Fragmentation mechanisms of kidney stones in shock wave lithotripsy can be detected with microCT X-ray imaging

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Introduction

In lithotripsy shock waves (SWs) are used to fragment kidney stones in the body. Lithotripsy was introduced in 1980 and today about 75% of kidney stones in the United States are treated with SWs – primarily because it is a non-invasive procedure with few complications. However after 25 years of clinical use there is still little agreement as to the mechanism or mechanisms by which shock waves comminute stones in the body [1]. The two most likely mechanisms are fatigue due to the stresses induced by the incident shock wave (e.g., spall and shear) and the violent collapse of cavitation bubbles in the fluid around the stone.

We carried out *in vitro* experiments to track the fragmentation process of artificial and human kidney stones. The fragmentation process was monitored using X-ray micro-computed tomography (μCT). The μCT images provide snap-shots of the structure of the stone and because it is non-destructive the progression of fracture could be followed during a treatment [2]. The fracture images provide insight into the mechanisms of failure.

Methods and Materials

Artificial stones were made of Ultracal-30 (U30) gypsum cement (US Gypsum Co.) and were cast in cylinders 6.5 mm in diameter and 8 mm long. The stones were formed, stored and tested in a fluid environment and never came into contact with air [3]. The acoustic properties of the stones were measured to be in the range of human stones.

The human used in this study had been surgically removed from patients and dried. The stones were rehydrated for more than 40 days in deionised, degassed water. The sound-speed in the stones was measured during the rehydration process to ensure that the stones were indeed fully hydrated. After treatment the human stones were chemically analysed.

Stones were treated within polypropylene vials (15 mm x 46 mm long) which had a plastic mesh (2 mm spacing) mounted approximately 10 mm from the bottom. The vials were filled with deionised degassed water and the stones placed on the mesh. Saturated, degassed gauze was then packed around the stone to keep it in place. The vial was further degassed and then capped with a lid such that no air bubbles were present in the vial. Finally, the lid was sealed with silcone sealant.

The vials were then placed within a desktop micro-computed tomography (μCT) X-ray imager (Model 20, Scanco, Switzerland). The μCT scanner can produce a two-dimensional gray-scale image of the X-ray absorption in one plane within the stone. By translating the stone vertically and carrying out consecutive scans it is possible to produce a full three-dimensional reconstruction of the internal structure of a kidney stone. The scans in this study were done with a 20 μm voxel size. In our analysis each two-dimensional image was saved as a JPEG file and the images were read into Matlab and the analysis carried out using the Matlab Image Processing Toolbox.

After the initial μCT imaging (which provided a baseline, 0 SW, image) the stones in the vials were treated with shock waves from a clinical electromagnetic lithotripter (Storz Modulith SLX). To facilitate coupling a water tank was placed on the patient table; the tank had a low density polyethylene window through which the shock waves from the therapy head could pass into the tank. The tank was filled with deionised, degassed water. The vial was mounted in the tank with the flat bottom towards the shock wave source and was positioned such that the stone was at the focus of the lithotripter (as determined by the fluoroscopic imaging system provided with the lithotripter)—see Fig. 1. The stones were treated with volleys of SWs fired at 2 Hz at energy level 7 which results in a pressure pulse with an peak pressure of about 60 MPa. After each volley of SWs the vial was removed from the lithotripter and taken to the μCT scanner to be imaged again. This process was repeated until significant damage had occurred to the stone (usually with 150 SWs). The stones remained within the sealed vials at all times during the treatment which allowed us to maintain orientation of the stone for both the imaging and treatment.

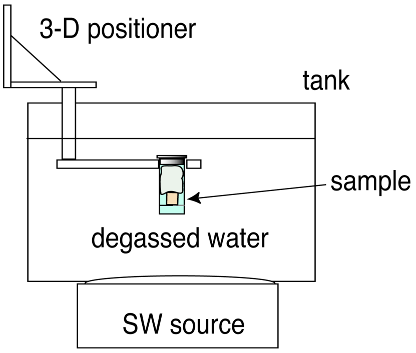

Figure 1: Experimental set-up with the stone inside a vial which is placed at the focus of the shock wave source.

Results

All μCT images are 2D slices through the middle of the stone with the SWs were incident from below (as in Fig. 1). Figure 2 shows U30 stones that were placed vertically within the vial, so that SWs entered through the flat end of the stone. Shock waves were fired in volleys of 25 SWs. After 50 SWs cracks can be seen growing from the outer surface of the stone. After 75 SWs the cracks had reached the centre-line and a vertical crack had grown towards the distal surface. This failure process is consistent with both spall (50 SWs) and shear induced fatigue (75 SWs) [4].

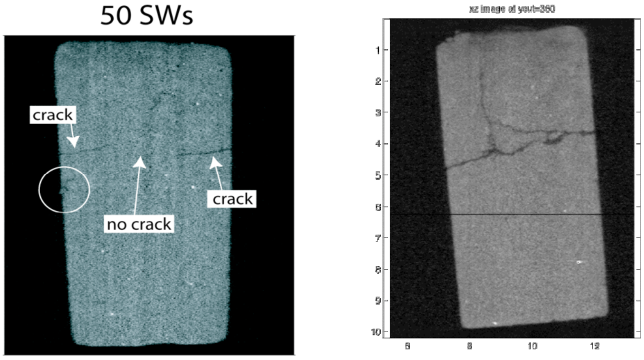

Figure 2: Vertical U30 stone Left: After 50 SWs cracks have started to grow from the outer surface. Right: After 75 SWs a vertical crack grows towards the distal surface.

Figure 3 shows snap-shot of a U30 stone placed in horizontal orientation after 100 SWs. In this case the curvature of the surface and the associated refraction prevented efficient coupling of the acoustic wave into the stone. The damage that was observed was principally pitting to the proximal surface of the stone along with cracks emanating from the tips of the pits. This is consistent with a cavitation process.

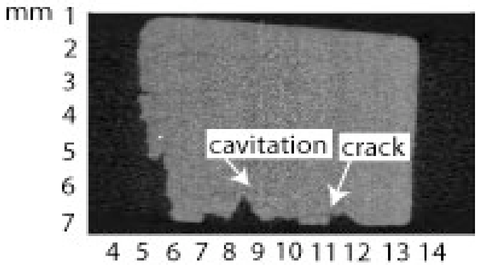

Figure 3: Horizontal U30 stone after 100 SWs. Principal damage is due to cavitation on the proximal surface.

For the human stones µCT images were taken after volleys of 10 SWs. The human stones were broadly divided into two groups: *Homogeneous* appearing to be almost uniform µCT image with only a few lamellae. *Inhomogeneous* consisting of a homogeneous core surrounded by what appared to be a porous middle layer and an thin (<1 mm thick) outer shell—see Fig. 4.

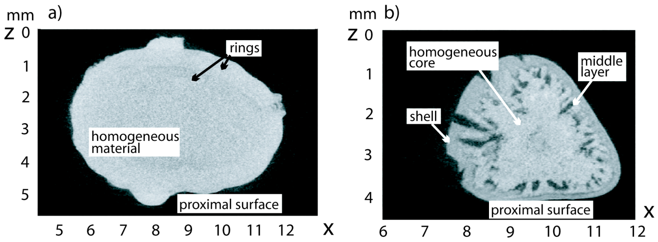

Figure 4: Human stones prior to SWs. Left: Homogeneous stone with a few layers. Right: Inhomogeneous stone with a three layers of distinct morphology.

Figure 5 shows representative images of the damage to homogeneous and inhomogeneous human stones. In this case both stones were at least 98% calcium oxylate monohydrate (the most common form of stone). We consistently found that homogeneous stones fractured with large cracks that initiated near the distal portions of the stone. This is consistent with a spall-like mechanism. Inhomogeneous stones always lost the proximal shell and middle layer first by what appeared to be a cavitation pitting process. Once the core was exposed spall-like fracture would start to occur near the distal surface.

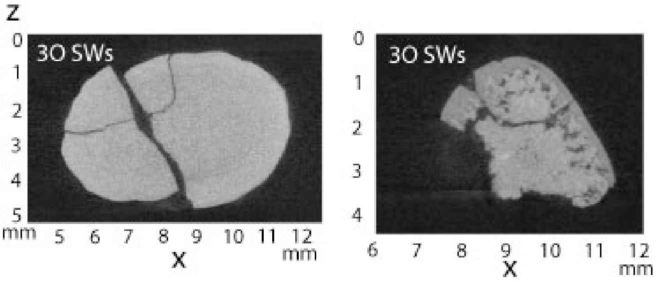

Figure 5: Typical µCT images of human stones after 30 SWs. Left: Homogeneous with spall-like fracture. Right: Inhomogeneous stone the proximal surface was removed by cavitation-like pitting before the distal crack could form.

Conclusions

The µCT images show that multiple processes are present in the fragmentation of both artificial and human stones in lithotripsy and that these mechanisms to act with similar efficiency. For a particular stone, one mechanism may dominate depending on both the orientation and the internal structure of the stone, e.g., spall dominates in homogeneous stones with flat surfaces. However, in general for typical human stones with complex shapes and internal structures, multiple processes participate in a synergistic manner.

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