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● *Original Contribution*

EFFECTS OF STONE SIZE ON THE COMMINUTION PROCESS AND EFFICIENCY IN SHOCK WAVE LITHOTRIPSY

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Abstract—The effects of stone size on the process and comminution efficiency of shock wave lithotripsy (SWL) were investigated in experiments, numerical simulations and scale analysis. Cylindrical BegoStone phantoms with approximately equal height and diameter of either 4, 7 or 10 mm, in a total aggregated mass of about 1.5 g, were treated in an electromagnetic shock wave lithotripter field. The resultant stone comminution was found to correlate closely with the average peak pressure, $P_{+(avg)}$, incident on the stones. The $P_{+(avg)}$ threshold necessary to initiate stone fragmentation in water increased from 7.9 to 8.8 to 12.7 MPa, respectively, as stone size decreased from 10 to 7 to 4 mm. Similar changes in the $P_{+(avg)}$ threshold were observed for the 7- and 10-mm stones treated in 1,3-butanediol, in which cavitation is suppressed, suggesting that the observed size dependency is due to changes in stress distribution within stones of different size. Moreover, the slope of the correlation curve between stone comminution and $\ln(\overline{P}_{+(avg)})$ in water increased with decreasing stone size, whereas the opposite trend was observed in 1,3-butanediol. The progression of stone comminution in SWL exhibited size-dependence: the 7- and 10-mm stones fragmented into progressively smaller pieces, whereas a significant portion (>30%) of the 4-mm stones reached a stalemate within the size range of 2.8 ~ 4 mm, even after 1000 shocks. Analytical scaling considerations suggest size-dependent fragmentation behavior, a hypothesis further supported by numerical model calculations that reveal changing patterns of constructive and destructive wave interference and, thus, variations in the maximum tensile stress or stress integral produced in cylindrical and spherical stone of different sizes. (E-mail: pzhong@duke.edu) **© 2016 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Shock wave lithotripsy, Stone fragmentation, Size effect, Stress waves, Constructive and destructive wave interference.**

INTRODUCTION

Since the original Dornier HM3, contemporary shock wave lithotripters have evolved progressively within the technology for shock wave generation, focusing, patient coupling, imaging and overall functionality of the system (Lingeman 1997; Rassweiler et al. 1992). Despite this, the efficiency of shock wave lithotripsy (SWL) has not improved appreciably in the past two decades (Gerber et al. 2005; Graber et al. 2003; Lingeman et al. 2009). This lack of progression has been attributed, in part, to an incomplete understanding of the fundamental mechanisms and associated dynamic processes responsible for stone comminution (SC), as well as identification of key lithotripter field parameters (Lingeman et al. 2003; Zhong 2013) and other factors, such as coupling interface quality (Leighton and Cleveland 2010; Lingeman et al. 2003; Pishchalnikov et al. 2006), that may influence treatment outcome.

Multiple mechanisms of stone fragmentation have been proposed, including spalling (Chaussy et al. 1980; Lubock 1989; Whelan and Finlayson 1988), cavitation (Coleman et al. 1987; Crum 1988; Holmer et al. 1991), compression-induced tensile failure (Chaussy 1982; Chaussy et al. 1980; Lokhandwalla and Sturtevant 2000), quasi-static squeezing (Eisenmenger 2001) and dynamic squeezing with emphasis on shear wave generation (Sapozhnikov et al. 2007). Among these, spalling (Mihradi et al. 2004; Xi and Zhong 2001), cavitation (Calvisi et al. 2008) and shear wave stress (Cleveland and Sapozhnikov 2005) have been found to depend critically on the size or geometry of the stone. Furthermore,

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acoustic pulse energy E_{eff} (Delius et al. 1994; Eisenmenger 2001; Granz and Köhler 1992; Koch and Grunewald 1989) and peak average pressure $P_{+(avg)}$ incident on the stone (Smith and Zhong 2012) are two lithotripter field parameters that have been correlated with SC. However, the size dependency in the thresholds of $P_{+(avg)}$ and E_{eff} required to initiate stone fragmentation has not been investigated.

This study was motivated by the general observation that the rate of stone comminution during SWL is not uniform (Smith and Zhong 2013), but rather is characterized by a rapid initial increase to a maximum within a few hundred shocks, followed by a slow progressive decay within a few thousand shocks toward the end of treatment (Zhong 2013). When a stone is disintegrated, the refraction of the incident lithotripter shock wave (LSW) into the resulting fragments and the interaction of different stress waves inside the stone material will change (Xi and Zhong 2001), leading to varied stone comminution rates (Xi and Zhong 2001; Zhong 2013). Similarly, reflection of the LSW from the fragments and its impact on cavitation produced in the surrounding fluid may also change as treatment progresses (Calvisi et al. 2008; Iloreta et al. 2008). These two fundamental and constantly evolving processes in SWL, coupled with the continuing change in the intrinsic (*i.e.,* pre-existing) flaw distribution inside the residual stone and the extrinsic flaw population created by cavitation bubbles on the surface of the fragments (both the stone and fragments are being further disintegrated as the treatment progresses), will dictate the overall comminution processes (Zhong 2013). Furthermore, treatment strategy will influence how these two critical processes may eventually contribute to SWL outcome (Maloney et al. 2006; Pishchalnikov et al. 2006; Zhou et al. 2004). Although stress waves and cavitation can act synergistically in SWL to produce effective SC (Zhu et al. 2002), the influence of continuously evolving fragment size during SWL on treatment progression and outcome is largely unknown.

Insight into the relative importance of various fragmentation mechanisms has been sought by numerical modeling of the propagation of acoustic pulses into kidney stone simulants. Finite difference studies of 2-D elasticity models (Dahake and Gracewski 1997a, 1997b), ray-tracing analysis (Xi and Zhong 2001) and numerical studies based on the finite-element method (Mihradi et al. 2006) highlighted the importance of focusing effects induced by stone geometry. Axisymmetric finite-difference models (Cleveland and Sapozhnikov 2005) refined previous studies by considering the realistic strain rates produced by rapid lithotripter pulse rise time. Additional studies with the same numerical model, in combination with experiments (Sapozhnikov et al. 2007), assessed the role of various possible stone breakup mechanisms and indicated that tensile stress induced by shear waves emanating from the lateral boundary of cylindrical U30 stones (placed at the lithotripter focus with its flat surfaces aligned parallel to the incident LSW front) dominates the spallation mechanism in the creation of the first fracture in the posterior region of the stone. Furthermore, fracture of individual cylindrical stones in a lithotripter field was analyzed by using a finite-element model that incorporates cohesive interface elements, and the results were compared with experimental observations (Mota et al. 2006).

In this study we have combined experiment, scaling analysis and numerical simulation to investigate the effect of stone size on the comminution process and efficiency in SWL. Comminution experiments were carried out using artificial kidney stones of different size groups either individually or in groups with approximately matched total mass. Similarity theory considerations were invoked to assess the possibility of self-similar behavior in LSW–stone interaction on a change of scale. Numerical simulations of the refraction or reflection of an incident pressure pulse by isolated, single stones of different shape and size were used to illustrate the origin of various stress waves and how their interactions may lead to the maximum tensile stress or stress integral produced inside the stone. The numerical results are discussed in comparison with the experimental observations.

METHODS

To assess the effect of stone size on comminution efficiency, artificial kidney stones of cylindrical shape with approximately equal diameter and height (4, 7 and 10 mm) were prepared from BegoStone Plus (BEGO USA, Lincoln, RI, USA) with a powder-to-water mixing ratio of 5:1. These artificial stones mimic the acoustic and mechanical properties of calcium oxalate monohydrate and brushite stones, which are known to be difficult to fragment in SWL (Dretler 1988; Esch et al. 2010; Liu and Zhong 2002; Zhong and Preminger 1994; Zhong et al. 1993). To reduce the influence of stone mass on treatment outcome, either one 10-mm[i] stone ($\sim$1.50 g), three 7-mm stones ($\sim 3 \times 0.40 = 1.20$ g) or fourteen 4-mm stones ($\sim 14 \times 0.11 = 1.54$ g) were used in each experiment so that the total mass of the stone materials in each group was approximately matched. In addition, experiments employing single cylindrical stones of different sizes (4, 7 or 10 mm) were carried out at the lithotripter focus to determine the number of shocks required

[i]The 10-mm cylindrical stone has a diameter of 9.5 mm and a height of 10 mm.