The effect of surface finish and interstitial fluid on the cement-in-cement interface in revision surgery of the hip

The mechanical performance of the cement-in-cement interface in revision surgery has not been fully investigated. The quantitative effect posed by interstitial fluids and roughening of the primary mantle remains unclear. We have analysed the strength of the bilaminar cement-bone interface after exposure of the surface of the primary mantle to roughening and fluid interference. The end surfaces of cylindrical blocks of cement were machined smooth (Ra = 200 nm) or rough (Ra = 5 μm) and exposed to either different volumes of water and carboxymethylcellulose (a bone-marrow equivalent) or left dry. Secondary blocks were cast against the modelled surface. Monoblocks of cement were used as a control group. The porosity of the samples was investigated using micro-CT. Samples were exposed to a single shearing force to failure.

The mean failure load of the monoblock control was 5.63 kN (95% confidence interval (CI) 5.17 to 6.08) with an estimated shear strength of 36 MPa. When small volumes of any fluid or large volumes were used, the respective values fell between 4.66 kN and 4.84 kN with no significant difference irrespective of roughening (p > 0.05). Large volumes of carboxymethylcellulose significantly weakened the interface. Roughening in this group significantly increased the strength with failure loads of 2.80 kN (95% CI 2.37 to 3.21) compared with 0.86 kN (95% CI 0.43 to 1.27) in the smooth variant. Roughening of the primary mantle may not therefore be as crucial as has been previously thought in clinically relevant circumstances.

The number of revision procedures for total hip replacement, including those which are primarily cemented, is increasing. It has been estimated that by 2030 the rate of revision carried out in the United States will increase by 137% compared with the current decade. With revision of a cemented stem, removal of the entire old cement mantle is a time-consuming process exposing the patient to considerable blood loss and, with decreasing bone stock, posing a high risk of proximal femoral fracture. The strength of the bond between the remaining bone and the new cement after revision is significantly lowered, raising the question whether removal of the whole of the old cement mantle is acceptable. In selected cases the performance of a cement-in-cement revision could diminish such risks. However, this technique is still used relatively rarely because of controversy regarding some of its aspects. Some authors have suggested that absolute dryness cannot be achieved. Li et al explored a clinically rare situation when the primary mantle canal was flooded with high-viscosity bone marrow. They claimed that the strength of the bilaminar cement decreased by 80% compared with a cement monoblock. The implementation of modern drying techniques before and during secondary cementing leaves relatively small volumes of fluid to interfere with the procedure. However, absolute dryness may not be achievable in some cases. This poses the question as to whether any volume of fluid left on the primary surface of the mantle should be regarded as unacceptable with this technique. We are not aware that the quantitative effect of interstitial fluid on the strength of the cement-in-cement interface has been investigated previously.

Since the original description of the method by Greenwald et al., many authors have recommended roughening of the primary surface of the mantle so that the bond can be increased at the microscopic level.
Whenever reaming of the primary mantle canal is required to accommodate the secondary stem, roughening is unavoidable, but this may destroy the primary mantle or cement-bone interface leading to early loosening. There are no published data which quantify the effect of roughening on the strength of the cement-in-cement interface. It is not known whether roughening plays any role in the presence of interstitial fluid. Since more recent clinical studies seem to be uncertain on this issue, further mechanical evidence is necessary to justify a possible change to the technique of cementing.

We therefore examined the mechanical aspects of the cement-in-cement technique using a laboratory model. Our objectives were to determine the strength of the interface created on the base of a raw and roughened primary mantle surface. The effects of the interstitial fluid and the roughness of the surface of the primary mantle were investigated.

Materials and Methods

A cement-in-cement laboratory model was developed in which the primary surface was created on one end of cylindrical blocks of polymethylmethacrylate cement (PMMA). These were then machined to reproduce either smooth or rough variants representing the surface finish of either a raw or reamed surface of the primary mantle. The surface was either left dry or coated with one of two volumes of either low- or high- viscosity fluid. The secondary cement was cast against the modelled surface so that the junction between them formed the cement-in-cement interspace. Specimens used in this study were created with a wedged indentation around the whole circumference of the cylindrical sample at the cement-in-cement interface in order to both increase the stress in this region and to reduce the likelihood of failure initiated at a pore in the body of the cement.

The porosity of the samples at the interface was assessed and the strength of the interface determined by measuring the stress at failure under shear loading. Further details of all the procedures are given below.

The surface finish of the primary mantle. Using a third-generation cementing technique, six replicates of a standard primary cement mantle interface were created using a standard polished Exeter stem (Stryker, Newbury, United Kingdom) implanted into artificial femora (Sawbones, Malmo, Sweden) at 23°C ± 1°C. The stems were extracted 24 hours later. The femora were randomly divided into Malmo, Sweden) at 23°C ± 1°C. The stems were extracted Kingdom) implanted into artificial femora (Sawbones, standard polished Exeter stem (Stryker, Newbury, United Kingdom) and the mean value was estimated within France) while the smooth group was left unreamed. All the procedures are given below.

The surface finish of the primary mantle. Using a third-generation cementing technique, six replicates of a standard primary cement mantle interface were created using a standard polished Exeter stem (Stryker, Newbury, United Kingdom) implanted into artificial femora (Sawbones, Malmo, Sweden) at 23°C ± 1°C. The stems were extracted 24 hours later. The femora were randomly divided into two groups, ‘rough’ and ‘smooth’, with three samples in each. The cement mantles of the rough group were reamed using flexible reamers (Stryker, Hérouville-Saint-Clair, France) while the smooth group was left unreamed. All the femora and contained mantles were split in half to allow characterisation of the surface finish. Four measurements of surface roughness (Ra) were taken from each sample with a total of 12 measurements per mantle, using a Talsysurf 120L profilometer (Taylor-Hobson, Leicester, United Kingdom) and the mean value was estimated within the groups. These values were used to reproduce the smooth and roughened surfaces of the primary mantle in the laboratory models.

Creation of the primary surface model. Surgical Simplex P cement with 10% barium sulphate (Stryker, Limerick, Ireland) was used for all the tests. Mixing was performed at a speed of 1 Hz under a vacuum of 74 kPa in a bowl. The environmental temperature was kept at 12°C ± 1°C. In order to model the primary surface of the mantle, cylindrical blocks of cement of 25 mm in diameter, with a neck of diameter 20 mm at one end, were cast. During this step, cement was used in its doughy phase at three minutes from the start of mixing, and was applied in the mould in a retrograde fashion with a gun. The samples were cured for 24 hours in a dry environment at 23°C ± 1°C.

The flat surface at the necked end of each specimen was then machined using a lathe (Hardinge Machine Tools, Leicester, United Kingdom) so that the highest possible uniformity across each group could be guaranteed. Different rotary speeds and traverse rates of the tool were used to create a spectrum of surface finishes. Six samples per variant were created and the surface finish measured on each specimen. The mean value of each group was calculated and compared against the primary surface finish for smooth and roughened mantles obtained previously. Using this information, further sets of smooth and rough samples were machined using the lathe settings for the surface finish closest to the mean of the smooth and roughened mantles, respectively. A flat interface surface was used in order to avoid the potentially confounding factor of the shape of the stem.

Viscosity of the interstitial fluid. The influence of fluid was examined by injecting liquid onto the modelled interface before casting the secondary cement block. Two fluids of different viscosity were used; distilled water (viscosity $\eta_{H_2O} = 0.89$ mPas at 25°C) and a 2% solution of carboxymethylcellulose in water (CMC, $M_w \sim 250$ 000; Sigma-Aldrich, Gillingham, United Kingdom) representing in the environment of the experiment (25°C) the viscosity of bone marrow at body temperature ($\eta_{CMC} = 400$ mPas).

Volume of the interstitial fluid. Two volumes of each fluid were also examined; 0.02 ml/cm² which is sufficient to cause a thin surface film over the investigated surface and 0.4 ml/cm² which allows the surface to be completely submerged. These were compared against dry examples. Monoblock specimens, created by casting the entire notched cylinder in one step, were produced to act as an internal control group.

The secondary mantle. In order to model the bila minar cement mantle, another block of the same dimensions was cast against the neck end of the first to create the specimen shown in Figure 1. A mould insert was used to create a narrower cross-section within the secondary cylinder at the end in contact with the primary cement. This arrangement ensured that the interface was at the narrowest cross-sectional area of the specimen, providing a stress concentration across the interface during the strength...
testing performed later. The cement was poured into the mould in its liquid phase at between 90 and 120 seconds after the start of mixing to allow for an optimal interfacial bond.\textsuperscript{4,5,7,13-15} Samples were removed from the moulds after curing for 24 hours in a dry environment at 23°C ± 1°C and then tested.\textsuperscript{19}

Investigated variants. Nine sets of specimens were investigated: monoblock control (M), smooth dry (SD), roughened dry (RD), smooth with small CMC volume (SW), roughened with small CMC volume (RW), smooth with large water volume (SWL), roughened with large water volume (RWL), smooth with large CMC volume (SCL) and rough with large CMC volume (RCL). Specimens with a small volume of water were not tested since the results indicated that these would be unlikely to change the experimental outcome. Seven specimens were used in each group.

Interface strength. All the specimens were loaded under shear to failure (Fig. 1) in the air at 23°C ± 1°C, at a speed of 1 mm/min using a materials testing machine (Autograph AGS; Shimadzu, Kyoto, Japan). The force to failure and strain were determined from the load-displacement data recorded during testing and compared between the groups. Because of the shape of the specimens and the method of clamping, a small component of bending across the interface was added to the region of the neck. In order to understand the stresses at the interface level and to make comparisons with published results, investigating models under pure shear, a linearly elastic finite-element model of the specimen was generated using ABAQUUS version 6.9 software (Simulia, Providence, Rhode Island). The experimental clamping and loading were replicated. The finite-element model was meshed with linear hexahedral and tetrahedral elements. A mesh convergence study was performed to assess the density of the mesh required to extract the maximum stress at the interface. The maximum shear stress was then compared with the value calculated by assuming pure shear at the interface and a correction factor determined.

Micro-CT analysis of the interface and interstitial fluids. The interface of one specimen from each of the sets with large volumes of fluid (SWL, RWL, SCL and RCL) was investigated using micro-CT. The specimens were imaged at a resolution of 74 μm (Scanco μCT80; Scanco Medical, Brüttisellen, Switzerland). Cylindrical regions of interest of 17.8 mm in diameter and 10 mm in length were defined across the interface. All the images were segmented using a constant threshold followed by porosity calculation.

Statistical analysis. The strength test results were compared by using one-way analysis of variance (ANOVA), the distribution of the variables investigated being checked using Kolmogorov-Smirnov and Lilliefors tests, followed by post hoc analysis and power calculations. A p-value ≤ 0.05 was considered to represent a statistically significant difference.

Results
Primary mantle surface finish. The surface finish of the primary cement mantle after removal of the highly polished Exeter stem had a mean Ra value of 0.19 μm (95% confidence interval (CI) 0.14 to 0.24). Exposure of such a surface to the powerful burr altered the surface roughness to a mean Ra of 3.40 μm (95% CI 2.90 to 3.90).

Modelling the primary surface finish. Use of the lathe allowed for the creation of samples with a lowest mean Ra of 0.21 μm (95% CI 0.19 to 0.22). The highest practical roughness which could be achieved using the lathe was 5.42 μm (95% CI 5.03 to 5.81).
Interface strength. From the finite-element model, the maximum shear stress at the interface level was found to be approximately 1.8 times that calculated by assuming pure shear, i.e., by dividing the applied force by the interface cross-sectional area. This method was then used to estimate the shear strength of the specimens from the measured force at failure.

In the smooth variant with a large volume of CMC (SCL group), the fluid prevented bonding completely in two cases and significantly weakened the other samples with a mean force at failure of 0.86 kN and an estimated shear strength of 5 MPa. In the roughened variant (RCL), the same amount of viscous fluid allowed for a level of force at failure of 2.80 kN, with an estimated shear strength of 18 MPa. The difference between these two groups was statistically significant (p = 0.02).

The large volume of CMC groups, both smooth and rough, were significantly weaker compared with all other investigated groups and the monoblock control. No significant difference in the resistance to shear was observed between the latter groups including those with high volumes of water (p = 0.12 to 1.00). In these cases, roughening of the surface did not change the strength of the interface significantly (p = 0.99 to 1.00) and failure did not occur along the line of the interface in any single sample. While the monoblock showed the highest resistance to shear with a mean force at failure of 5.63 kN and an estimated shear strength of 36 MPa, the difference was not statistically significant (p = 0.12 to 0.51) unless compared against the high volume of CMC groups. These observations are summarised in Table I and Figure 2.

Power calculations for the one-way ANOVA results obtained in our study showed a value of 0.9999 at α = 0.05.

Micro-CT analysis. The porosity of the specimens measured using micro-CT, as measured from the two-dimensional image slices, is shown in Figure 3. The porosity across the interface was found to be similar or smaller than that over a larger section of the specimen for the roughened specimen with CMC and both rough and smooth specimens with water as the interstitial fluid. However, the specimen with the smooth interface and a large volume of CMC had a rise in porosity at the interface which could clearly be seen as a large region without bonding in the transverse image slices (Fig. 4). This agreed with the strength studies and indicated that the large volume of viscous CMC solution prevented the two cement surfaces from fully bonding.

Discussion
Our aim was to investigate the effect of the fluid present at the application of secondary cement during cement-in-cement

### Table I. Comparison of an average breaking force (kN, mean and CI) among all the investigated variants

<table>
<thead>
<tr>
<th></th>
<th>Smooth</th>
<th>Rough</th>
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<tbody>
<tr>
<td>No fluid</td>
<td>M 5.63 (5.17 to 6.08)</td>
<td>SD 4.77 (4.34 to 5.19)</td>
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<tr>
<td>Small volume of fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>N/A†</td>
<td>Not tested‡</td>
</tr>
<tr>
<td>2% CMC</td>
<td>N/A</td>
<td>SW 4.66 (4.2 to 5.11)</td>
</tr>
<tr>
<td>Large volume of fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>N/A</td>
<td>SWL 4.83 (4.41 to 5.25)</td>
</tr>
<tr>
<td>2% CMC</td>
<td>N/A</td>
<td>SCL 0.86 (0.43 to 1.27)</td>
</tr>
</tbody>
</table>

* M, monoblock control; SD, smooth dry; RD, roughened dry; SW, smooth with small volume of CMC in water; RW, roughened with small volume of CMC in water; SWL, smooth with large water volume; RWL, roughened with large water volume; SCL, smooth with large CMC volume; RCL, rough with large CMC volume
† N/A, not available
‡ in the course of experiment this variant proved to add no further information and was not tested
The revision of the hip and to quantify the relationship between
the volume and viscosity of the fluid and the shear strength of
the bilaminar cement. The effect that roughening of the pri-
mary mantle may have posed on the overall strength of this
construct was also studied. The behaviour of the cement-in-
cement bond was examined across a regular flat interface in
order to isolate the factors influencing its strength from other
parameters observed clinically.

The laboratory model used in our study was not
intended to represent fully the conditions
in vivo. For example, the potential influence of the biological environ-
ment on the primary surface of the mantle was not taken
into account. Biological factors acting over the years may
change the chemical potential of the primary surface, such
as the availability of the polymethylmethacrylate mono-
mer necessary for bonding with the secondary cement.14
Potential corrosion of the stem and a related electro-
chemical influence on the surface of the primary mantle
may also have an effect.23

A single load to failure was used in our experiments to
compare the different variants of the bilaminar cement
interface. While the loading in vivo would be cyclical, it
was assumed that the single load would yield proportion-
ally similar results because the strength of such a construct
would be related to the extent of the polymerisation
between the two layers of cement. The observed effect at
the interface was also expected to be comparable, irrespec-
tive of the test to failure used.

Standardised fluids were used in our study because sam-

dles of blood or bone marrow, possibly coming from differ-
ent donors, were likely to differ, adding unnecessary

variability which could have affected the final data and
their interpretation. Previous studies have used a number
of analogue materials to represent the marrow.24,25 We
selected CMC because the viscosity could be controlled and
maintained at a constant value across all of the tests in the
standardised environment of our experiment.26

Despite its limitations, our model was a valid experi-
mental tool which allowed comparison between specimens with
different conditions at the interface and with previously
published studies having similar methods.12,13,15,16

In our study monoblock controls were found to fail with
a mean load of 5.63 kN. The corresponding shear stress at
failure occurring at the interface level was estimated to be
36 MPa and was consistent with observations by other
authors which range from 30 MPa to 42 MPa.12-16

Contrary to findings of Li et al,13 only large amounts of
highly viscous fluid, such as the CMC representing bone
marrow, were found to significantly weaken the cement-in-
cement interface. Dry or low-viscosity variants showed
some decrease of strength compared with the control, but
the difference failed to reach statistical significance. This
suggested that the avoidance of the accumulation of a vis-
cous fluid at the surface, or its elimination by copious irri-
gation with water, prevented significant weakening of the
bond. The limited effect of the low-viscosity fluid could be
explained by its relatively easy escape during the applica-
tion of the secondary cement. This is likely to occur in clin-
ical practice with the use of a cement gun, when the nozzle
and cement slowly advance in a retrograde fashion within
the femoral canal or the old mantle. This effect could be
reinforced by the careful use of a suction drain.

Our study showed that a high level of roughening could
be beneficial only when viscous fluid could not be elimi-
nated. Then the force to break the weakest samples in the
roughened variant never dropped below 1.6 kN, with the
strongest sample in the smooth counterpart group breaking
at a load of 1.4 kN. The mean estimated stresses to failure
of the two groups were 18 MPa and 5 MPa respectively.
Importantly, a number of samples in the smooth variant

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**Fig. 3**

Graph showing the porosity measurements from micro-CT image slices as a function of the position in the specimen. SWL, smooth with large water volume; RWL, roughened with large water volume; SCL, smooth with large volume of carboxymethylcellulose (CMC); RCL, roughened with large CMC volume.

**Fig. 4**

Micro-CT image of the SCL sample at the interface showing a large region without bonding (arrow).
failed to bond at all. Roughening created in this group allowed for strengths above the 3 MPa which have been reported in the proximal femur after completely renewing the cement at the first revision, suggesting the benefit of this technique compared with revision to all-new cement.\textsuperscript{4,10} The beneficial effect of roughening in the presence of viscous fluid did not prevent a decrease of 50% in the interfacial strength compared with monoblock control or even the variant with a large volume of low-viscosity fluid. Purposeful roughening of the old mantle added little benefit. This contradicted previous recommendations.\textsuperscript{2,4-7,11,12,14,17}

Roughening is likely to damage the old cement because high-power tools are required. Therefore, widening of the primary mantle canal to accommodate a new stem is probably the only exception which justifies this process, as has been observed by Duncan et al.\textsuperscript{8}

The results obtained from the load-to-failure study were confirmed by analysis of porosity. This reinforced the low predictability of the results when the bilaminar cement technique was used in the presence of large quantities of viscous fluids. Large defects at the interface level were present in the smooth variant, while some samples in the roughened group showed relatively low levels of porosity. This highlighted that the cement-in-cement technique should only be executed when removal of viscous fluids is guaranteed.

Revision using the old cement is not a new concept, and the technique is finding more advocates as suggested by the clinical mid-term results published in recent years.\textsuperscript{4-8,11,17} It is being recommended in selected patients requiring revision of the cemented stem in the presence of a well-preserved cement-bone interface. It is likely to be safe when care is taken to replace the bone marrow and to prevent damage to the old cement and the underlying bone.

When the primary mantle is being dried slight residual moisture is unlikely to jeopardise the safety of the procedure. A small amount of fluid, especially that of low viscosity, has little effect on the bilaminar cement bond. Even then sound biomechanical results can be achieved, especially when compared with procedures which involve revising the entire cement. Despite this observation care should still be taken when this step of the revision surgery is taking place.

Investigation using models with more representative curved surfaces and cyclic loading, especially in a biological environment, are now recommended to validate further the use of the cement-in-cement technique of revision.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References