The effect of the extracorporeal shock wave lithotriptor on bone cement

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For the purpose of studying its applicability for acrylic cement removal during total hip revision surgery, experiments with an extracorporeal shock wave lithotriptor were carried out. High-energy shock waves (HESW) were focussed on discs of polymethylmethacrylate bone cement. The average discharge was 18.1 kV; the number of shock waves 0, 100, 250, 500, 1000, and 2000; the application rate was 85 shocks/min. Macroscopic or radiographic effects were not in evidence. Microscopically, typical lesions in a small concentric focal area with a diameter of 8.5 (± 2.5) mm were found. The individual lesions were smaller than 0.1 mm, and displayed characteristic shapes. The area porosity increased with the number of shocks. The maximal area porosity caused by the HESW, measured by quantitative microscopy, was 4% after 2000 shock waves. The lesions were also studied by scanning electron microscopy. It can be concluded that HESW causes only microscopic lesions on the frontal surface of discs of bone cement, and that these lesions are small compared to the pores normally present in bone cement, when applied clinically.

INTRODUCTION

Polymethylmethacrylate is used as a grouting material to locate and fix total hip arthroplasties in the bony cavity. After 10 years about 10% of the arthroplasties need revision. The absolute number of revisions is increasing, because total hip replacement is now a widely used procedure. Removal of bone cement is a meticulous process, associated with many complications. Several methods have been described to facilitate removal. Recently, extracorporeal shock wave lithotripsy was proposed for this purpose. The purpose of this project was to obtain information about the effect of high-energy shock waves (HESW) on acrylic cement.

MATERIALS AND METHODS

Sulfix-6* bone cement was used. Cement preparation was carried out in a plastic bowl with a spatula, according to the instructions of the manufac-
turer. The stirring frequency was 1–2 rounds/s, the room temperature 21 (±1) °C. After mixing, the cement was poured into a cylindrical mold. In this way, two 26-mm-diameter cylindrical cement bars were prepared. One bar was left to cure under atmospheric circumstances, the other bar was set under pressure of 20 (±2) MPa in a hydraulic press during the curing phase (15 mins).

The bars were then sectioned into discs of 2.5 (±0.2) mm, using water cooling. The sections were polished, checked macroscopically and radiographically, and evaluated for area porosity by quantitative microscopy (automatic gray discrimination of video images). These measurements were performed in two rectangular directions across the polished side. The discs were placed in a water bath, with a temperature of 37.5 (±1.5) °C. The experiment was performed with a Siemens Lithostar lithotriptor. The high-energy shock waves were orientated perpendicular to the polished disc area. The target location was selected using a two-directional radiographic image identification system. The average discharge was 18.1 kV, the number of shock waves on the different slices 0, 100, 250, 500, 1000, and 2000. The application rate was 85 shocks/min, the standard rate of the device used. Thereafter the discs were checked macroscopically and radiographically, and again evaluated for area porosity. Some slices were sputter-coated with gold and examined by scanning electron microscopy (SEM).

In order to determine an optimal and reproducible experimental set-up, the pressure at different sites of the focus of the lithotriptor was measured. The pressure measurements were performed using a piezoelectrical crystal transducer (Imotec) connected with a 100-mHz oscilloscope (Gould DSO, 4072). Pressures at different kilovoltages (kV) were registered and a field of relative pressures around the focus was determined by positioning the transducer at different sites. These measurements revealed that the site of the maximum pressure was not identical with the radiological focus, but located 10 mm away from the shock-wave tube along the axis of the focus (Fig. 1(a), (b)). Considerably elevated pressure could still be measured several centimeters away from the radiological focus, while in the lateral plane the pressure rapidly decreased 2–4 mm away from the radiological focus. The pressures depended largely on the voltage (kV) discharge applied, in a somewhat regressive way. These pressure measurements indicate that it is incorrect to define a focus; it is better to speak of a focal area. The Lithostar creates pressures in a cigar-like focal area.

RESULTS

Macroscopically and radiologically, pores were visible on the slices cured under atmospheric pressure; the slices of the bars cured under high pressure showed no pores. The microscopically estimated area porosity revealed significantly different results between the discs cured under atmospheric pressure and those cured under high pressure (Table I).
Figure 1a. Pressures in the central axis of the focal area at different distances (in mm) from the radiological focus X at different kV discharges.

Figure 1b. Pressures lateral to the central axis of the focal area at different distances (in mm) from the radiological focus X at different kV discharges.

TABLE I
The Effect of the Extracorporeal Shock Wave Lithotripter on Bone Cement: Area Porosity Estimated of Total Disc Surface, Sulfix-6

<table>
<thead>
<tr>
<th>Number of Shots</th>
<th>Cured under Atmospheric Pressure</th>
<th>Cured under 20 MPa Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After ESWL</td>
</tr>
<tr>
<td>0</td>
<td>1.8 (1.6)</td>
<td>1.7 (1.6)</td>
</tr>
<tr>
<td>100</td>
<td>1.8 (2.0)</td>
<td>2.8 (3.0)</td>
</tr>
<tr>
<td>250</td>
<td>1.5 (1.6)</td>
<td>1.6 (1.2)</td>
</tr>
<tr>
<td>500</td>
<td>1.4 (1.7)</td>
<td>2.4 (1.9)</td>
</tr>
<tr>
<td>1000</td>
<td>1.7 (2.2)</td>
<td>2.6 (3.1)</td>
</tr>
<tr>
<td>2000</td>
<td>1.1 (1.7)</td>
<td>2.2 (3.1)</td>
</tr>
</tbody>
</table>
After the application of the shock waves, no macroscopical or radiographical changes were visible. Microscopically, no changes in the overall percentage of estimated area porosity could be found (Table I). However, in all cases typical lesions were visible microscopically in a concentric area around the focal center (Fig. 2(a), (b)). The diameter of this area was 8.5 (±2.5) mm.

Figure 2a. Microscopic view of disc before HESW. Original magnification ×30.

Figure 2b. Typical lesions seen in the focal area after 2000 shock waves. Original magnification ×30.
No correlation between the diameter of this area and the number of shots was apparent. The average size of the larger lesions in the center of the focal area, measured microscopically, was 0.07 (±0.01) mm. The distribution of the area porosity around the focal center was measured in the cases of the discs cured under pressure (Fig. 3). The size of the lesions made by the HESW were small compared to the pores occurring in the discs cured under atmospheric pressure. Incidental cracks of the rim of a pore were seen, when this pore had been in the center of the focal area. SEM of the typical lesions showed a more or less complete circular damage, with a relatively unimpaired central part (Fig. 4).

**DISCUSSION**

The extracorporeal shock wave lithotriptor was introduced in medicine in the late seventies. By generating HESW it is possible to disintegrate kidney stones in a contact-free and noninvasive way. Karpman et al. introduced HESW generated by a lithotriptor as a technique which might be utilized in orthopedics to facilitate the removal of the femoral prosthetic component and bone cement out of the femoral canal. Experiments were done with three canine femurs containing stainless-steel rods fixed with bone cement. The area treated with HESW showed many microfractures of the bone cement and a disruption of the cement–bone interface, as was established by reflected light and scanning electron microscopy. Weinstein et al. also used canine femora. After treatment, the bones were sectioned transversely, and mechanical push-out tests were performed. Results indi-
cated that HESW does have a loosening effect. The bone–cement interface was inspected with scanning electron microscopy; microfractures, loose-bodies, and widening were seen, with few lesions of the surrounding bone.

The goal of this study was to obtain information about the effect of HESW on bone cement. The shock waves can be generated in different ways. In the Siemens Lithostar this is done by large-surface, electromagnetic pressure transducers. Shock waves are focussed by means of an acoustical lens. The shock wave is composed of low and high frequencies.

The intensity of treatment can be varied by two parameters: the discharge voltage and the number of shocks. It seems that a relative increase in head voltage is more effective then a relative increase in the number of shocks. In this study only the number of shocks was varied, discharge voltage was chosen as submaximal for the device used.

After being evoked, the shock waves are conducted to the body by a water-containing medium. Water is chosen because its acoustic impedance is similar to that of soft tissue and cancellous bone. Hence excitation of a disc of bone cement in a water bath can be considered as a simplified model for the excitation of the cancellous bone–cement interface. High-energy shock waves can travel through two or more substances without dissipating a significant portion of energy if there is no change in acoustic impedances. Energy transfer will mainly occur at the interface of media which have different impedances. When a shock wave hits the frontal surface of a stone, it will be separated into two directions according to the acoustic impedance. A part of the shock wave will be reflected, the other part will enter the stone.
This latter part is transmitted through the stone with a very high pressure front. If this pressure exceeds the compressive strength of the stone, it will disintegrate. On the opposite side of the stone, at the stone-water interface, the reflecting waves produce negative pressure waves in the stone. As a result, a highly elevated positive pressure front passes through the stone, followed by a negative pressure front very close to the interface. This pressure wave causes tensile stress, whereby the stone can be broken. Because the tensile strength of a stone is usually much smaller than the compressive strength, this mode appears to be the most dominant one.

It has been described, that shock waves generated by ESWL can cause violent acoustic cavitations in water.\textsuperscript{13,14} When these cavitations collapse near a boundary, they can cause significant damage in two ways. First, during the cavitation collapse a very rapid liquid jet evolves, which can impact the nearby boundary. Secondly, after the jet has penetrated the cavitation, a toroidal ring of vapor is generated, which eventually also collapses and causes damage. These effects will be mainly seen on the frontal surfaces of the materials concerned.

The effect of the HESW on bone cement discs were visible microscopically, and the lesions were small compared to the pores normally present. No disintegration of the discs was seen, indicating that the tensile and compressive stresses generated were not strong enough to cause breakage. Microfractures were only seen in relation with a pore in the focal area, indicating that these pores probably act as stress risers. Because the pores disturb the measurements of the area porosity caused by the HESW, a bar cured under high pressure was used as well. Discs of such bars do have a very low porosity, as was established in a previous study.\textsuperscript{15} The typical lesions seen on the frontal surfaces of the discs were probably caused by cavitational effects, which may explain their typical form.

There was no difference in area porosity when measured over the total disc surface. This can be explained by the fact that the focal area amounted to only about 16% of the total disc surface. Discs were placed in the radiological focus of the lithotriptor, although there is a discrepancy between the radiological and the pressure focus. At 18.1 kV discharge voltage the influence of this discrepancy on pressure height is small.

The conclusion is that HESW causes microscopic lesions in a small area on the frontal surfaces of cement discs. The lesions are small relative to the pores usually present in bone cement. The lesions increase in magnitude proportionally with the number of shock waves. However, pores in bone cement, present after \textit{in vivo} application, may behave as stress risers and initiate cracks secondary to HESW. Moreover, in the clinical situation bone cement may be mixed with blood and grease, and the interface of bone cement and cancellous bone will be structurally complex. The effect of HESW on this interface needs further investigation.

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References


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