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HIP

The damping effect of cement as a potential mitigation factor of squeaking in ceramic-on-ceramic total hip arthroplasty

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Objectives
Studies reporting specifically on squeaking in total hip arthroplasty have focused on cementless, and not on hybrid, fixation. We hypothesised that the cement mantle of the femur might have a damping effect on the sound transmitted through the metal stem. The objective of this study was to test the effect of cement on sound propagation along different stem designs and under different fixation conditions.

Methods
An *in vitro* model for sound detection, composed of a mechanical suspension structure and a sound-registering electronic assembly, was designed. A pulse of sound in the audible range was propagated along bare stems and stems implanted in cadaveric bone femurs with and without cement. Two stems of different alloy and geometry were compared.

Results
The magnitudes of the maximum amplitudes of the bare stem were in the range of 10.8 V to 11.8 V, whereas the amplitudes for the same stems with a cement mantle in a cadaveric bone decreased to 0.3 V to 0.7 V, implying a pulse-attenuation efficiency of greater than 97%. The same magnitude is close to 40% when the comparison is made against stems implanted in cadaveric bone femurs without cement.

Conclusion
The *in vitro* model presented here has shown that the cement had a remarkable effect on sound attenuation and a strong energy absorption in cement mantle and bone. The visco-elastic properties of cement can contribute to the dissipation of vibro-acoustic energy, thus preventing hip prostheses from squeaking. This could explain, at least in part, the lack of reports of squeaking when hybrid fixation is used.

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Article focus
- Study the effect of cement on squeaking incidence in ceramic-on-ceramic total hip arthroplasty.
- The hypothesis is that the visco-elastic properties of cement could contribute to the dissipation of vibro-acoustic energy, thereby damping sound propagation, and thus preventing hip prostheses from squeaking.
- We designed an *in vitro* model to test the effect of cement on sound propagation along different stem designs and under different fixation conditions.

Key messages
- The *in vitro* model presented here has shown that the cement had a remarkable effect on sound attenuation and a strong energy absorption in cement mantle and bone.
- In this setting, the cement mantle had a marked effect on sound attenuation and behaved as a strong energy buffer.
- The cement mantle at the femoral side has great potential to suppress squeaking.

- This new information could explain the lack of reports of squeaking when hybrid fixation is used and could became part of the decision-making process about the best fixation method for a patient for whom ceramic-on-ceramic is determined to have clear benefits.

Strengths and limitations

- Strengths: This is the first research that explores the influence of the cement mantle on squeaking using acoustic emission principles.
- The *in vitro* measurement setup used was able to detect transmitted energy of less than 1% in the stems implanted with cement compared with 62% in the stems implanted without cement.
- Limitations: *In vitro* test where variables like biological live tissue, water and different cement mantle qualities have not been considered and have clear potential to affect sound transmission.

Introduction

Alumina ceramic bearings have been reported to reduce or eliminate wear problems with replacement joints, and are associated with good long-term clinical performance.[1] However, a small number of patients have reported audible sounds, a condition that has been termed 'squeaking hip'.[2,3] In isolated cases, the squeaking has been intolerable to patients, necessitating revision.[4,5] With a prevalence varying from less than 3% up to 20%, this phenomenon is currently recognised as a new mode of clinical failure for ceramic bearings.[2,6]

The aetiology of squeaking is associated with several factors: patient demographics (weight, height, male gender); implant design (geometric features, neck size, metallic alloys); loading conditions (bearing surface clearance and acetabular orientation); and the natural vibration frequencies of the components.[7-14]

Regarding components, the femoral stem and its design have been found to have an important influence on the incidence and characteristics of squeaking in total hip prostheses.[8,15]

The incidence of audible sounds in series assessing implants when cemented stems are combined with ceramic bearings has been reported as less than 1%, and in some cases, this complication was not reported at all.[16-19] By contrast, the majority of reports of a squeaking hip have involved non-cemented fixation.[2,6]

It is known that discontinuities in sound-propagation media, such as change in density or mechanical properties (e.g. tensile strength, elastic module or tensile stresses), presence of material defects (e.g. pores, cracks or impurities), and water content, are responsible for variations in sound speed and its dispersion.[20] According to these principles, factors such as the interface conditions between the components, environmental influences (e.g. bone ingrowth or cement layers), lubrication and contact areas should play a major role in sound propagation.

To date, the effect of cement on squeaking in ceramic-on-ceramic total hip arthroplasty devices has not been considered. We hypothesised that the cement mantle might have a damping effect on the sound transmitted through the metal stem. To test this hypothesis, we designed a model in which a pulse of sound in the audible range was propagated along the stem under three different conditions of material interfaces, using a bare metal stem, a stem implanted without cement in a cadaveric bone femur and a stem cemented in a cadaveric bone femur.

Materials and Methods

Assessment of the effect of cement on sound propagation. To test the damping effect of cement on sound propagation, an experimental study was conducted. Five pairs of fresh human cadaver femurs of five male donors aged > 75 years were thawed at room temperature (20°C) prior to preparation and implantation of the stems. The soft tissues and the periosteal layer were thoroughly debrided. Conventional anteroposterior and mediolateral radiographs were taken from all specimens excluding pre-existing pathology or fracture sequelae.

Two different prosthetic stem designs were selected. The first was a polished tapering cemented stem (Exeter NR; Stryker Orthopaedics, Mahwah, New Jersey), and the second was a non-cemented design stem (Accolade; Stryker Orthopaedics), for which there is existing evidence of a higher incidence (11%) of squeaking hip.[15,21]

Measurements of sound attenuation were taken using the following methodology: the first two measurements on two different positions (proximal and distal) were taken on each bare stem design (Accolade and Exeter). For each pair of cadaveric bone femurs the protocol was the same. The Accolade stem was implanted without cement in a cadaveric bone femur and three different measurements were taken at the proximal, medial and distal positions. Using the same specimen, the Accolade stem was implanted with cement and the same measurement strategy was carried out. This methodology was repeated with the corresponding cadaveric pair specimen using the Exeter stem.

The cementing technique was performed by the same operator using Simplex cement at room temperature (23°C) for both stem designs. This included sealing the intramedullary canal with an ultra-high molecular-weight polyethylene (UHMWPE) bone plug, hand mixing the cement, washing and drying the femoral canal and finger packing the cement. Cementless fixation of the Accolade stem was accomplished following the conventional technique proposed by the manufacturers. In the case of the Exeter stem, cementless fixation was achieved by using a stem of larger size than of the last rasp used to prepare the femur.

Consequently, this experimental design first required two sets of measurements on each bare stem type.

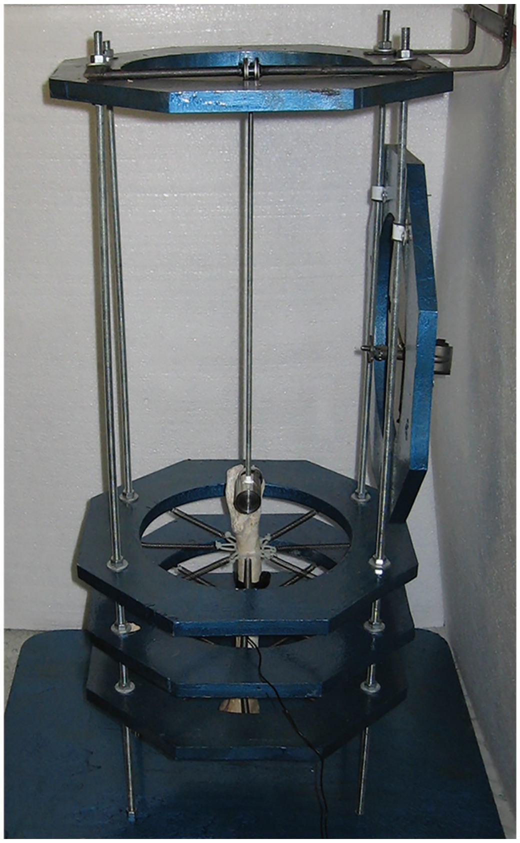

Fig. 1a

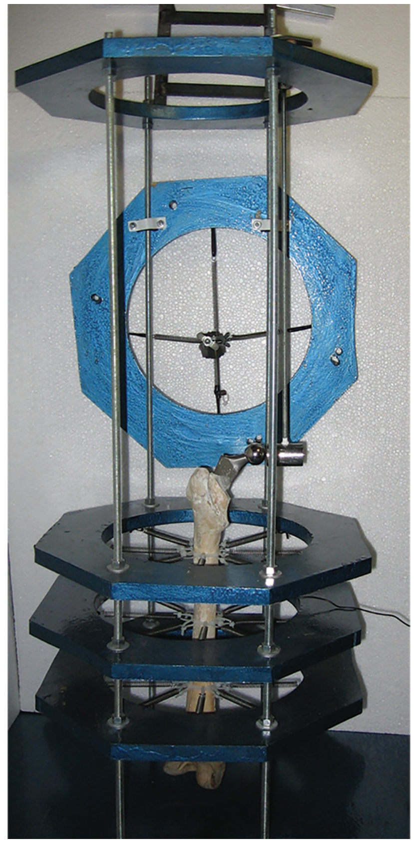

Fig. 1b

Photographs showing a) front view of the setup with the three octagonal rings supported by four roads and a stem implanted in a cadaveric bone femur aligned at the centre of the rings; and b) lateral view of the setup.

Second, the sound attenuation was calculated for each stem design. In total, 30 measurements were taken, 15 with the stem implanted using cement and 15 without cement. Therefore, 64 measurements were conducted.

The setup for sound detection was composed of a mechanical suspension structure (MS) and a sound-registering electronic assembly (SA). The MS was built with three wooden octagonal rings, with both the bare stem and the stem implanted in a cadaveric femur (with or without cement) fitted to eight springs (10 mm in diameter and more than 200 mm long), radially distributed with respect to the axis of the stem or the femoral medullary canal. Each spring was fitted to the metal stem or femur diaphysis using plastic straps, while the opposite spring end was fixed to the octagonal rings and kept under strain by a screw mechanism bolted to these rings. This ensemble allowed centring of the prosthesis, and equilibrated the forces applied to it. Each octagonal ring was supported by four threaded rods (9.5 mm in diameter) fixed to an anti-vibratory wood base (20 × 700 × 700 mm^3) (Fig. 1). This elastic structure avoided the production of unwanted vibrations or damping effects generated by rigid supports, which could have interfered with the measurements.

The measurement protocol consisted of excitation of the metal femoral head assembled on the femoral stem, using a physical pendulum strike. The resultant mechanical pulse travelled along the femoral stem, and was detected by a piezoelectric device (PD), with a high-sensitivity violin microphone (WCP-60V; Cherub Technology Inc., Arcadia, California), with the PD clamped to the implant or bone in the appropriate measurement position (proximal, medial or distal). The PD was responsible for transduction of a mechanical vibration into an electrical pulse. Furthermore, the signal generated was amplified by an audio amplifier (AA) designed and built in our laboratory, which has a working frequency range of 0.4 kHz to 20 kHz and an amplification factor of 10. All spurious electrical signals generated by laboratory lighting and power were eliminated by electronic filters.

The amplified electrical pulses were filtered using an audio recording console (RC) (M616EXUSB; Yamaha, Tokyo, Japan) in serial connection with a passive 31-band equaliser (Behringer USA Inc., Bothell, Washington). Finally, the signals were captured by a 60 MHz digital oscilloscope (DO) (SDS6062; Owon, Xiamen, China) and transmitted to a personal computer (PC). This allowed a time resolution of better than one or five microseconds, respectively, for stems implanted in the femur or bare stem. When the pendulum strikes the metal femoral head, it generates a soundtrack and an electric pulse which are similar in relative amplitudes and temporal duration. The temporal duration covers a range close to 1.4 ms, on the bare stem, and 0.3 ms on the femur. The pulses are composed of several peaks and troughs.

The reproducibility of electric and sound pulses was verified by comparing the magnitudes of digitally captured electric and sound pulses on each kind of measurement. The registered soundtrack and electric pulses are analysed and filtered by means of Cool Edit Pro (Syntrillium, Scottsdale, Arizona) and MATLAB R2011 (MathWorks Inc., Natick, Massachusetts) software, respectively. The calculations, signal comparisons and statistics are performed with Origin version 8.0 software (OriginLab, Northampton, Massachusetts) A 'cleaned' signal is produced by filtering the noisy signal with a narrow band filter ranging from 20 Hz to 52 Hz.

Calculations. The pendulum stroke on the metal femoral head generates a mechanical pulse. This comprises local forces and strains applied to material media (prosthesis, bone cement, trapped air, and bone) in which the pulse propagation takes place. The succession of stresses and compressions develops during a time interval (t_P), which is the pulse width. The strain fluctuation can be measured by means of the PD, which produces an electrical pulse of amplitude ($A(t)$), measured in volts. This magnitude must be involved in the attenuation experienced by the pulse during its propagation, caused by several energy-dissipation mechanisms.[14] The pulse-attenuation efficiency (R_{att}) can be evaluated by:

$$R_{att} = 100\left(1 - \left|\frac{A_C}{A_0}\right|\right) \tag{1}$$

where the absolute value of the maximum amplitudes of cemented or non-cemented (A_C) and bare (A_0) stems were taken at the proximal, medial and distal positions and the proximal and distal positions (because of the limitation of the bare stem length), respectively.

The resultant energy loss (R_E) caused by the conduction and dispersion of the mechanical vibration through the heterogeneous porous media (composed of air, bone cement, metal and dry bone) could be roughly estimated using the following calculation:

$$R_E = 100\frac{E_C}{E_0} \tag{2}$$

where the pulse energy, measured cemented or non-cemented (E_C) and bare (E_0) stems, was taken at the same measurement positions (proximal, medial and distal or proximal and distal for the bare stem). These energies are associated with the squared amplitude $A^2(t)$ at a particular time (t).[20] Thus, the pulse energy, E_X, developed during the time interval, Δt_X, is a fraction of the input energy, E_{in}, as follows:

$$\frac{E_C}{E_{in}} \approx \frac{\alpha \int_0^{\Delta t_C} A^2(t)\,dt}{mgh_0} \tag{3}$$

where index X refers to stem condition (cemented (C), non-cemented (NC), or bare stem (0)), and α is the scaling constant, associated with the conversion of the electrical signal to energy. The input pulse energy, E_{in}, is caused by the pendulum stroke, with weight $m \times g$ (mass (m) × gravitational acceleration (g)) when left to drop from a height, h_0. The height is another constant along all measurements, and thus, the energy ratio required by equation (2) and deduced from (3) is:

$$\frac{E_C}{E_0} \approx \frac{\int_0^{\Delta t_C} A_C^2(t)\,dt}{\int_0^{\Delta t_0} A_0^2(t)\,dt} = \frac{I_C}{I_0} \tag{4}$$

where I_C and I_0 are the pulse energy integrals dependent on the specific $A(t)$ function and pulse width Δt. Now, I_X is restricted to cemented (I_C) or non-cemented (I_{NC}) stems, in order to compare with bare stem (I_0). Finally, transmitted energy ratio, R_{TE}, is obtained by combining equations (2) and (4) as follows:

$$R_E \approx 100\left(1 - \frac{I_C}{I_0}\right) \tag{5}$$

Statistical analysis. The calculations of the maximum amplitude, A, pulse energy integral I, pulse (sound)-attenuation efficiency R_{att}, and transmitted energy ratio, R_{TE}, were performed with Origin software version 8.0 (OriginLab). In addition, the same software was used for statistical processing in order to obtain the mean values and standard deviations (SD) of the three measurements on each femur and the two measurements on the bare stem, which were less than 10%. Based on previous measurements, a significance level of 0.05, and 80% power, a sample size of five matched pairs was sufficient to detect differences in order to duplicate the standard deviation of the pulse attenuation efficiency between cemented and cementless fixation of the stems.

The frequency response of measured signals, $A(t)$, was analysed by means of the fast Fourier transform (FFT) algorithm. Each design compared cemented and non-cemented designs against the bare stem. Finally, the percentage of sound attenuation was compared between both designs.

Results

The pendulum strikes on the metal femoral head generated sound tracks and electric pulses, composed of a

Fig. 2a

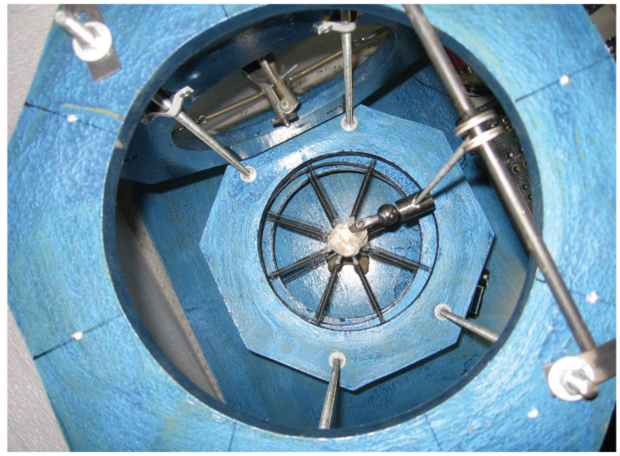

Fig. 2b

Comparison of the sound frequencies between the Accolade stem with and without cement. The frequencies observed with the stem without cement were in the audible range. When the same stem was implanted with a complete cement layer the frequencies were far below the audible range.

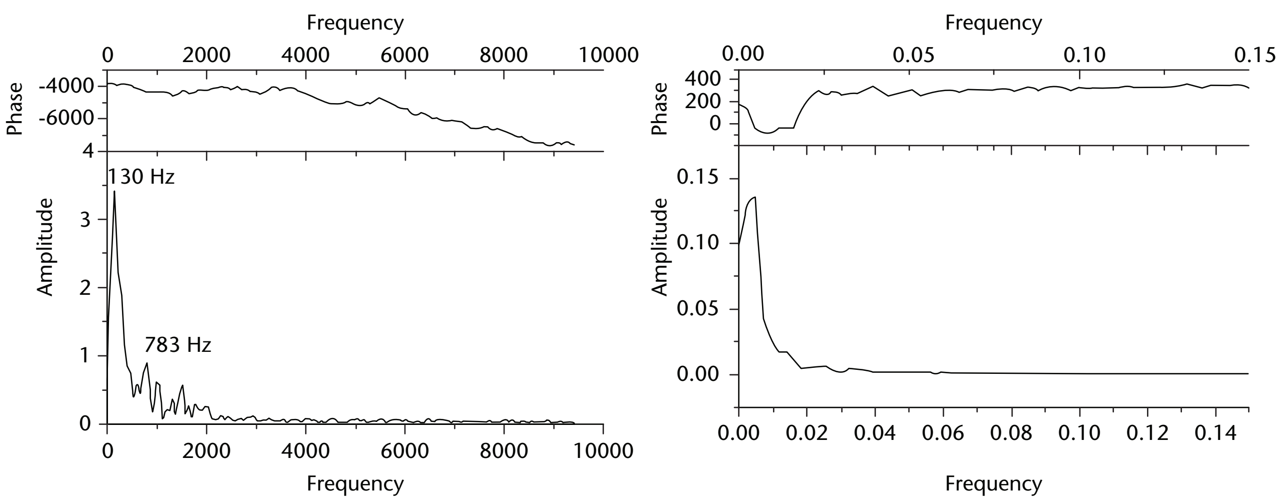

Fig. 3

Comparison of the amplitudes between the Accolade stem with (right) and without (left) cement. When the stem is cemented, both the pulse width and the amplitude are significantly declined.

succession of peaks and valleys prevailing in the pulse width Δt. The initial pendulum energy was distributed in a pulse composed of mechanical vibrations in the audible range (below 2000 Hz), as measured by FFT analysis of the bare stem. This excitation was fully 'filtered' after cementing in femoral bone, with no audible components perceived.

Comparison of the measured amplitudes in both stem designs did not identify any meaningful differences. The most relevant features were associated with abrupt sound attenuation and transmitted energy, due to stem cementing in both cases. Moreover, the magnitudes of the maximum amplitudes of the bare stem A_0, were in the range 10.8 V to 11.8 V (SD 0. 5), whereas the amplitudes for the same stems with cement A_C decreased to 0.3 V to 0.7 V (SD 0.03), implying a pulse-attenuation efficiency, R_{att}, of 97% (SD 2%). This implies a transmitted energy, R_{TE}, of less than 1% (SD 0.05%).

In addition, this marked pulse attenuation was also associated with reduction in pulse width, from 1400 μs to 2700 μs (SD 10) in the uncemented stems, to 28 μs to 430 μs (SD 10) in the cemented stems, and with the noticeable filtering of audible frequencies (Fig. 2), as shown by FFT analysis.

There was also a significant difference between the stems implanted without cement and the bare stems alone. The amplitudes of non-cemented A_{NC} stems were in the range of 6.5 V to 7.8 V (SD 0.5), which represents roughly a pulse-attenuation efficiency, R_{att}, of 57% (SD 4%), which is 40% (SD 3%) smaller than in cemented stems (Fig. 3). The transmitted energy detected in the stems implanted without cement is close to 62% (SD 7%), compared with less than 1% of the stems implanted with cement (see supplementary material).

Discussion

Squeaking hip is considered the most common complication in ceramic-on-ceramic bearings. Although squeaking is not usually accompanied by pain or other symptoms, it can have significant social and psychological consequences when severe. In rare cases, the squeaking has been intolerable to the patient, prompting revision. Thus, squeaking has emerged as a new and previously unanticipated clinical failure mode for ceramic bearings in the 21st century.[15]

The aetiology of squeaking in ceramic-on-ceramic hip replacements appears to be multifactorial, elusive and controversial. Factors such as acetabular component position, patient height and weight, and level of activity of the patient, have been implicated as being associated with audible sounds in some studies, but not in others.[7,9,10]

Squeaking can be the result of higher demand on the prostheses, edge loading, neck/socket impingement, third body wear, or metal deposits on the ceramic head. It has been shown that the increase in friction at a ceramic bearing surface is not enough to generate squeaking. The frictional energy as a form of vibration has to be transmitted to a flexible stem (which amplifies the vibration by resonating) in order to produce an audible sound, a process called friction-induced vibrations.[8]

The design, alloy and neck geometry of the stem have been shown to play a key role in the sound production.[15,21] The tapering titanium alloy prosthesis (Accolade; Stryker Orthopaedics) was found to have a significantly higher incidence of squeaking compared with other designs. In a numerical study of squeaking, it has been observed that increasing Young's modulus of the stem, adding CoCrMo alloy as well as 316 L stainless steel to the stem, and adding a damping layer of UHMWPE to the acetabular component can improve the vibrant stability of the system and thereby suppress the squeaking.[22,23]

The acetabular component design itself was found to have no major influence on the dynamic behaviour of the system, but seems to play an important indirect role in influencing the magnitude of friction. If friction is not enough to excite vibrations to audible magnitudes, no squeaking will occur.[12] In a meta-analysis carried out by Stanat and Capozzi[24] on 11 articles reporting on prostheses with alumina bearing surfaces and on 12 articles on all bearing surfaces, there was no significant relationship between metallic components with a raised edge and any audible sounds.

Regarding fixation, higher incidences of squeaking hip have been reported from series that combined ceramic bearings with non-cemented stems.[6,15]

When cemented stems are involved, squeaking hip does not seem to be a problem. Hamadouche et al[17] studied two different series of patients and found a survival rate for their prostheses of 93.2% at six years and 85.6% at 20 years, with two different designs (one with and one without pegs), using both components cemented in 85 hips, and a hybrid combination in four hips. Recently, Bizot et al[19] reported the results of a series of 71 hybrid total hip arthroplasties with ceramic-on-ceramic bearing surfaces in patients under 55 years of age, with a nine-year survival rate for the prosthesis of 93.7%, using revision for any cause as the endpoint. None of these studies reported cases of squeaking hip. It is noteworthy that in some of these studies with different prosthesis designs, the absence of surveys specifically addressing the complication of squeaking hip could be partially responsible for the lack of reports of this complication, thus underestimating the real incidence. In contrast, Boyer et al[25] used a specific questionnaire for squeaking hip. They reported the results of a series of ceramic-on-ceramic hip replacements with 63 cemented stems and 20 non-cemented stems, and after a mean follow-up of ten years, only a single case of squeaking hip was detected.

Research over the past 15 to 20 years has focused on acoustic emission (AE) monitoring to provide insight into implant condition and to provide early detection of wear and loosening.[26] Mavrogordato et al[27] investigated the use of embedded acoustic emission sensors in the *in vitro* testing of a simplified total hip stem construct subjected to loading in a hydraulic test machine. Davies, Tse and Harris[28] and Sugiyama, Whiteside and Kaiser[29] have also investigated the use of acoustic emission testing in orthopaedics, looking at micromovements within the surrounding bone and fixation to bone cement. More recently, Rashid and Pullin[30] have examined the use of acoustic emission technology in the field of orthopaedics. However, this is the first research that explores the influence of the cement mantle on squeaking production using acoustic emission principles.

The *in vitro* measurement setup used in the current study was able to detect transmitted energy of less than 1% in the stems implanted with cement compared with 62% in the stems implanted without cement. In this setting, the cement mantle had a marked effect on sound attenuation and behaved as a strong energy buffer. The sound attenuation efficiency of the cemented stems implanted in cadaveric bone is close to 40% compared with the stems implanted without cement in the same conditions. This reflects the efficiency of sound and energy attenuation, when a complete layer of bone cement exists between bone and metal stem.

The interpretation of sound waves proposed in this study could be applied in the clinical setting to the detection of frictional problems caused by impingement and loose stems. Also, this information could be used as a complementary follow-up method for changes at the cement mantle.[28-30] In addition, the detection of the natural frequency of a stem could represent an initial screening process used by the industry to determine the tendency or otherwise of a specific implant to produce squeaking.

Consequently, when ceramic-on-ceramic becomes the bearing of choice, we believe that the visco-elastic properties of cement could contribute to the dissipation of vibro-acoustic energy, thereby damping sound propagation, and thus preventing hip prostheses from squeaking. This new information could became part of the decision-making process about the best fixation method for a patient for whom ceramic-on-ceramic is determined to have clear benefits.

However, the impact on the clinical setting of sound attenuation of the femoral cement mantle in avoiding squeaking remains unclear and should be evaluated in further clinical studies.

Supplementary material

ë Photographs showing upper view of the elastic structure with the springs supporting the cadaveric bone femur and a table showing comparisons between stems are available with this article online at www.bjr.boneandjoint.org.uk

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- A. Ozols: Research design, Acquisition of data, Analysis of data.
- C. Fernandez: Acquisition of data, Analysis of data.
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ICMJE conflict of interest
- None declared