Published in final edited form as:
Urol Res. 2010 August ; 38(4): 315–319. doi:10.1007/s00240-010-0298-x.

A simple method for fabricating artificial kidney stones of different physical properties

Eric Esch[1], **W. Neal Simmons**[1], **Georgy Sankin**[1], **Hadley F. Cocks**[1], **Glenn M. Preminger**[2], and **Pei Zhong**[1,2]

[1]Duke University, Department of Mechanical Engineering and Materials Science, 100 Science Drive, Durham NC 27708, USA

[2]Duke University Medical Center, Department of Surgery - Urology, 3167 Trent Drive, Durham, NC 27710, USA

Abstract

A simple method for preparing artificial kidney stones with varying physical properties is described. BegoStone was prepared with a powder to water ratio (by weight) ranging from 15:3 to 15:6. The acoustic properties of the phantoms were characterized by using an ultrasound transmission technique, from which the corresponding mechanical properties were calculated based on elastic wave theory. The measured parameters for BegoStone phantoms of different water contents are: longitudinal wave speed (3148 – 4159 m/s), transverse wave speed (1813 – 2319 m/s), density (1563 – 1995 kg/m^3), longitudinal acoustic impedance (4.92 – 8.30 Kg/m^2*s), transverse acoustic impedance (2.83 – 4.63 Kg/m^2*s), Young's modulus (12.9 – 27.4 GPa), bulk modulus (8.6 – 20.2 GPa), and shear modulus (5.1 – 10.7 GPa), which cover the range of corresponding properties reported in natural kidney stones. In addition, diametral compression tests were carried out to determine tensile failure strength of the stone phantoms. BegoStone phantoms with varying water content at preparation have tensile failure strength from 6.9 – 16.3 MPa when tested dry and 3.2 – 7.1 MPa when tested in water-soaked condition. Overall, it is demonstrated that this new BegoStone preparation method can be used to fabricate artificial stones with physical properties matched with those of natural kidney stones of various chemical compositions.

Keywords

Renal calculi; shock wave lithotripsy; artificial stones; physical properties; longitudinal and transverse wave speeds; tensile fracture strength

Introduction

Since its introduction in the early 1980s, shock wave lithotripsy (SWL) has become the primary treatment modality for renal calculi [1-2]. Over the past decade, significant efforts have been made to better understand the physical mechanisms of stone comminution [3-7] and to compare the performance of different clinical lithotripters [8-9]. Such basic research often relies on the use of artificial kidney stones because of the scarcity and large variations in the composition, structure, and physical properties of natural kidney stones. It has been shown that the variations in stone physical properties can lead to significant differences in

Correspondence: Pei Zhong, tel: (919) 660-5336, pzhong@duke.edu.
Proceedings of the 3rd International Urolithiasis Research Symposium held in Indianapolis, IN, USA, December 3-4, 2009

wave reflection and refraction (or transmission) at the stone-fluid interface, as well as varying fragilities of natural [10-11] and artificial kidney stones [12] in SWL.

Several different types of stone phantoms have been developed previously, including Z-brick and Plaster-of-Paris blocks. Overall, two gypsum-based plaster materials have been used most extensively for fabricating stone phantoms. These stone phantoms are BegoStone [13], which has acoustic and mechanical properties similar to hard kidney stones composed of calcium oxalate monohydrate (COM) and brushite, and Ultracal 30 [14], which mimics more closely the acoustic and mechanical properties of soft kidney stones composed of uric acid or magnesium ammonium phosphate hydrogen (MAPH).

It is desirable to develop artificial kidney stones that can cover the wide range of physical properties observed in natural kidney stones. These stone models may facilitate in-depth investigation and comparison of different clinical lithotripters. Recently, a new composite stone phantom made of BegoStone and albumen has been developed with resultant tensile failure strength and acoustic properties varying across the range of those observed in natural kidney stones [15]. The preparation of this composite stone phantom, however, is time-consuming. In this study, we present a simple method for changing the physical properties of BegoStone phantoms by variation of powder to water mixing ratio during sample preparation. We have shown that by controlling water content in the phantom, both acoustic and mechanical properties of the artificial stones can be adjusted across the range reported in natural kidney stones.

Materials and Methods

Stone Phantom Preparation

For physical property characterization, BegoStone Plus (BEGO USA, Lincoln, RI) or Ultracal 30 (US Gypsum, Chicago, IL) powder in amounts from 6 to 20 g was mixed with filtered tap water and stirred with a spatula until the appearance of homogeneous slurry for 30 to 60 seconds. Immediately, the slurry was degassed under vacuum for 20 seconds to evacuate air bubbles. Before the cure time (~ 5 minutes), the slurry was filled into polytetrafluoroethylene cylindrical molds machined in-house. All samples were allowed to cure for 12-24 hours at room temperature, demolded by press-pin or tapping on the back surface of the mold with a wood hammer, before sliced into dish-shape samples using a diamond saw (SMART CUT 6001 UKAM Industrial Superhard Tools, Valencia, CA). Afterwards, these samples were let dry in air for at least 4 hours before testing under dry condition, or soaked in water for at least 1 hour before testing under wet condition.

To determine the effect of water content on the physical properties of the stone phantoms, the amount of water used for sample preparation was varied. In prior use as a kidney stone phantom, BegoStone Plus has been prepared at 15:3 powder to water ratio by weight, so for this study samples were prepared using 15:3, 15:4, 15:5, and 15:6 powder to water ratio. Attempts to decrease BegoStone water content below 15:3 failed to produce moldable slurry; the resulting powder cake was too dry. For comparison to BegoStone, Ultracal 30 samples were prepared using a powder to water ratio of 100:38, which is the standard mixing ratio recommended by the manufacturer of Ultracal 30 for its original purpose - casting art molds. This ratio provides workable slurry with a similar cast time to BegoStone. Attempts to prepare Ultracal 30 samples with higher water content led to settling within the slurry during curing, resulting in samples with an apparent hardness and strength gradient in the direction of gravity.

Measurement of Acoustic Wave Speeds

Both longitudinal and transverse acoustic wave speeds of the stone phantoms were measured using an ultrasound transmission technique [16-17]. Stone phantoms were molded into a 40 × 13 mm (height × diameter) cylinder, then sliced into disk-shape samples of 13 × 0.5 ~ 2.5 mm (diameter × thickness) using the diamond saw. The time-of-flight through each sample was measured using a pair of transducers - 10 MHz for longitudinal and 5 MHz for transverse wave (Panametrics-NDT ultrasound transducers, Olympus NDT, Waltham, MA), respectively. The ultrasound transducers were coupled to opposite sides of the sample using one transducer as a transmitter and the other as a receiver. The transducers were coupled to the samples with ultrasound gel (Medline, Mundelein, IL) for longitudinal wave speed measurement, and with a viscous coupling gel (Olympus NDT, Waltham, MA) for shear wave speed measurement. The transducers were connected to a pulser/receiver (Panametrics-NDT 5072PR Olympus, Waltham, MA) and the output was registered on a digital oscilloscope (LeCroy 9310A LeCroy, Chestnut Ridge, NY) operated at 100 MHz sample rate. The time of flight in samples of different thicknesses were measured and linear regression versus sample thickness was applied to determine the longitudinal and transverse wave speeds.

Having measured the longitudinal and transverse wave speeds (C_L, C_T), density (ρ) of the stone phantom was calculated from mass and volume measured with precision balance and digital micrometer, respectively. From these measurements, longitudinal and transverse acoustic impedance ($Z_{L,T} = \rho \times C_{L,T}$) were calculated. In addition, based on the theory of elastic wave propagation in a homogenous and isotropic medium, the Young's (E), bulk (K), and shear (G) moduli, as well as the Poisson's ratio (ν) of the stone phantom were calculated using the following equations:

$$E=\rho C_T^{\,2}\frac{[3-4(C_T/C_L)^2]}{[1-(C_T/C_L)^2]} \quad (1)$$

$$K=pC_L^{\,2}\left(1-\frac{4}{3}\left(\frac{C_T}{C_L}\right)^2\right) \quad (2)$$

$$G=\rho C_T^{\,2} \quad (3)$$

$$\nu=\frac{1-2(C_T/C_L)^2}{2-2(C_T/C_L)^2} \quad (4)$$

Diametral Compression Test

Diametral compression is a technique of measuring tensile failure strength of brittle materials by compression of a right cylindrical sample along its diameter [18]. Diametral compression has been used to measure tensile failure strength of natural [19] and artificial kidney stones [15]. In this work, stone phantoms were made in 6 × 10 mm (diameter × height) cylindrical polystyrene molds with 6 mm press-fit steel pins for demolding. The resulting cylinders were sliced into disk-shape samples of 6 × 1.5 to 3.5 mm (diameter × thickness). Diametral compression was conducted on a universal testing machine (LR10K Lloyd Instruments Ltd, West Sussex, UK) with a 1 kN load cell and a compression rig to ensure planar compression. Individual samples were loaded in the rig center with two layers of paper towel (shown as shims in Fig. 1a) cushioning either side of the sample to eliminate stress concentration between the steel compression rig and the artificial stone sample. Compression was applied at 1 mm/min rate until the sample fractured along the diameter in which the load was applied (Fig. 1b). Under such conditions, the tensile failure strength (σ_{max}) of the sample was calculated using the following equation [18],

$$\sigma_{\max}=\frac{2P}{\pi DT} \quad (5)$$

in which P is the applied load at the time of fracture, D is the sample diameter and T is the sample thickness.

Stone Fragmentation

To assess fragility, stone phantoms made of BegoStone and Ultracal 30 were molded to 10 mm spheres and fragmented by a commercial electromagnetic shock wave lithotripter (Modularis, Siemens USA, Malvern PA). Each stone phantom received 200 shocks produced by the Modularis at an output energy setting of E3.0. After comminution, stone fragments were sieved sequentially through 4.0-, 2.8- and 2.0-mm grids and fragmentation efficiency was determined by percentage of fragments less than 2 mm in size.

Results & Discussion

Results of the measured longitudinal and transverse wave speeds (C_L, C_T), and density (ρ) of BegoStone stone phantoms prepared with varying powder to water ratios are summarized in Table 1. Corresponding data measured from Ultracal 30 samples and for natural kidney stones [17] are also listed for comparison. Table 2 shows the derived mean values of mechanical and acoustic properties for the stone phantoms and natural kidney stones, including longitudinal and transverse acoustic impedance (ρC_L, ρC_T), Poisson's ratio (ν), Young's modulus (E), bulk modulus (K), and shear modulus (G). The range of property values for natural kidney stones is approximately covered by the BegoStone phantoms prepared with different powder to water ratios. In particular, BegoStone phantoms with 15:3 powder to water ratio approximately match the properties of (hard) COM stones, while BegoStone phantoms with 15:6 powder to water ratio approximately match the properties of (soft) MAPH stones. In the intermediate range, BegoStone samples can be fabricated to match properties of brushite and uric acid stones. Measurement results of Ultracal 30 stone phantoms prepared with powder to water ratio of 100:38 compare reasonably well with previously reported values of C_L = 2840 m/s, C_T = 1430 m/s, and ρ = 1700 kg/m^3, in which a 100:100 mixing ratio was used [14]. These physical properties of Ultracal 30 are between the values of MAPH and uric acid stones. In addition, Ultracal 30 samples with less water content were prepared in an effort to increase sample hardness, but the slurry was too dry to mold into homogeneous samples.

The longitudinal and transverse acoustic impedances of BegoStone samples of varying water content are shown in Figure 2. Also shown are the reported acoustic impedances of natural kidney stones of various compositions [17], displayed as horizontal dashed lines. These results demonstrate that BegoStone phantoms can be prepared to cover the range of acoustic impedances (a critical parameter that determines the reflection and transmission of an incident lithotripter shock wave at stone boundary) reported in natural kidney stones.

The tensile failure strength of BegoStone phantoms with varying powder to water ratio is shown in Figure 3 for both dry and soaked samples. The tensile failure strength is an important material property because most kidney stones are brittle and easy to fail under tension than under compression [17, 19]. The results also demonstrate that soaking of the stone phantoms significantly reduces their tensile failure strength, as a result of decreased surface energy. In comparison, at 15:3 powder to water mixing ratio, BegoStone phantoms have higher tensile failure strength (16.3 ± 1.8 MPa in dry and 7.12 ± 0.27 MPa in wet condition) than the corresponding value of the 100:38 powder to water mixing ratio Ultracal 30 phantoms (5.98 ± 0.27 MPa in dry and 2.33 ± 0.15 MPa in wet condition). Accordingly, these BegoStone phantoms have been found to be less fragile than the Ultracal 30 phantoms. Following exposure to 200 shocks produced by the Modularis, a stone comminution efficiency of 51.0 ± 3.4% was produced in the BegoStone phantoms compared to 68.1 ± 4.2% in the Ultracal 30 phantoms (Fig. 4).

Conclusion

A simple method for fabricating artificial kidney stone phantoms of varying acoustic and mechanical properties is described. By changing the water content in the BegoStone phantoms during sample preparation, the acoustic and mechanical properties of the stone phantoms can be adjusted to match the values within the range reported for natural kidney stones from COM to MAPH.

Acknowledgments

This work was supported in part by the NIH through grant RO1 DK052985 (PZ) and a Pratt Engineering Undergraduate Fellowship (EE) at Duke University.

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Abbreviations

COM	calcium oxalate monohydrate
MAPH	magnesium ammonium phosphate hydrogen
C_L	longitudinal wave speed
C_T	transverse wave speed
ρ	density
ν	Poisson’s ratio
E	Young’s modulus
K	bulk modulus
G	shear modulus

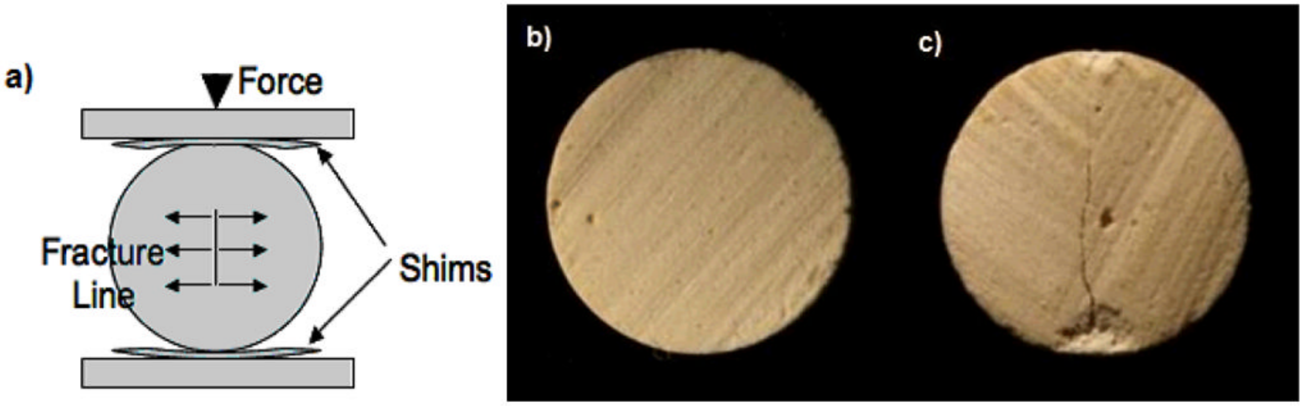

Fig. 1.

a) Schematic diagram of the diametral compression test for measuring the tensile failure strength in a disk-shape stone phantom, **b)** BegoSone sample prepared with 15:3 powder to water mixing ratio by weight before diametral compression test, and **c)** another sample after diametral compression test. Note that the crack line was formed along the diameter in which the load is applied. Samples exhibiting other fracture patterns were excluded, as other patterns indicate non-tensile failure modes. The diameter of the sample is 6 mm with a thickness of 2.5 mm.

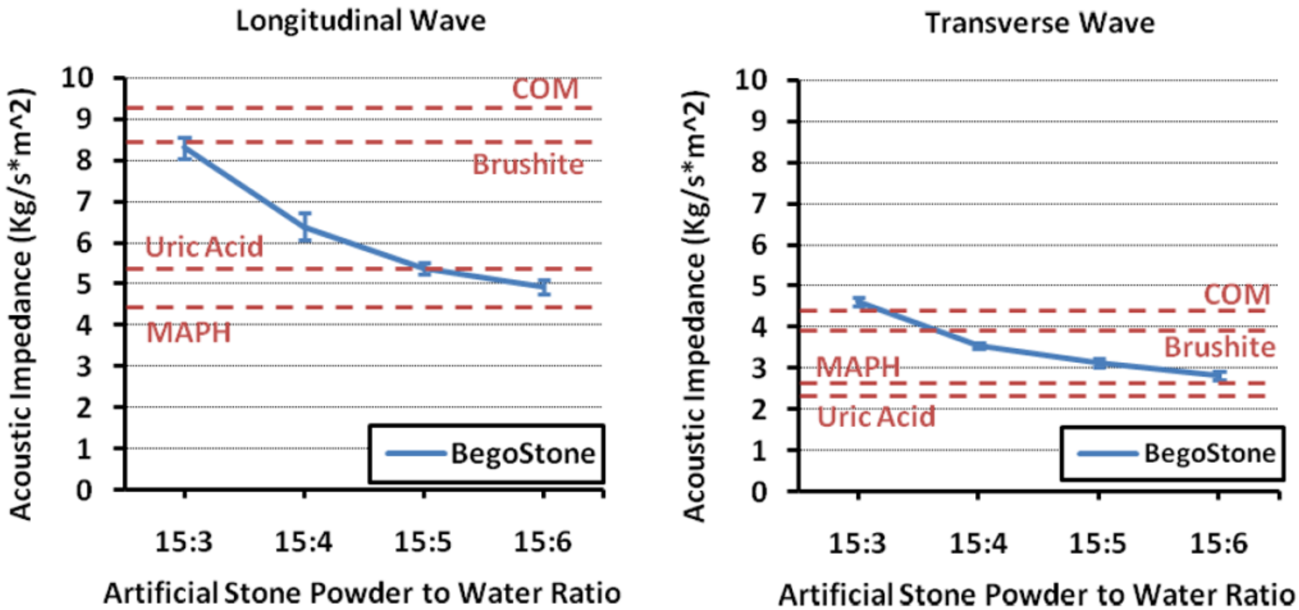

Fig. 2.

Longitudinal and transverse acoustic impedances of BegoStone phantoms of different powder to water mixing ratios. The means of the corresponding values for natural kidney stones (data taken from ref. 17) are also displayed in dashed lines for comparison. Sample size is n = 6 ~ 7. Error bars are std. error of mean.

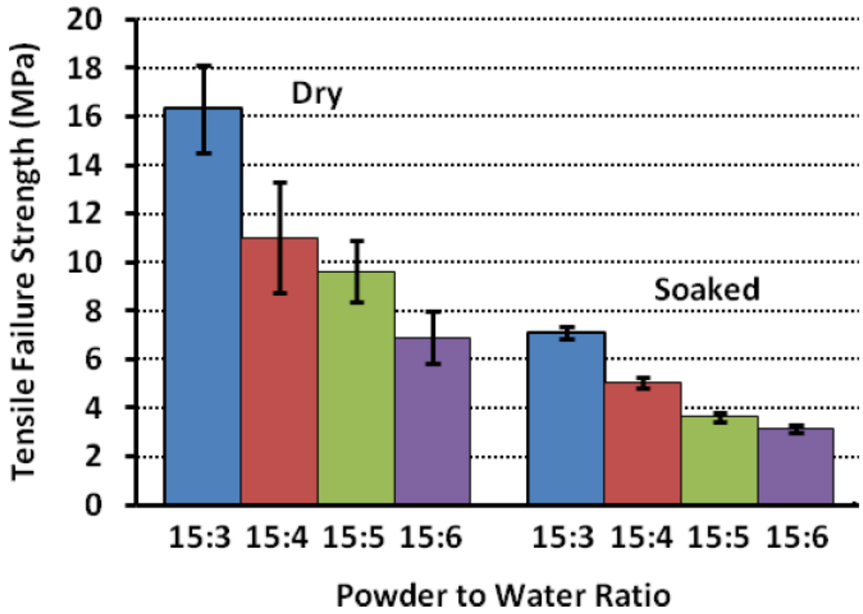

Fig. 3.
Tensile failure strength of BegoStone phantoms of different powder to water mixing ratio measured under dry and soaked conditions. Sample sizes are: n = 4 ~ 10. Error bars are std. error of mean.

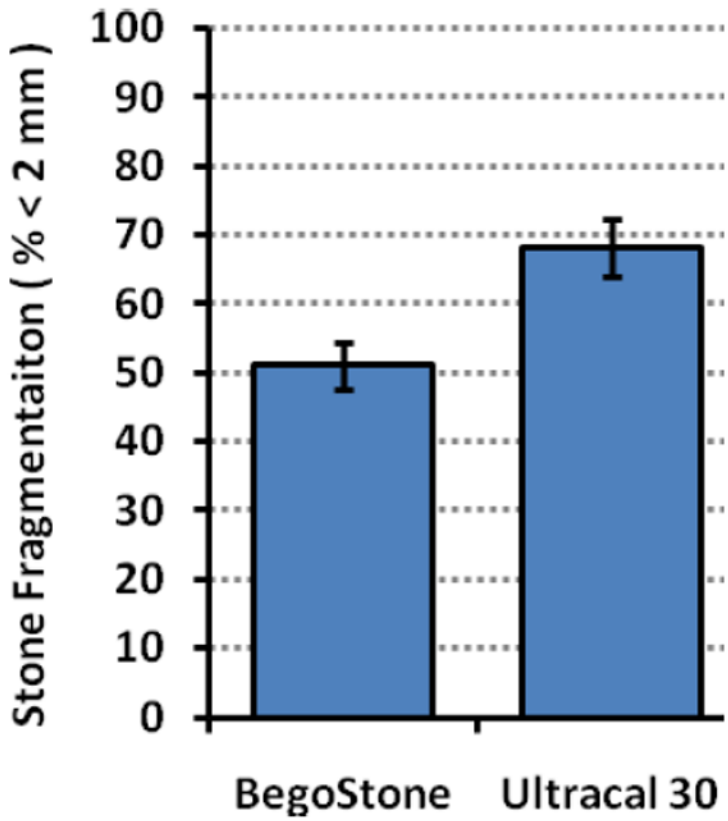

Fig. 4.

Stone comminution efficiency of BegoStone and Ultracal 30 artificial stones after 200 shocks in a Siemens Modularis lithotripter at energy level E3.0. BegoStone and Ultracal 30 phantoms are prepared using powder to water ratios 15:3 and 100:38, respectively. Sample size is: n = 4 ~ 6. Error bar represents std. deviation.

Table 1

Longitudinal and transverse wave speeds, and density of BegoStone phantoms with different powder to water ratios, Ultracal 30 stone phantom, and natural kidney stones of different chemical compositions. Data are presented in mean ± standard error of the mean. Sample size is: n = 4 ~ 7.

Stone Material	*Powder to water ratio*	C_L (m/s)	C_T (m/s)	ρ (Kg/m^3)
BegoStone	15:3	4159 ± 114	2319 ± 34	1995 ± 18
	15:4	3519 ± 180	1956 ± 38	1815 ± 10
	15:5	3254 ± 42	1892 ± 50	1650 ± 17
	15:6	3148 ± 58	1813 ± 34	1563 ± 23
Ultracal 30	100:38	3180 ± 93	1880 ± 111	1693 ± 43
Kidney Stones[#]	COM	4535 ± 58	2132 ± 25	2038 ± 34
	Brushite	3932 ± 134	1820 ± 22	2157 ± 16
	Uric Acid	3471 ± 62	1464 ± 12	1546 ± 12
	MAPH	2798 ± 82	1634 ± 25	1587 ± 68

[#] Natural kidney stone data from ref. 17.

Table 2

Derived physical properties of natural kidney stones and artificial stones phantoms. Values are calculated from means of measured values shown in Table 1.

Stone Material	*Powder to water ratio*	$\rho C_L \times 10^6$ (Kg/m^2*s)	$\rho C_T \times 10^6$ (Kg/m^2*s)	ν	*E* (GPa)	*K* (GPa)	*G* (GPa)
BegoStone	15:3	8.30	4.63	0.27	27.4	20.2	10.7
	15:4	6.39	3.55	0.28	17.7	13.2	6.9
	15:5	5.37	3.12	0.25	14.7	9.6	5.9
	15:6	4.92	2.83	0.25	12.9	8.6	5.1
Ultracal 30	100:38	5.384	3.18	0.231	14.7	9.1	6.0
Kidney Stones#	COM	9.24	4.35	0.33	24.5	9.2	24.3
	Brushite	8.48	3.93	0.36	19.5	7.2	23.8
	Uric Acid	5.37	2.26	0.39	9.2	3.3	14.2
	MAPH	4.44	2.59	0.24	10.5	4.2	6.8

Natural kidney stone data from ref. 17.