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THE STUDY OF THE SURFACE GEOMETRY OF RENAL STONE FRAGMENTS AFTER SHOCK WAVE AND ULTRASOUND DISINTEGRATION

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Abstract

Computerized image analysis was used for characterizing the irregular boundaries of calcium oxalate stone fragments resulting from shock wave and ultrasound disintegration. The complexity of the contour of the fragments was determined to evaluate the surface roughness of the rugged profile of the samples. Crack propagation on the crystal surface of the mineral phase was studied using fractal geometry. A significant difference was observed in the boundary variation of the calcium oxalate stone fragments treated by shock wave and ultrasound. Crack propagation in the mineral phase crystal was found to depend on the method of fragmentation used. There is also an experimental evidence that the surface topography of the stone fragments produced by shock wave depends on the microhardness of the stone material.

Key Words: Hydrated calcium oxalate, urinary calculi, stone fragmentation, extracorporeal shock wave lithotripsy, percutaneous ultrasounds, image analysis, Fourier descriptors, fractal analysis, microhardness.

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Introduction

Currently, there is a great interest in the treatment of kidney stones by *in-vivo* fragmentation techniques using noninvasive shock wave methods (Chaussy and Fuchs,1989; Finlayson and Ackermann, 1989) as well as invasive ultrasonic (Marberger, 1983), electrohydraulic (Matouschek, 1984), laser (Watson et al., 1987) and micro-explosions (Watanabe et al., 1987) fragmentation methods. There are only a few domains where the use of high technology in therapeutics has undergone such a rapid evolution as has the treatment of urinary calculi (Dretler, 1990). Work on the destruction of calculi by physical procedures points to the lack of fundamental data on the mechanical properties of renal calculi of all types (Johrde and Cocks, 1985). Although efforts have been made to classify the fragility of urinary calculi (Dretler, 1988), the basic parameters that control the disintegration of stones such as size, position, stone material, the configuration and intensity setting of shock wave (Smith and Manne, 1990; Zhong et al., 1990), etc... have not been thoroughly investigated.

The study of the morphology of urinary stone particles resulting from extracorporeal shock wave lithotripsy (ESWL) treatment showed that fragmentation involved separation of crystalline layers and fracture and cleavage of the crystal (Khan et al., 1986). Kambe proposed that the main mechanism of fragmentation of urinary stones by underwater shock wave is the tensile stress at the solid-water acoustic interface (Kambe et al., 1988). The major physical phenomenon that is thought to govern fragmentation of calculi, is the rapid build-up of a pressure gradient when a focused shock wave encounter solids of different acoustical properties (e.g.: impedance) (Chaussy and Fuchs, 1989). When the shock wave hits the front surface of a stone, some energy is reflected creating a compressive stress. A compressive pulse will then travel through the stone and at its back surface, reflection of the compression pulse creates a tensile stress travelling backward (Ison, 1987). If the stresses are strong enough, these forces produce microrupture. A train of such waves leads to the destruction of the calculi (Jocham et al., 1986).

The influence of the chemical composition of urinary calculi on the results of ESWL was studied and it was shown that calculi with different radiographic appearances respond differently to shock wave fragmentation (Dretler, 1988; Doré et al., 1990). It is believed that unorganized compact structure in urinary calculi are more resistant to ESWL or *in-situ* fragmentation techniques as opposed to heterogeneous structures or structures presenting various degrees of organization that offer less resistance to fragmentation (Jungers et al., 1989). Furthermore, the physical explanation of fracture requires knowledge of the stress distribution in the particle and its redistribution due to initiation and propagation of cracks as well as of relevant fracture resistance properties (Kienzler and Schmitt, 1990). However, in the fragmentation of urinary calculi *in-vivo*, there are many unknowns making the physical explanation of fracture difficult.

In the present study, we focus on the surface topography of the stone fragments using image analysis techniques. The objectives of this study are to investigate the effect of the size reduction process on the micro and macro-morphology of the fractured stones and to evaluate the association between the morphic features and the microhardness of the fractured calculi.

Materials and Methods

Samples of urinary calculi were obtained from different hospital centers where ESWL and ultrasound treatment are used for disintegrating urinary calculi. The composition of the samples was determined by crystallographic analysis, infrared spectrometry and X-ray powder diffraction analysis. Only calcium oxalate monohydrate (COM) or calcium oxalate dihydrate (COD) stones were used in this study.

The size/shape parameters were determined using an image analysis system previously described (Akbarieh et al., 1987; Thibert et al., 1988). It is based on the determination of Fourier descriptors of the contour which calculate invariant shape descriptors. These shape descriptors will characterize the fragments in terms of roundness, elongation, boundary variation, etc... . For example, the boundary variation (P_3) can be calculated with the normalized Fourier coefficients (a_n, a_{-n}) using:

$$P_3 = \Sigma \ |a_n|^2 + |a_{-n}|^2 \qquad (1)$$

P_3 measures the boundary variation in part of the frequency spectrum thus giving quantitative information on the complexity boundary. Since P_3 is calculated from normalized Fourier descriptors, it is a dimensionless number, which permits useful comparisons with other samples. The details of the calculations have been previously described (Laurin et al., 1986; Akbarieh and Tawashi, 1987).

Fractal geometry was used to evaluate the irregularity of the cracks produced on the mineral phase crystal. The crack lines produced by shock wave or ultrasound on the surface of the mineral phase crystal were studied using the walk-around step-length method (Mandelbrot et al., 1984; Clark, 1986). The fractal dimension was determined from the plot of L_λ vs λ for a range of step-length using:

Table 1: Composition (%w/w) of renal stone fragments studied.

ESWL			Ultrasound		
No.	COM	COD	No.	COM	COD
1	93%	-	1	96%	-
2	60%	-	2	92%	4%
3	53%	45%	3	35%	58%
4	34%	57%			
5	26%	57%			
6	20%	67%			
7	17%	80%			

$$L_\lambda = k \ \lambda^{1-D} \qquad (2)$$

where L_λ is the perimeter (mm), k is a constant, λ is the step-length (mm) and D is the fractal dimension (Mandelbrot, 1977). The fractal dimension is a measure of the "space-filling" ability of a curve thereby reflecting the rugosity or irregularity of the crack. The fractal dimension of at least 6 crack lines was determined.

In order to study the effect of the hardness of the stone on the characteristics of the surface produced after fragmentation, we determined the microhardness of the stone fragments using the Vickers hardness test. The microhardness of each sample was determined by mounting stone fragments in an epoxy resin until complete hardening for 24 hours. The mixture was ground through 600 grit SiC paper, then polished with 0.05μm alumina and left over anhydrous $CaSO_4$ in a desiccator for another 24 hours. The Micro-Hardness Tester M-II (Sankei Co.,Tokyo,Japan) was used with a load of 50 g for all the samples and at least 10 measures were made for each sample. The Vickers hardness number was determined using the following formula (Kumareson and Devarayanan, 1989):

$$VHN = 1.854 \ (P/d^2) \qquad (3)$$

where VHN is the Vickers hardness number (kg/mm^2), P is the load applied (kg) and d is the diagonal of the indentation mark (mm).

Results and Discussion

Table 1 gives the composition of the calcium oxalate stones used in this study. Figures 1-4 show fragments of COM and COD stones obtained from ESWL and ultrasound fragmentation processes. It is observed that the fragments produced by ESWL have a surface topography or macromorphology that is different from the fragments produced by ultrasound. These differences could be detected with the use of machine vision and quantitative image analysis. Although no significant differences were observed in the roundness and elongation parameters, the study of the boundary variation of the samples shows a statistically significant difference in the boundary variation (Table 2). These differences are consistent whether the fragments are COM or a mixture of COM and COD.

This can be explained by the fact that the new surfaces produced are associated with the mechanisms operating in size reduction. In other words, the surface aspect of the fragments will be associated with the cavitation effect in the case of ultrasound and with the wave expansion mechanism in the case of ESWL.

In ultrasound, the acoustic waves activate gas bodies located in the microcracks of the urinary calculi leading to cavitation bubble. It is hypothesized that the growth of cavitation within the solid by the ultrasonically generated wave-train leads to crack propagation and expansion along weak dislocation lines (Sarfarazi and Ghosh, 1987). The sudden release of pressure leads to the fracture of the urinary calculi into fragments with high boundary variation and surface irregularity.

In ESWL, the main mechanism of fragmentation may be the reflection of the shock wave at the liquid-solid interface of the urinary calculi produce an expansion wave in the stone. In turn, strong expansion waves produce tears below the reflecting surface and in the end shattering of the stone occurs. Thus, initially, the fragments produced may have been very irregular and jagged but as the process of fragmentation takes place, the interaction between these fragments cause attrition and abrasion of sharp edges as in any process where there are particle/particle interactions. Therefore, the observed fragments have a relatively lower boundary variation. Other mechanisms that may be involved in the fragmentation mechanism of ESWL may be the interaction of shock waves at crack or grain boundaries within the calculi, and surface cavitation effects.

The examination of the mineral phase crystal surface of COM under higher magnification obtained from ESWL and ultrasound revealed the presence of cracks. The cracks produced on the surface of the stone crystal had different crack propagation pattern (Figures 5-6). Unlike the cracks produced by ultrasound, the cracks produced by ESWL were more irregular and jagged. Fractal analysis showed a statistically significant difference between the crack lines formed by ESWL and ultrasound (Figure 7). In view of these findings, it appears that in ultrasound disintegration, the cavitation effect caused fragmentation along dislocation lines producing regular crack lines in the mineral phase of the stone. In ESWL, fragmentation was a result of a series of shock waves that lead to irregular crack lines.

Although fragments produced by ESWL have a relatively lower boundary complexity when compared with fragments produced by ultrasound, it could be high enough to adhere to tissues. Such fragments would take a longer time to be eliminated from the urinary tract. Their retention might be the cause for a retreatment rate of approximately 5% as observed in clinical experiences (Eisenberger and Rassweiler, 1987). This phenomena is not observed in the case of ultrasound disintegration because of the continuous aspiration of fragments during the procedure (Marberger, 1983).

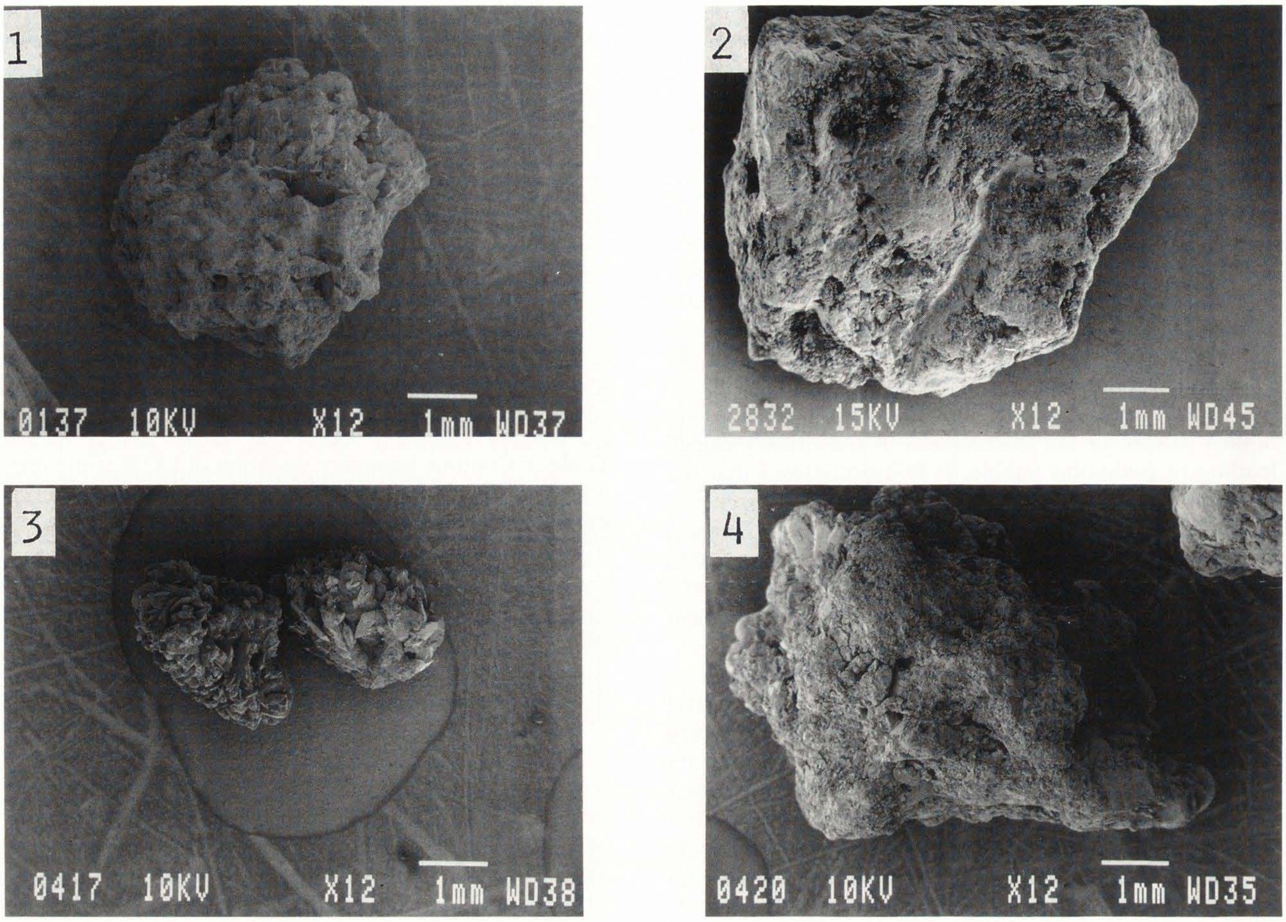
Table 2: The average boundary variation (± standard error of the mean (± S.E.M.)) of at least 50 fragments of urinary calculi.

Sample	Method		Level of significance
	ESWL	Ultrasound	
COM	2.390 ± 0.070	4.723 ± 0.157	$p < 0.001$
Mixture	2.470 ± 0.234	3.930 ± 0.798	$p < 0.05$

Table 3: Contour boundary variation of COM stone fragments obtained by ESWL and the corresponding Vickers microhardness (± S.E.M.).

Boundary Variation	VHN (kg/mm^2)
2.086 ± 0.129	133.8 ± 8.3
2.519 ± 0.116	156.5 ± 5.2
2.564 ± 0.224	160.6 ± 7.4

It has been established that fracture of solids depends on the mechanism by which force has been applied on the solid and on the intrinsic properties of the material. It is also known that surface hardness is the result of the interaction of factors such as crystal structure, adhesive forces between individual crystallites, packing arrangements, etc. Thus for a composite material such as a urinary calculi, the multiple interactions of these factors will contribute to the surface properties of the stone fragments. Evidence for the effect of these intrinsic properties has been demonstrated in a limited study of stone fragments. The microhardness of COM fragments obtained from ESWL was studied as a function of boundary variation (Table 3). Results obtained show that boundary variation increases with the increase in microhardness and that the harder the material, the higher the irregularity and the jagging of the contour. It indicates also that material hardness is equally important as the method of breakage, in determining the degree of irregularity of the newly generated surfaces. Evidently, more studies are needed to understand the role of structural properties in fragmentation and quantitative data may allow to sort out the influence of such factors in the amelioration of the techniques of stone disintegration.



Figures 1-4: Fragments of COM (**Figs.1,2**) and COD (**Figs.3,4**) stone after ESWL (**Figs.1,3**) and ultrasound (**Figs.2,4**).

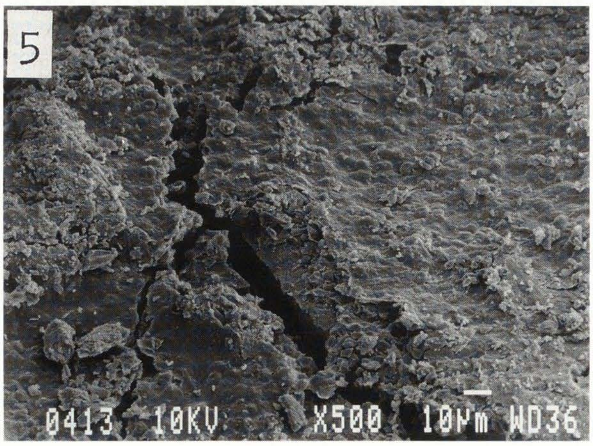


Figure 5: COM crystal surface after ESWL.

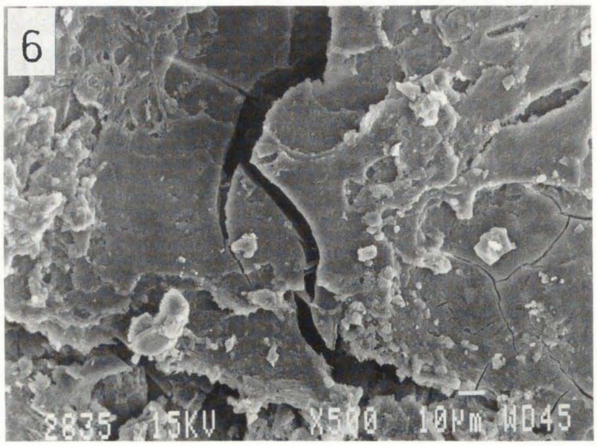


Figure 6: COM crystal surface after ultrasound.

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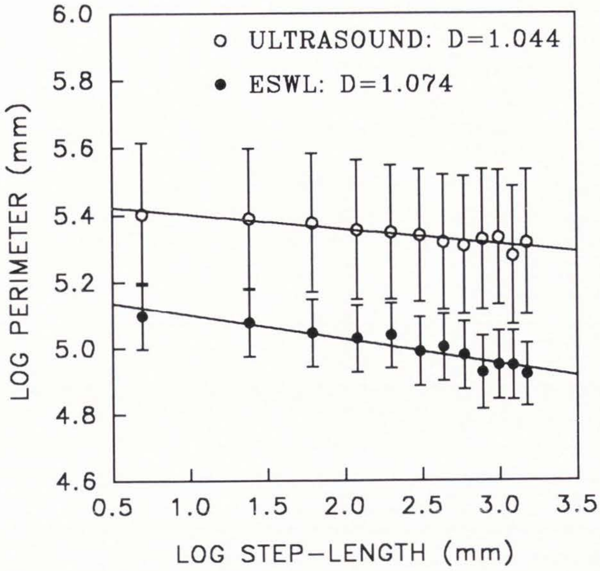

Figure 7: The fractal dimension (D) of the cracks produced by ultrasound and ESWL are significantly different ($p<0.05$) [each point is the average of at least 6 crack lines ±S.E.M.].

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Discussion with Reviewers

S.P. Dretler: Does final interpretation have anything to do with fragment selection?

Authors: This study focuses on the analysis of shape characteristics and surface irregularities of fragments. The number of fragments tested and the number of specimens examined are sufficient to reflect the difference between the two main fragmentation processes in stone disintegration. The analysis was conducted on at least 50 fragments for each of the 10 specimens presented in this study. The fragments were randomly selected.

T.J. Mackin: Why did the authors choose to use fractal analysis to study the characteristics of urinary stone fragments instead of size and size distribution parameters?

Authors: It has been shown by Turcotte (J. Geophys. Res. 1986; 91(B2): 1921-1926) that fragmentation is a scale-invariant process and the use of fractals is appropriate. In the text, we defined fractal dimension as a measure of the space-filling ability of a curve thereby reflecting the irregularity or roughness of a line. The roughness of the fragment is a very sensitive parameter that reflects the history of the surface. Every fragment carries the traces or patterns of the pathway used to produce it.

If we take, as Dr Mackin suggests, size and size distribution to characterize our samples we have two shortcomings: a) size is a one-dimension measure lacking the degree of information that contour can provide, and b) the need to have all particles included to assess the distribution. In this type of experiment, it is almost impossible to obtain all the fragments resulting from the disintegration of a given renal stone.

T.J. Mackin: What is the contribution of the newly generated fracture surface?

Authors: Meloy (Powder Technol. 1985; 41: 197-202) discussed the fate of the original surface area during fragmentation. The results of a modelling experiment indicate that the probability of a fragment having some of the original surface area is directly proportional to the fragment's size. Also, it has been shown that the total surface area of those fragments contain some of the original surface area which is constant regardless of how finely these fragments are ground. In our experiment the original surface area of the calculi is distributed in a constant manner in the daughter fragments, it will affect in a similar way all fragments analyzed. Consequently, the newly generated fracture surface after fragmentation will reflect the pattern of size reduction process used.

W.G. Robertson: What effect does the organic matrix content of stones have on the two types of fragmentation procedures?

Authors: In this study , the stones contained approximately 4% (w/w) of organic material. There is no doubt that the organic content of stones will affect the two types of fragmentation procedures. The presence of the organic matrix may give some slight degree of plasticity which might make the fragmentation easier. In addition, the behavior of stones under any fragmentation procedures will be also a function of the mineral phase, structural aspects and packing arrangement.

W.G. Robertson: What effect does increasing content of calcium phosphate have on the fragmentation properties of calcium oxalate stones?

Authors: We believe that the increasing content of calcium phosphate will have a definite effect on the fragmentation process. Per se, calcium phosphate (brushite) is a brittle material and in the context of calcium oxalate stone, the increase brushite concentration could favour the fragmentation. However, one should bear in mind other factors such as the presence of different hydrated forms of calcium phosphate or different crystal habit modifications which will have an effect on the behavior of such stones during disintegration.