Urol Res (2010) 38:307–313
DOI 10.1007/s00240-010-0295-0

SYMPOSIUM PAPER

Evaluating the importance of mean stone density and skin-to-stone distance in predicting successful shock wave lithotripsy of renal and ureteric calculi

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Received: 21 June 2010 / Accepted: 25 June 2010 / Published online: 13 July 2010

Abstract Shock wave lithotripsy (SWL) is considered the first line treatment for the majority of patients with renal and ureteric calculi, with success rates from contemporary series varying from 60 to 90%. Success is dependent on many patient and stone-related factors. We conducted a retrospective analysis of mean stone CT density (MSD) and skin-to-stone distance (SSD) to determine their influence on the success of SWL of renal and ureteric calculi. Data from all patients treated at the St. Michael's Hospital Lithotripsy Unit from May 2004 to June 2009 were reviewed. Analysis was restricted to those patients with a pre-treatment non-contrast CT scan conducted at our center demonstrating a solitary renal or ureteric calculus $\leq$20 mm in maximal diameter. Successful treatment of renal stones was defined as those patients who were stone free or had asymptomatic, clinically insignificant residual fragments $\leq$4 mm in diameter, as measured by KUB X-ray, 3 months after a single SWL treatment. Successful treatment of ureteric stones was defined as being stone free on KUB X-ray, 2-weeks post-SWL. Demographic, stone, patient, treatment and follow-up data were collected from a prospective database and review of CT and KUB imaging by two independent urologists and one radiologist. Data were analyzed with logistic regression, Chi square analysis and ANOVA where appropriate. 422 patients (69.7% male) with a mean age of 51.4 years (SD 12.9) and mean BMI 27.0 kg/m^2 (SD 4.9) were analyzed. Mean stone size was 78.9 mm^2 (SD 77.3) for ureteral stones and 66.1 mm^2 (SD 63.2) for renal stones, with 95 (43.6%) of the renal stones located in the lower pole. The single-treatment success rates for ureteral and renal stones were 62.3% and 68.8%, respectively. On univariate analysis, predictors of SWL success, regardless of stone location, were age ($p = 0.01$), BMI ($p = 0.01$), stone size ($p < 0.01$), MSD ($p < 0.01$) and SSD ($p < 0.01$). On multivariate analysis, MSD >900 HU (OR = 0.49, CI: 0.32–0.75) and SSD >110 mm (OR = 0.49, CI: 0.31–0.78) were both significant predictors of outcome. We have identified in a large series of renal and ureteric calculi that both MSD and SSD can reliably predict SWL outcomes. This data can be used in combination with other patient and stone-related factors to facilitate optimal treatment-based decisions and provide patients with more accurate single-treatment success rates for SWL.

Keywords Shock wave lithotripsy · Predictors · Success · Urolithiasis

Introduction

Due to its high sensitivity and accuracy in diagnosing urolithiasis, in combination with novel techniques to reduce radiation dosages, abdominal/pelvic non-contrast CT imaging (NCCT) has increased in popularity over the past two decades and has currently replaced urography as the gold standard in diagnosing urolithiasis [1–3]. CT imaging provides information regarding patient and stone-related factors that impact the successful treatment of urolithiasis.

Proceedings paper from the third international urolithiasis research symposium, Indianapolis, Indiana, USA, December 3–4, 2009

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Although many treatments exist for urolithiasis, shock wave lithotripsy (SWL) continues to be a first line treatment for both ureteral and renal stones [4, 5]. Despite its popularity, however, contemporary SWL treatment success varies widely as measured by efficiency quotients between 0.36 and 0.67 [6–11]. With such a broad range in SWL efficiency quotients, there are several patients who fail their initial SWL treatment, either by a lack of stone fragmentation or their inability to clear all fragments. This treatment failure results in unnecessary exposure of the renal parenchyma to trauma with the potential for acute renal injury, hemorrhage, edema and pain. Furthermore, SWL failure necessitates further treatment and thus augments the medical costs to both the patient and the health care system.

Many urologists have developed methods to predict the success of SWL in treating urolithiasis. The only nomogram developed utilized many stone parameters that affected treatment outcome, including stone size, location and multiplicity [12]. Other studies have used NCCT-based parameters in an attempt to predict stone composition and subsequent SWL success. Nakada et al. [13] were able to differentiate between uric acid and calcium oxalate monohydrate stones using peak attenuation measurements and Sheir et al. [14] could differentiate between pure stone classes. Table 1 reviews the studies examining mean stone density (MSD), skin-to-stone distance (SSD), and MSD to stone size ratio as predictors of SWL success.

Our study evaluates the ability of MSD and SSD, as measured by NCCT, in predicting the successful SWL treatment of both renal and ureteric calculi. Additionally, mathematical manipulations of MSD are evaluated in an attempt to improve its predictive value of treatment success.

Materials and methods

All adult patients with radiopaque renal and ureteric calculi who were treated at the St. Michael's Hospital Lithotripsy Unit from May 2004 to June 2009 were included. Analysis was restricted to those patients with a pre-treatment NCCT (5-mm collimation width, GE Lightspeed QXI 4-slice multidetector, 120 kV, 240 mA; General Electric, Milwaukee, WI) conducted at our center demonstrating a solitary, radiopaque renal or ureteric calculus between 5 and 20 mm in maximal diameter. Exclusionary criteria included absolute contraindications to SWL such as pregnancy, active urosepsis, uncorrected coagulopathy and patients currently anticoagulated (Table 2).

All lithotripsy treatments were performed using the Philips Lithotron Ultra. During SWL, patients received neuroleptic anesthesia and were treated with up to 3,000 shocks for renal stones and up to 4,000 shocks for mid- and distal ureteral stones, up to a maximum power of 23 kV at 120 shocks per minute. Power was gradually augmented during the initial minute of treatment. Stones were targeted by biplanar fluoroscopy at regular intervals throughout the treatment. Patients were discharged home later the same day.

Patient demographics, stone and treatment characteristics and SWL outcomes were prospectively recorded in a clinical database. Stone characteristics based on the pre-treatment NCCT were separately reviewed and recorded by two urologists and one radiologist. Stone characteristics include location, size, MSD and SSD. MSD was measured using bone windows on the magnified, axial NCCT image of the stone in the maximal diameter, where the elliptical region of interest incorporated the largest cross-sectional area of stone without including adjacent

Table 1 Review of literature on the role of stone density and skin-to-stone distance

Reference	Year	*n*	Stone location	Predictors of successful treatment	
				Stone density	Skin-to-stone distance
Joseph et al. [22]	2002	30	Renal	Yes	–
Pareek et al. [16]	2005	64	Lower calyx	No	Yes
Gupta et al. [23]	2005	112	Renal and proximal ureter	Yes	–
Yoshida et al. [24]	2006	62	Renal and proximal ureter	Yes	–
Perks et al. [25]	2007	76	Renal and ureter	Yes	–
El-Nahas et al. [18]	2007	120	Renal	Yes	No
Weld et al. [26]	2007	200	Renal	Yes	No
Perks et al. [20]	2008	111	Renal	Yes	Yes
Kacker et al. [27]	2008	325	Renal and ureter	Yes	–
Jacobs et al. [28]	2008	85	Renal and ureter	–	No
Bandi et al. [29]	2008	94	Renal and ureter	Yes	No
Ng et al. [19]	2009	94	Proximal ureter	Yes	Yes
Patel et al. [30]	2009	83	Renal	No	Yes

Table 2 Study inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Renal/ureteric stones screened and treated for the first time	Multiple stones on the same side
SWL at St. Michael's Hospital (SMH)	Stones treated at SMH, but followed-up elsewhere
Follow-up at SMH (1 week, 3 months post treatment)	Renal or ureteric stone >20 mm in maximal diameter
Complete demographic and stone information	
CT scan at SMH prior to SWL treatment	

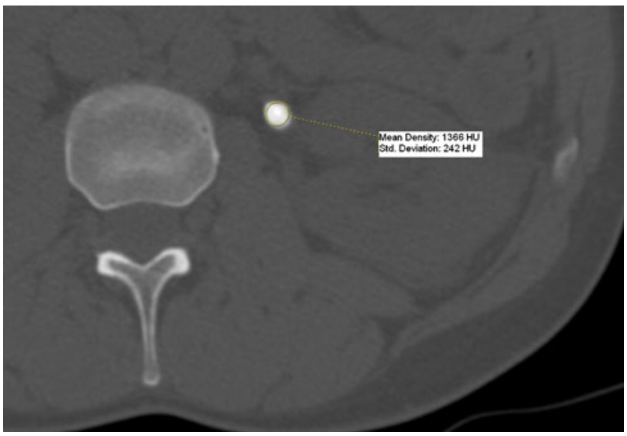

Fig. 1 Technique used to measure mean stone density (MSD). 5-mm collimation width, bone windows, elliptical region of interest incorporating largest cross-sectional area of stone without including adjacent soft tissue

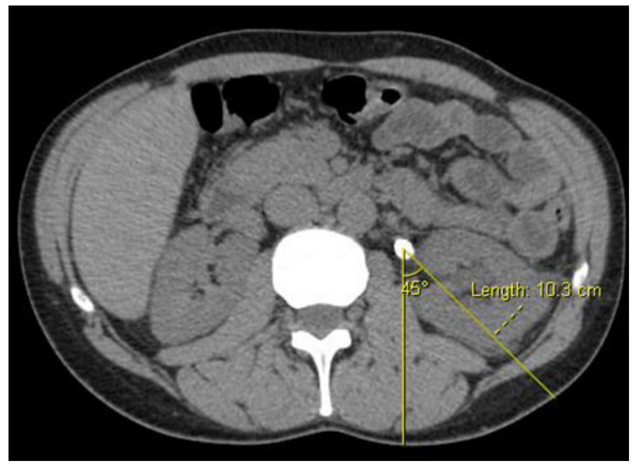

Fig. 2 Technique used to measure skin-to-stone distance (SSD), utilizing the distance 45° from the horizontal and vertical measurements

soft tissue (Fig. 1). SSD was measured in the axial plane 45° off the vertical axis, as this is where the Philips Lithotron Ultra shock wave generator is positioned at the time of lithotripsy (Fig. 2). The MSD attenuation ratio was calculated by dividing the mean Hounsfield units of each stone by its cross-sectional area, as measured in the axial CT scan.

Successful SWL treatment of renal calculi was defined as those patients who were rendered stone free or had asymptomatic, clinically insignificant residual fragments ≤4 mm in maximal diameter 3 months after a single SWL treatment, as measured by KUB X-ray. Successful treatment of ureteric calculi was defined as stone free on KUB X-ray, 2 weeks following a single SWL treatment.

Statistical comparisons of patient demographics, stone density, size, stone location, presence of ureteric stent and MSD were calculated using logistic regression, ANOVA or Chi square analysis, where appropriate. Mantel–Haenszel common odds ratio (OR) estimates were used to determine the MSD and SSD thresholds that best predict successful lithotripsy. Statistic analyses were performed using Statistical Package for Social Sciences, version 16, SPSS, Chicago, IL, USA

Results

The demographic data is summarized in Table 3. The overall mean age was 51 ± 13 years, with gender equivalency between the renal and ureteric calculi groups. The mean BMI was 27.0 ± 4.9 kg/m^2 and mean area for the combined renal and ureteric stones was 66.1 ± 63.2 mm^2. In the renal calculi group, 43.6% of stones were located in the lower pole.

One hundred and thirty seven renal stones were treated, with a single-treatment success rate of 62.8% (Table 4). 123 ureteric stones were treated with a single-treatment stone free rate of 60.3% (Table 5). The single-treatment success rate of shockwave lithotripsy for all 403 stones was 61.6% (Table 6). Neither the presence of ureteric stents at the time of lithotripsy nor the locations of the calculi within the kidney (i.e., lower pole calyx vs. other locations) were predictive of success. Predictors of success for upper tract calculi include age, BMI, stone area, MSD and SSD.

SSD was a predictor of treatment success for both renal ($p < 0.01$) and ureteric calculi ($p = 0.04$). There was a positive correlation between BMI and SSD for patients treated for all upper tract calculi, with a Pearson correlation coefficient of $r = 0.47$, $p < 0.001$.

Table 3 Patient demographics and stone parameters as measured by non-contrast CT

	Renal calculi ($n = 218$)	Ureteral calculi ($n = 204$)	All calculi ($n = 422$)
Males	139 (47.3)	155 (52.7)	294 (69.7)
Age (years)	53.4 (12.7)	49.3 (12.9)	51.4 (12.9)
BMI (kg/m^2)	27.1 (5.1)	26.9 (4.8)	27.0 (4.9)
Left side	115 (50.7)	112 (49.3)	227 (53.9)
Lower pole calculi	95 (43.6)	n/a	95 (22.5)
Ureteral stent pre-SWL	25 (58.1)	18 (41.9)	43 (10.2)
Stone area (mm^2)	78.9 (77.3)	52.3 (39.3)	66.1 (63.2)
Maximal stone length (mm)	9.0 (3.7)	5.5 (2.2)	7.3 (3.5)
Mean stone density (HU)	793.6 (260.0)	739.1 (180.0)	767.2 (230.0)
Mean stone density ratio (HU/mm^2)	18.2 (10.7)	29.49 (10.2)	23.6 (11.9)
Skin-to-stone distance (mm)	98.1 (24.6)	130.1 (25.7)	113.6 (29.8)

Data are expressed as mean (SD) or n (%), where applicable

Table 4 Univariate analysis of factors affecting single-treatment SWL success for renal calculi

	Successful treatment ($n = 137$)	Unsuccessful treatment ($n = 62$)	p value
Males	94 (76.4)	38 (61.3)	NS
Age (years)	52.4 (11.8)	56.0 (14.5)	NS
BMI (kg/m^2)	26.9 (4.9)	27.6 (5.7)	NS
Left side	75 (54.7)	35 (56.5)	NS
Stone location			
Upper calyx	17 (70.8)	7 (29.2)	NS
Middle calyx	20 (74.1)	7 (25.9)	
Lower calyx	69 (72.6)	26 (27.9)	
Renal pelvis	27 (57.4)	20 (42.6)	
Ureteropelvic junction	4 (66.7)	2 (33.3)	
Ureteral stent pre-SWL	14 (10.2)	11 (17.7)	NS
Stone area (mm^2)	67.7 (66.8)	115.9 (94.5)	<0.01
Mean stone density (HU)	766.7 (260.0)	862.7 (270.0)	0.02
Mean stone density ratio (HU/mm^2)	19.3 (10.6)	14.1 (9.0)	<0.01
Skin–stone distance (mm)	95.1 (21.7)	106.8 (29.1)	<0.01

Data are expressed as mean (SD) or n (%), where applicable

MSD is a strong predictor for successful lithotripsy of all upper tract calculi ($p < 0.01$), as stones with higher MSD are less likely to be successfully treated with one lithotripsy treatment. As the scatter plot seen on Fig. 3 demonstrates, there is a positive correlation between MSD and stone area, based on the Pearson correlation coefficient ($r = 0.41$, $p < 0.001$), with larger stones tending to have a higher MSD.

With larger stones having a tendency toward greater MSD, we built on a concept developed by Nakada et al. and utilized by Magnuson et al., whereby the MSD of a calculus was divided by its diameter in an attempt to eliminate the confounder of size when predicting stone composition [13] and successful lithotripsy [15]. Thus, we calculated an attenuation ratio by dividing the Hounsfield units by the area of the stone. This novel MSD ratio did not predict SWL outcomes for renal, ureteric, or all combined stones either by univariate or multivariate analyses.

Examination of MSD and SSD was undertaken to determine the ideal cut-points for predicting SWL outcomes (Table 5). As indicated in Table 7, the stone attenuation threshold that best predicts failure was >900 HU [odds ratio (OR) 0.49, confidence ratio (CI) 0.32–0.75), whereas the SSD that best predicts SWL failure was >110 mm (OR 0.49, CI 0.31–0.78).

Discussion

Non-contrast abdominal/pelvic CT imaging is considered the gold standard for diagnosing patients with upper tract urolithiasis due to its high sensitivity and specificity, while clearly delineating the number, size and location of any urinary calculi [1–3]. With treatment options usually determined by a combination of CT-based stone

Table 5 Univariate analysis of factors affecting single-treatment SWL success for ureteric calculi

	Successful treatment ($n = 123$)	Unsuccessful treatment ($n = 81$)	p value
Males	94 (76.4)	61 (75.3)	NS
Age (years)	47.1 (13.1)	51.9 (13.5)	0.01
BMI (kg/m^2)	26.2 (4.7)	28.1 (4.8)	<0.01
Left side	71 (63.4)	41 (36.6)	NS
Stone location			
Proximal ureter	64 (52.0)	47 (58.0)	NS
Middle ureter	10 (8.1)	9 (11.1)	
Distal ureter	49 (39.8)	25 (30.9)	
Ureteral stent pre-SWL	12 (9.8)	6 (7.4)	NS
Stone area (mm^2)	46.4 (36.9)	61.5 (41.1)	<0.01
Mean stone density (HU)	716.1 (170.8)	773.9 (197.3)	0.03
Mean stone density ratio (HU/mm^2)	29.3 (8.0)	29.7 (12.9)	NS
Skin–stone distance (mm)	115.0 (22.0)	122.0 (23.0)	0.04

Data are expressed as mean (SD) or n (%), where applicable

Table 6 Univariate analysis of factors affecting single-treatment SWL success for all upper tract calculi

	Successful treatment ($n = 260$)	Unsuccessful treatment ($n = 143$)	p value
Males	179 (68.8)	99 (69.2)	NS
Age (years)	50.1 (12.3)	53.7 (14.0)	<0.01
BMI (kg/m^2)	26.6 (4.8)	27.9 (5.2)	0.01
Left side	146 (56.4)	76 (53.1)	NS
Stone location			
Kidney	137 (52.7)	62 (43.4)	NS
Ureter	123 (47.3)	81 (56.6)	
Ureteral stent pre-SWL	26 (10.0)	17 (11.9)	NS
Stone area (mm^2)	57.6 (55.6)	85.1 (74.3)	<0.01
Mean stone density (HU)	742.8 (220.0)	812.4 (230.0)	<0.01
Mean stone density ratio (HU/mm^2)	24.1 (10.7)	23.0 (13.7)	NS
Skin–stone distance (mm)	110.6 (28.6)	122.1 (30.4)	<0.01

Data are expressed as mean (SD) or n (%), where applicable

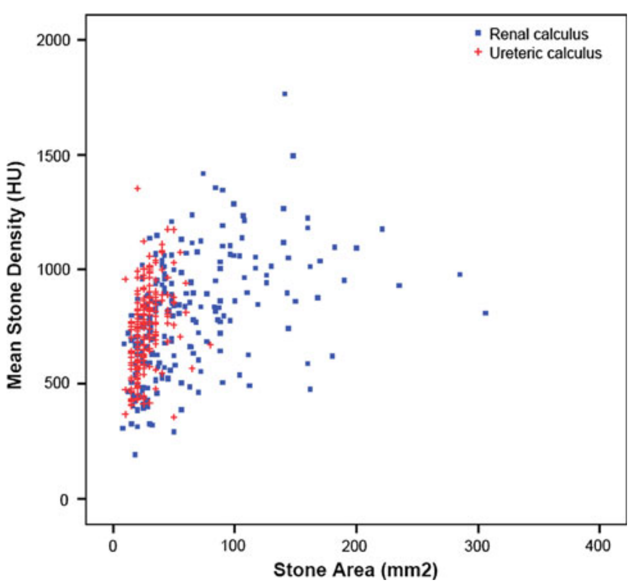

Fig. 3 Scatter plot of the mean stone density versus stone area; Pearson $r = 0.41$, $p < 0.001$

Table 7 Multivariate logistic regression predicting successful SWL of all upper tract calculi based on stone density and skin–stone distance

	Estimates (SE)	p value	Adjusted OR (95% CI)
Density > 900 HU	−0.71 (0.24)	<0.01	0.49 (0.32–0.75)
SSD > 110 mm	−0.72 (0.22)	<0.01	0.49 (0.31–0.78)

Variables above were dichotomized based on distribution to create contiguous variables

parameters and clinical information, success rates for single-treatment SWL remain adequate, with efficiency quotients between 0.36 and 0.67 [7–11]. This study examines the utility of adding SSD and MSD to the decision-making process when choosing among the treatment options available to both clinicians and patients for radiopaque calculi, using the largest dataset to date.

Both SSD and MSD are important and significant predictors of lithotripsy success for both ureteric and renal calculi, and do so in a continuous fashion. Nonetheless, many clinicians prefer to employ specific cut-points for clinical decision-making: an SSD of greater than 110 mm and MSD greater than 900 HU each yields an odds ratio of 0.49, translating into SWL success rates that are approximately half of those for patients with MSD and SSD values below these thresholds.

When calculating SSD, we did not utilize the same methodology as Pareek et al. [16] whereby the SSD was merely the mean of three measurements taken at 0°, 45° and 90° from the stone center to the skin. Instead, as displayed in Fig. 2, we utilized only the 45° distance between the stone and skin. This variation in measurement was made due to the differences in lithotriptors used in the respective studies. Pareek et al. utilized the Sonolith 4000+, which has its shock wave generator positioned directly underneath the patient, whereas in our study, the Philips Lithotron Ultra has its generator positioned posterior-lateral, corresponding to the 45° line utilized to measure SSD.

A positive correlation exists between SSD and BMI when examining all upper tract calculi. BMI and SSD are certainly interrelated, but body fat distribution varies between gender and race [17] and cannot be reliably utilized as a surrogate marker for SSD. The utility of BMI in predicting successful SWL is variable, as El-Nahas et al. [18] found BMI to be a significant predictor of success. Conversely, BMI failed to predict successful SWL outcomes in Ng et al.'s study, whereas SSD remained a significant predictor [16, 19]. In our study, BMI was a significant predictor of successful SWL in ureteric, but not renal calculi. This may be related to different paths taken by the shock wave, as shock waves directed at renal stones pass only through thin posterior abdominal wall muscle, perirenal fat and renal tissue. With proximal ureteric stones, there is usually the ascending or descending colon in the blast path, which will dissipate energy from the lithotripter's shock head when filled with gas. For mid ureteric stones, with the patient prone, again the colon intervenes. Finally, in the distal ureter, there is the large buttock musculature in the supine position and bowel in the prone position.

Mean stone density is an equally significant predictor of SWL success in our study. There are two widely accepted methods for measuring MSD. The first method involves measuring an elliptical region of interest incorporating the largest cross-sectional area of stone while in the bone windows, ensuring no inclusion of the surrounding soft tissue. The second method attempts to minimize the effects of volume averaging by creating three small, non-overlapping regions of interest which are assessed and averaged to obtain the MSD. Previous studies have indicated an excellent correlation between these two methods ($r^2 = 0.98$, $p < 0.001$) [20], and thus only the initially described method was utilized for this study as it is easier to perform, and as a result, has superior inter- and intra-observer reliability.

MSD appears to be affected by stone size, as indicated in several previous studies [3, 19, 20]. This finding was observed in our study as well, with stones of larger areas having higher Hounsfield units. We utilized a 5-mm low-resolution beam collimation, which might yield artificially lower attenuation values for smaller stones [3]. When utilizing 1-mm high-resolution beam collimation, there was no correlation between MSD and the number of shocks needed to comminute calcium stones [21]. However, using this 5-mm collimation lowers the radiation exposure to the patients.

In an attempt to resolve this correlation between stone size and MSD, Nakada et al. [13] created a new variable by dividing the Hounsfield unit of the calculus by its maximal diameter. This newly created attenuation/size ratio was found to possess a higher negative predictive value than MSD alone in predicting stone composition. Magnuson furthered the concept by utilizing this new variable "Hounsfield density" as a predictor for successful lithotripsy. In our study, we utilized a variation on Nakada's calculation, and instead divided the Hounsfield units by the area of the stone as measured on CT. We calculated each stone's area (in two dimensions) rather than utilizing stone diameter to achieve a truer calculation of stone size, as stones are rarely true spheres but rather ellipsoid or spiculated in shape. This newly created ratio was not significant in our study when examining all upper tract calculi and may have simply acted as a surrogate variable for stone size. However, as clearly and mathematically explained by Williams et al. [31], this attenuation/size ratio assists in correcting for volume averaging effects in smaller stones while artificially lowering this value for larger stones, thus making this new variable difficult to interpret.

Potential limitations of this study include the retrospective design. However, all data was collected in a prospective fashion, with the investigators blinded to the study design and measured SSD and MSD at the time of lithotripsy. Additionally, by using the newly created ratio of attenuation/stone area rather than attenuation/stone diameter, the calculated value of this novel variable decreases more significantly with increasing stone area while concomitantly increasing the error proportions, and as such, calls into question the variable's utility. Finally, successful lithotripsy was assessed by KUB and/or tomography, and not CT, which overestimates success rates.

Conclusions

This study demonstrates the importance of mean stone density (< 900 HU) and skin-to-stone distance (<110 mm) in predicting successful SWL of both renal and ureteric calculi. These factors should be considered in conjunction with other image-based stone variables in the individualized clinical setting to select the most efficient and efficacious urolithiasis treatment.

Conflict of interest statement None.

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