The effect of bone porosity on the shear strength of the bone–cement interface

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Abstract This study investigated the relationship of bone porosity and bone–cement interface shear strength. One hundred forty-six samples were taken from the distal metaphysis of 20 bovine femora. After cementation, the shear strength of the bone–cement interface was tested. According to the porosity, the samples were divided into four groups. Group I (porosity <80%) had a median interface shear strength of 4.03 MPa, group II (80% ≤porosity <85%) 7.06 MPa, group III (85% ≤porosity <90%) 9.44 MPa, and group IV (porosity ≥90%) 14.85 MPa. The differences between the four groups were statistically significant. Greater porosity yielded a stronger bone–cement interface shear strength under the identical cementation technique. The optimum porosity of cancellous bone is more than 90% which can be found by reaming or drilling to deeper bone in cemented acetabular fixation.

Résumé L'objet de cette étude est d'apprécier les relations entre la porosité osseuse et l'interface ciment-os. 146 échantillons osseux prélevés sur la métaphyse distale de 20 fémurs bovins ont permis de tester l'interface ciment-os après cimentation. suivant leur degré de porosité, les échantillons ont été divisés en 4 groupes. Groupe I porosité < 80% avec des forces, au niveau de l'interface de 4,03 MPa, groupe II porosité comprise entre 80 et 85% (7,06 MPa), groupe III

porosité comprise entre 85 et 90% (9,44 MPa) et groupe IV porosité inférieure à 90% (14,85 MPa). Les différences entre ces 4 groupes sont statistiquement significatives. une plus grande porosité permet l'application de forces plus importantes au niveau de l'interface ciment-os après cimentation. La porosité optimum au niveau de l'os spongieux doit être supérieur à 90% et cette porosité peut être augmentée par l'alésage et les trous d'ancrages au niveau de la zone de fixation acétabulaire.

Introduction

Aseptic loosening is the leading cause of failure in cemented arthroplasty. This type of loosening occurs because of movement at the bone–cement interface. These movements can be reduced by a stronger interlock between cement and host bone.

The bone–cement interface is a composite formed by bone and cement. The shear strength of polymethylmethacrylate (PMMA) bone cement is around 40 MPa and of bone between 3 and 10 MPa. Therefore the more cement that can be forced into host bone, the stronger the interface will be. The penetration of PMMA into bone depends on the available space, i.e. porosity. So the shear strength of the bone–cement interface is greater in cancellous rather than cortical bone [9].

Although the effect of cement viscosity, pressurisation, and bone bed cleanliness on the strength of the bone–cement interface have been investigated [10], the relationship between the bone porosity and the interface strength is not clear. In this study the relationship between the porosity of the cancellous bone and the shear strength of the interface is explored. If the optimal bone porosity can be

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established the strength of fixation of cemented implants could be improved.

Materials and methods

Twenty fresh bovine femora were collected and kept in physiological saline at room temperature. Fat pad, ligaments, and patella were removed. Four axial slices, each 3 cm in thickness, were taken from the distal metaphysis of each femur. Four cylindrical samples were obtained from each slice of bone using a crown drill bit with an inner diameter of 8.8 mm (CORB Needle Biopsy Set, Zimmer/Hall, Warsaw, Indiana, USA). Saline irrigation was employed during drilling to avoid thermal necrosis. In order to obtain samples with different porosities, one cylindrical sample was taken from the centre of the bone slice, one from near the cortex, and the other two from 1/3 and 2/3 of the distance between the centre of the bone slice and the cortex. All samples were kept in physiological saline at room temperature. The marrow fat and debris were removed using the pressurised lavage system.

The porosity of each core of cancellous bone was measured before cementation using digital photography and a purpose-built MATLAB (The MathWorks, Inc.) script. Initially, to check the validity of the digital imaging technique of porosity measurement against the reference standard (direct examination of the bone slices under microscope), 32 cylindrical samples of cancellous bone were prepared and the porosity of each was measured by these two methods. The agreement between the two was tested using the method of Bland and Altman [6]. In 99% of the time the porosity measured by digital method fell within 0.6% and 1.4% from that obtained by the reference standard.

Palacos R (Biomet Merck, Swindon, UK) bone cement was used. Sterile cement was mixed at 23°C and in accordance with the manufacturer's recommendations.

Each bone core sample was placed in a tight-fit hollow plastic cylinder. Bone cement was injected from the top and a tight-fit plunger was inserted to apply a constant pressure. PTFE lubricant spray (RS Components Ltd., Northants, UK) was used to prevent adherence of bone cement to the plastic. Samples were removed from the jig at 15 minutes and after 24 hours were placed in the metal jig of the DARTEC Series HC-10 (DARTEC Ltd, Stourbridge, England) shear testing machine.

Strain rate was set to 1 mm/s for 10 seconds (Toolkit 96 software). This was considered as the distance needed to break an 8.8 mm sample. The load applied (kN) and the displacement (mm) were recorded (5,000 data points for each experiment). Each experiment was continued for 10 seconds when invariably all samples failed under shear. A

Fig. 1 Load–displacement. The maximum load in kN and the corresponding displacement was noted and the ultimate shear strength was calculated

load–displacement curve was drawn to check the overall relationship of the two (Fig. 1).

Statistical methods

The normality of the distribution of the data was tested with skewness, kurtosis, omnibus, and modified Levene equal variance tests and it was unanimously rejected. Therefore the use of nonparametric statistical tools was deemed appropriate.

The Kruskal-Wallis test was employed to investigate the existence of a difference between the groups. To locate the actual difference, the Mann-Whitney nonparametric test was used. Bonferroni correction was performed in order to

Table 1 Excluded samples from study

Description of discarded samples
Those with bone thermal necrosis during drilling despite the cooling lavage system
Inadequate cylindrical sample length (the minimum acceptable was 1 cm)
Inadequate sample width (less than 8.8 mm)
Mechanical failure during removal from the crown-drill coring device (using the provided obturator)
Failure of very thin trabeculae during pressurised lavage for cleaning of the sample
Mechanical failure during handling

Table 2 Mechanical properties of the bone–cement interface in the four groups

Property	Group 1	Group 2	Group 3	Group 4
Porosity	<80%	80≤ porosity <85%	85≤ porosity <90%	≥90%
Number of samples	38	37	35	36
Median shear strength (MPa)	4.03	7.06	9.44	14.85
Range of shear strength (MPa)	0.01–5.63	5.47–8.05	7.92–11.8	10.85–82.69

avoid a type I error when multiple comparisons between the four groups were made.

A pilot study with ten cemented bone samples showed a standard deviation of the shear strength of 2 MPa. With a power of 0.8 and a significance level of 0.05, 30 samples were needed in each group in order to show a 2 MPa difference (priori definition) of shear strength between the groups. The pilot study also revealed that the porosity of the samples were close together and could be best divided into four distinct groups: porosity <80%, 80≤ porosity <85%, 85≤ porosity <90%, and porosity ≥90%.

Results

From the initial 20 bovine femora, 320 cylindrical samples of bone were obtained. One hundred and forty-two defective samples were discarded (Table 1).

Following cementation another 32 samples failed during removal from the cementation jig or preparation. This left a final number of 146 intact cemented samples for shear testing. The samples were divided into four groups according to their porosity, as guided by the pilot study (Table 2).

The porosity related to the anatomical location of the sample. Porosity decreased circumferentially with the most porous being central and the least subchondral.

The differences in the shear strength of the interface in the four study groups were all statistically significant (Table 3).

Therefore it can be concluded that more porous bone will create stronger bone–cement interface shear strength under the same cementation technique.

Discussion

The employment of a digital image analysis technique for the measurement of bone porosity was the key success factor in this study. This method is sample preserving as it eliminates the need to interfere with the normal structure of the bone (cutting, merging into the mercury, etc.). It is reliable and has strong agreement with the reference standard. There is no intra-observer error of measurement as repeated measurements are on the same image with the same script, leading to the same result.

Literature review shows that the effect of the cancellous bone porosity on the shear strength of the bone–cement interface had not been previously examined. This is probably due to technical difficulties with regards to direct noninvasive measurement of the bone porosity. The available methods are destructive, experimental and expensive, or alter the mechanical properties of the bone before

Table 3 Summary of statistical tests used

Groups	Value ^a	<i>p</i> value ^b
Kruskal-Wallis	135.92	<0.0001
Mann-Whitney between groups 1 & 2	7.45	<0.0001
Mann-Whitney between groups 1 & 3	7.34	<0.0001
Mann-Whitney between groups 1 & 4	7.4	<0.0001
Mann-Whitney between groups 2 & 3	7.3	<0.0001
Mann-Whitney between groups 2 & 4	7.34	<0.0001
Mann-Whitney between groups 3 & 4	7.25	<0.0001

^a Test statistic value

^b All *p* values mentioned are after Bonferroni correction for multiple comparisons. The differences between all groups are statistically significant

Table 4 The shear strength of the bone–cement interface as reported in the literature

Study	Interface shear strength (MPa)
Köbel et al. (1976) [14]	5.35±0.89
Halawa et al. (1978) [10]	4–7 (range)
Krause et al. (1982) [15]	41.99±5.89
Bean et al. (1987) [5]	6–15 (range)
Dohmae et al. (1988) [9]	4–11 (range)
Bannister et al. (1988) [4]	2–10 (range)
Bugbee et al. (1992) [7]	5–7 (range)
Majkowski et al. (1993) [16]	35.7±3.9
Balu et al. (1994) [3]	2.93±0.95

cementation. With the help of the digital photography method employed in this study, measurement of the bone porosity without destroying the sample became possible.

The results of the shear strength of the bone–cement interface vary due to the specimen selection, the geometry, preparation techniques employed [4], and the porosity of the bone (Table 4). The overall shear strength is higher than tensile strength.

The third generation cementing technique is associated with lower rates of aseptic loosening. This almost certainly applies more to the femur where cement is compressed into increasingly dense bone, ultimately as far as the cortex. The effect in the acetabulum is less convincing as bone becomes more porous and weaker the further it is from the subchondral region. There must come a point where there is so much cement at the bone–cement interface that it is stronger than host bone. At this point, increasing strength of the bone–cement interface is theoretically disadvantageous as it creates a stress riser that may cause fracture of bone trabeculae.

In the case of a cemented acetabular cup, multiple keyholes in the subchondral bone [8, 12, 13] and a flanged cup [11] improve the survival rate. From the mechanical point of view removal of the cartilage and clearance of the fovea [1, 18] increase the torsional stability of the cup. Reading et al. showed that up to six drill holes prior to cementation increase the torsional strength if the diameter of the drill holes is 1 cm [17]. The issue is whether deeper reaming and exposure of more porous cancellous bone increases the survival of the cup.

With more reaming of the acetabulum, more porous bone bed can be exposed. This not only increases the penetration of the cement to the bone bed, but also increases the surface area of the bone bed and the overall contact area of the cement and the bone. These two elements together increase the strength of the bone–cement interface. In clinical situations there are two major drawbacks when deep reaming is performed: the risk of pelvic penetration and the reduction of the available bone stock should the revision become necessary.

The more porous the bone bed the greater is the amount of cement penetration and the interface shear strength. What is unknown in vivo is whether mechanical failure will be avoided at the bone–cement interface at the expense of fracture of the adjacent weak porous bone [2].

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