. The location of points of insertion of muscles (say, with respect to the center of the femoral head) are required to calculate moment arms and thereby loads they produce at the hip joint. The neck-shaft angle, neck height, diameter of the femoral head, and other dimensions of a femur determine the shape of the prosthesis. Similarly, the intermedullary canal width has to be kept in mind while arriving at the prosthesis cross-sectional shape. In essence the external anatomical parameters are essential for the scientific dimensional design of any prosthesis and for determining the loads which may be imposed on it. The *in vivo* performance of a prosthesis depends upon a number of factors (already discussed) including the amount of interlocking between cement and cancellous bone at the bone-cement interface. Thus, quantification of the cancellous bone distribution along the medullary canal is also a worthwhile parameter. The criteria for selection was to choose an animal (femora) possessing the closest similarity to the human femora anatomically. Such an animal, due to the above-mentioned reasons, would be more likely to simulate the *in vivo* prosthesis performance in comparison to other animals. The following discussion is based on this criteria.

The sheep bears the least similarity to the human in respect to external femoral anatomy. In contrast to the human femur, moreover, the sheep has a very smooth medullary canal extending as far proximal as the femoral neck. Although the amount of cancellous bone in the proximal femur of the sheep and human, proportional to overall size, is quite similar, a significant distributional difference exists, defined by the ratio \(R\); As a result, very little cancellous bone exists in the area required for medullary stem fixation in the sheep as compared to the human. With decreased longitudinal cancellous bone depth to permit acrylic interlock, the biomechanical environment and response to load stresses in this animal would predictably be different from that of the human. Because the length-to-width ratio
of the sheep femur at isthmus is so much smaller than the human, dog, and baboon, special custom-made femoral stems would be needed (at considerable expense) to adjust to this proportional difference. Commercially available canine total hip stems would extend beyond the isthmus of the sheep and take up relatively less medullary space. A greater cement to implant stem cross-sectional ratio would be required, introducing additional thermal and mechanical variables to the model.

The baboon was chosen for this study because, as a primate, it was expected to bear the greatest anatomical similarity to the human, as our data verify. The dog also fits the stated criteria. Both animals are therefore likely to generate loads similar to the human, at least in comparison to the sheep, at the hip joint and to stress the implant to study the in vivo response in a similar way. Both animals are of adequate size to yield test specimens for further analysis. These are currently in use as experimental models [18,19,20] to study behavior of bone-cement composites over time in total hip replacement. The choice of a particular animal would depend upon the availability of that animal and other economic factors. The baboon is relatively unavailable, expensive to purchase and maintain, and difficult to handle. On the other hand, the dog is a docile animal which is easily trained to exercise and is readily available at prices which are still acceptable. Also, considerable experimental work has been published describing the similarities between canine and human femoral blood supply [21,22]. Thus, the use of the dog as an experimental model appears justified anatomically at this time.

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