Independent assessment of a wide-focus, low-pressure electromagnetic lithotripter: absence of renal bioeffects in the pig

Andrew P. Evan, James A. McAteer, Bret A. Connors, Yuri A. Pishchalnikov, Rajash K. Handa, Philip Blomgren, Lynn R. Willis*, James C. Williams Jr, James E. Lingeman† and Sujuan Gao‡

*Departments of Anatomy & Cell Biology, *Pharmacology & Toxicology, and ‡ Medicine, Indiana University School of Medicine, and †Methodist Hospital Institute for Kidney Stone Disease, Indianapolis, Indiana, USA*

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OBJECTIVE

To assess the renal injury response in a pig model treated with a clinical dose of shock waves (SWs) delivered at a slow rate (27 SW/min) using a novel wide focal zone (18 mm), low acoustic pressure (<20 MPa) electromagnetic lithotripter (Xi Xin-Eisenmenger, XX-ES; Xi Xin Medical Instruments Co. Ltd., Suzhou, PRC).

MATERIALS AND METHODS

The left kidneys of anaesthetized female pigs were treated with 1500 SWs from either an unmodified electrohydraulic lithotripter (HM3, Dornier MedTech America, Inc., Kennesaw, GA, USA; 18 kV, 30 SW/min) or the XX-ES (9.3 kV, 27 SW/min). Measures of renal function (glomerular filtration rate, GFR, and renal plasma flow) were collected before and after SW lithotripsy, and kidneys were harvested for histological quantification of vascular haemorrhage, expressed as a percentage of the functional renal volume (FRV). A fibre-optic probe hydrophone was used to characterize the acoustic field, and the breakage of gypsum model stones was used to compare the function of the two lithotripters.

RESULTS

Kidneys treated with the XX-ES showed no significant change in renal haemodynamic function and no detectable tissue injury. Pigs treated with the HM3 had a modest decline from baseline (≈ 20%) in both GFR ($P > 0.05$) and renal plasma flow ($P = 0.064$) in the treated kidney, but that was not significantly different from the control group. Although most HM3-treated pigs showed no evidence of renal tissue injury, two had focal injury measuring 0.1% FRV, localized to the renal papillae. The width of the focal zone for the XX-ES was ≈ 18 mm and that of the HM3 ≈ 8 mm. Peak positive pressures at settings used to treat pigs and break model stones were considerably lower for the XX-ES (17 MPa at 9.3 kV) than for the HM3 (37 MPa at 18 kV). The XX-ES required fewer SWs to break stones to completion than did the HM3, with a mean (SD) of 634 (42) and 831 (43) SWs, respectively ($P < 0.01$). However, conditions were different for these tests because of differences in physical configuration of the two machines.

CONCLUSION

The absence of renal injury with the wide focal zone XX-ES lithotripter operated at low shock pressure and a slow SW rate suggests that this lithotripter would be safe when used at the settings recommended for patient treatment. That the injury was also minimal using the Dornier HM3 lithotripter at a slow SW rate implies that the reduced tissue injury seen with these two machines was because they were operated at a slow SW rate. As recent studies have shown stone breakage to be improved when the focal zone is wider than the stone, a wide focal zone lithotripter operated at low pressure and slow rate has the features necessary to provide better stone breakage with less tissue injury.

KEYWORDS

renal injury, stone breakage, wide focal zone, pulse repetition rate

INTRODUCTION

All shock wave (SW) lithotripters are similar in the sense that they generate a signature acoustic pulse [1]. Subtle features of the pulse differ depending on the mode of SW generation (i.e. electrohydraulic, electromagnetic, piezoelectric) and the SWs produced by different lithotripters can differ considerably in amplitude, but the shape of waveforms produced by different lithotripters is basically the same. What makes one lithotripter different from another are the dimensions and pressure characteristics of the focal zone, the region of high pressure that surrounds the focal point of the SW source. The focal zone is ellipsoidal, elongated in the axis of SW propagation (acoustic axis, Z-axis), can be 40–100 mm long and is 4–12 mm wide. The width of the focal zone is an important factor affecting stone breakage. Recent *in vitro* and numerical modelling studies have shown that shear stress induced within a stone by passage of the SW is critical in breakage, and that stresses are enhanced when the SW passes along the outside surface of the stone [2–4], i.e. stone breakage is improved when the width of the focal zone is greater than the width of the stone. The width of the focal zone might also be a factor affecting clinical outcomes, and reports have shown reduced stone-free rates and a greater occurrence of adverse effects in patients

treated with narrow focal zone lithotripters [5–14]. Thus, the width of the focal zone is a factor in the efficacy and safety of lithotripters.

An electromagnetic lithotripter with an exceptionally wide (18 mm) focal zone has been used in the Peoples' Republic of China to treat patients at relatively low acoustic pressures (<20 MPa), and very slow SW rate (27 SW/min) [15]. The data on treatment outcomes included a 3-month stone-free rate of ≈ 86% and no significant complications (i.e. no perirenal haematomas). In the light of these encouraging clinical results, and because this lithotripter represents an innovative technology, we conducted an independent evaluation in a pig model to characterize the renal response to the administration of a typical clinical dose of SWs, as would be used to treat patients with this device. *In vitro* studies were also done to determine the stone breakage efficiency and acoustic output of this lithotripter.

METHODS AND MATERIALS

Anaesthesia was induced in adult female swine (45 kg; Hardin Farms, Danville, Indiana, USA) with an i.m. injection with ketamine (15–20 mg/kg) and xylazine (2 mg/kg). The pigs were then intubated and anaesthesia maintained by the inhalation of isofluorane (1–3%) and oxygen (100%). Surgery was conducted with the pig supine to place arterial, renal venous and bilateral ureteric catheters, as previously described [16]. Isotonic saline was infused i.v. at 1% of body weight/h throughout the experiment to maintain adequate hydration and urine flow. Inulin and para-aminohippuric acid (PAH) were infused i.v. at 70 mL/h to establish and maintain plasma concentrations of 20 mg/dL inulin and 1 mg/dL PAH.

For the experimental protocol for the Xi Xin-Eisenmenger lithotripter (XX-ES; Xi Xin Medical Instruments Co. Ltd., Suzhou, PRC) baseline cardiovascular and renal function measurements were begun 30 min after completing all surgery, and consisted of two 25-min clearances. Each pig was then placed semiprone on the lithotripter platform for SW treatment. Ultrasound gel was applied liberally to the contact area of the skin and the lithotripter platform was raised to bring the water cushion of the SW generator in contact with the pig for acoustic coupling. The lower pole calyx of the left kidney was located by fluoroscopy and positioned at the clinical focal point of the lithotripter, a point on the acoustic axis 4 cm proximal to the geometric focal point. Control pigs (group 1) received no SWs, while treated animals (group 2) received a dose of 1500 SWs delivered at settings (9.3 kV, 27 SW/min) typically used to treat patients with this lithotripter [15]. After treatment (or a 1 h sham period for group 1) the pigs were placed supine and two 25-min clearances obtained after a 1-h recovery period after lithotripsy.

The experimental protocol for the unmodified HM-3 lithotripter (Dornier MedTech America, Inc., Kennesaw, GA, USA) comprised the same baseline cardiovascular and renal function measurements begun 30 min after completing all surgery, and consisted of two 25-min clearances. The pig was then disconnected from the anaesthetic machine and transferred (unconscious) to the lithotripsy suite (≈ 5 min) where administration of isofluorane/oxygen anaesthesia was resumed and the pig placed in the HM3 lithotripter. F2 was targeted on the lower-pole calyx of the left kidney using fluoroscopy and administration of contrast material into the collecting system via the left ureteric catheter, as previously described [16]. Control pigs for the HM3 (group 3) received no SWs, while the treated group (group 4) received 1500 SWs at settings (18 kV, 30 SW/min) chosen to mimic the treatment parameters used with the XX-ES lithotripter. The position of F2 was checked at 500 and 1000 SWs, and the electrode changed at 1000 SWs. At the end of the treatment (or sham) session the pigs were immediately returned to the surgical suite for two 25-min clearance measurements beginning 1 h after lithotripsy.

Urine and plasma samples were analysed by standard colorimetric methods [17]. Clearances of inulin and PAH were calculated as estimates, respectively, of GFR and renal plasma flow (RPF). The concentration of PAH in renal venous blood was used to calculate the renal extraction of PAH (EPAH), which provides an index of renal tubular secretory function.

For the morphological analysis, kidneys were perfusion-fixed *in situ* at the end of the clearance period after lithotripsy [18], and removed for routine morphology and quantitative morphometric analysis, as previously described [19]. The lesion size was measured in the shocked (left) kidney and expressed as a fraction of functional renal volume (FRV) for whole-kidney parenchyma, based on serial sections that were digitally photographed for computer-assisted segmentation with coloration of haemorrhagic regions [19]. Six pigs treated with each lithotripter were used for morphological analysis.

SW measurements and mapping of the acoustic field were conducted in well degassed water (dissolved gas 10–30% saturation) using a data-acquisition system built around a fibre-optic probe hydrophone FOPH-500 (RP Acoustics, Leutenbach, Germany). Waveforms were typically collected in sets of 10–100 pulses using the Fast Frame setup of the Tektronix (TDS 5034) oscilloscope [20], and nonaberrant waveforms (omitting spurious waveforms due to cavitation interference along the surface of the fibre-optic cable) were averaged by aligning to the coincidence of the half-amplitude of the shock fronts using programs written in LabVIEW [21]. To determine the width of the focal zone the tip of the hydrophone was positioned in the plane of F2 for the HM3, and for the XX-ES at the target plane specified for clinical treatment with this lithotripter, i.e. ≈ 4 cm pre-focal to the geometric focus of the SW generator (Dr Du, personal communication).

Focal width was defined by the dimensions of the −6 dB zone, the pressure half-maximum of the acoustic field [22]. For mapping the acoustic field, the fibre tip of the FOPH-500 was moved in 1-mm steps, with a total excursion of 28 mm (14 mm radius). At least 10 pulses (at 9.3 kV for the XX-ES; 18 kV for the HM3) were collected for each position, and the values averaged.

The breakage of gypsum model stones held in a 2-mm mesh basket was used as a measure of lithotripter function. The efficiency of stone breakage was determined by counting the number of SWs needed until no fragments remained in the basket (breakage to complete fragmentation) [23]. For studies with the HM3 the basket was positioned so that the stone sat at the F2 focal point, determined using the alignment stylus of the lithotripter. With the XX-ES, the clinical focal point was localized using the ultrasound alignment system of the lithotripter, and marked within the tank using crossed laser beams. The shock source of the HM3 sits below its focal point, but with the

XX-ES lithotripter the treatment head sits above the treatment table. The water cushion of the treatment head of the XX-ES was immersed in the test tank and SWs were directed downward into the open mouth of the stone basket. The dissolved gas content within the HM3 tub was 10–20% of saturation, and in the XX-ES test tank was ≈ 20% of saturation.

Systemic blood pressure and renal function measurements at baseline were used as continuous outcomes and summarized as the mean (SEM). Baseline systemic blood pressure and renal function values were compared using one-way ANOVA among four experimental groups (1–4). Changes in blood pressure and renal function values from baseline were derived as the difference between baseline values and those at 1 h after lithotripsy. Paired *t*-tests were used to examine changes in blood pressure and renal function values within each group. Changes from baseline between treated group and control group with the same machine were compared using the two-sample *t*-tests. The values presented are the mean (SEM) and the significance level for all hypothesis tests was set at 0.05. Stone breakage data are presented as the mean (SD). The number of SWs to complete fragmentation were analysed using ANOVA, with $P < 0.05$ considered to indicate statistical significance.

RESULTS

SW treatment with the XX-ES lithotripter had no effect on the variables of kidney function in the left kidney (Table 1, Figs 1 and 2), and although five of seven pigs had visible haematuria, there was no quantifiable morphological lesion (0% FRV) indicative of vascular haemorrhage in the renal parenchyma (Fig. 3). Baseline values of systemic blood pressure and renal function were similar for all groups with both lithotripters (Table 1). Blood pressure in both group 1 and 2 decreased by 5–6 mmHg ($P < 0.05$, group 2 only), but there was no significant change in GFR and RPF (Fig. 1).

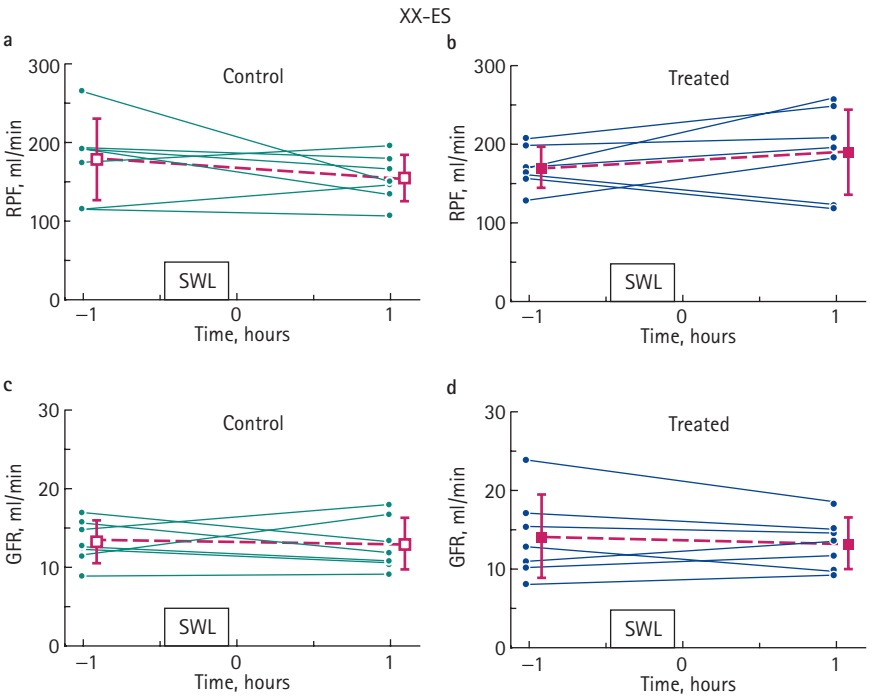
Blood pressure and RPF did not change in group 3, whereas the GFR decreased by 2.6 (1.1) mL/min ($P < 0.05$) over the course of the experiment (Fig. 2). The application of 1500 SWs (group 4) did not affect blood pressure, but resulted in a decrease in GFR of 4.7 (1.3) mL/min ($P < 0.01$) and RPF declined by 33 (16) mL/min ($P = 0.064$; Fig. 2) in the left kidney. However, the magnitude of change in renal function in the control (group 3) vs group 4 (SW-treated) was similar for GFR ($P = 0.196$) and RPF ($P = 0.329$). There was haematuria from the SW-treated kidney in all HM3-treated pigs, but only two kidneys had morphological evidence of tissue injury, each with a lesion size of 0.1% FRV. The injury was localized to small focal spots of haemorrhage in renal papillae in the lower pole (Fig. 3B). The mean (SEM) of the lesion of the six HM3-treated kidneys was 0.03 (0.02)% FRV.

TABLE 1 Basal values, as the mean (SEM), of cardiovascular and renal function

Machine/group (n pigs)	MAP, mmHg	GFR, mL/min	RPF, mL/min	EPAH, %
XX-ES lithotripter				
Controls (seven)	79 (3)	13.4 (1.0)	178 (20)	87 (3)
Treated (seven)	72 (1)	14.0 (2.0)	172 (10)	88 (2)
HM3 lithotripter				
Controls (nine)	69 (3)	13.6 (1.2)	172 (8)	83 (2)
Treated (eleven)	71 (3)	14.4 (1.5)	158 (12)	82 (3)

MAP, mean arterial blood pressure.

FIG. 1. Renal haemodynamics for pigs treated with the XX-ES, measured in the left kidney from group 1, panels a and c (control, no SWs) and group 2, panels b and d (1500 SWs at 9.3 kV and 27 SW/min) before and at 1 h after treatment. Solid lines show data from individual pigs; dashed denotes mean (SEM).



Renal PAH extraction was unchanged for all groups (sham or SW treatment) with either lithotripter and remained at a mean extraction value of 84%.

The lateral distribution of peak positive pressure (PPP) for the XX-ES (9.3 kV) and the HM3 (18 kV) lithotripters is shown in Fig. 4. The PPP decayed faster for the HM3 than for the XX-ES. The –6 dB (half-amplitude) width of the focal zone was ≈ 18 mm for the XX-ES and ≈ 8 mm for the HM3. These values confirm those originally published for the XX-ES, also collected with a fibre-optic probe hydrophone [15]. However, the focal width measured here

FIG. 2. Renal haemodynamics for pigs treated with the HM3, measured in the left kidney from pigs in group 3, panels a and c (control, no SWs) and group 4, panels b and d (1500 SWs at 18 kV and 30 SW/min) before and at 1 h after treatment. Solid lines show data from individual pigs; dashed lines denote the mean (SD).

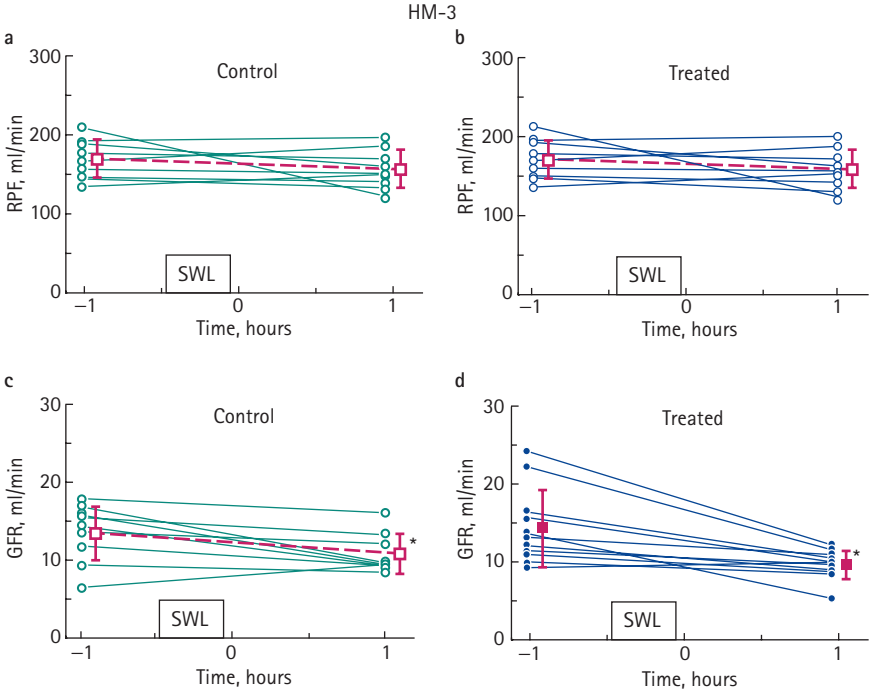


FIG. 3. Gross view and digitized images of tissue sections cut from kidneys treated with the XX-ES (panels a and c) or HM3 (panels b and d) lithotripter. There was no evidence of surface bleeding on any of the XX-ES (panel a) or HM3 (panel b) treated kidneys. There was no evidence of cortical or papillary haemorrhage in the XX-ES-treated kidneys (panel c at mid-coronal plane). Only two of the HM3-treated kidneys showed haemorrhagic change. Panel d shows a coronal section through one such kidney, in which lesion volume was determined to be 0.1% FRV. The injury is localized entirely to the renal medulla (arrows). ×1.5 (panels a–d).

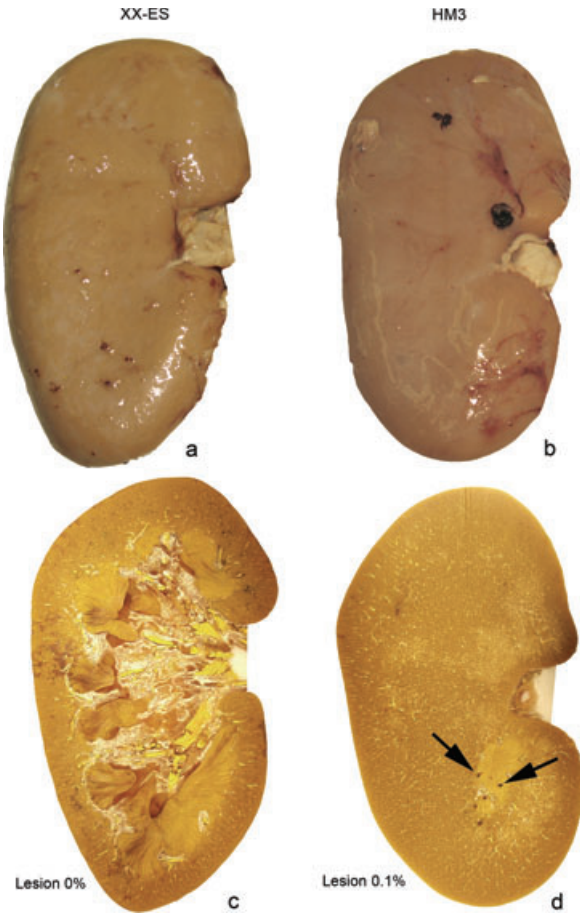
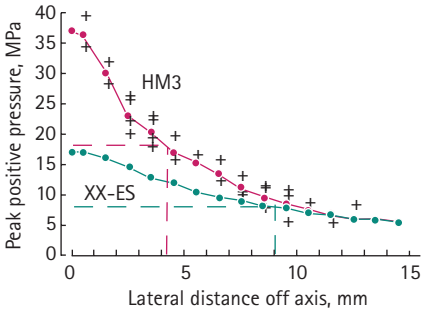


FIG. 4. The lateral distribution of PPP for the XX-ES (at 9.3 kV) and Dornier HM3 (at 18 kV) lithotripters. The −6 dB width (i.e. pressure half-maximum amplitude; dashed lines) of the acoustic field was ≈ 18 mm for the XX-ES and ≈ 8 mm for the HM3. Crosses show average values (10 SWs) for different scans of the acoustic field of the HM3.



for the HM3 was somewhat less than what we and others reported previously using polyvinylidene difluoride membrane hydrophones [24,25], and is consistent with the spatial sensitivities of these two hydrophones (0.1 mm for FOPH; ≈ 1 mm for polyvinylidene difluoride).

The PPP measured on the acoustic axis was about half for the XX-ES than for the HM3 (17 vs 37 MPa). Whereas the acoustic output of electromagnetic lithotripters tends to be very consistent, the output of an electrohydraulic lithotripter can vary considerably from shot to shot, and changes over the lifetime of the electrode [24,26]. For the HM3 lithotripter operated at a mean 18 kV, the PPP for sets of 100 SWs varied from 32 to 40 MPa over the 1500 SW limit imposed for each electrode.

Representative temporal profiles of acoustic pulses for the XX-ES and the HM3 on the acoustic axis, and at distances lateral to the axis, are shown in Fig. 5. Time zero along the horizontal scale marks the transition from positive to negative acoustic pressure, and waveforms are aligned to that point in each example. The top panel shows acoustic pulses measured on the axis of the lithotripters. The leading positive-pressure phase of the XX-ES pulse was smaller in amplitude but longer than for the HM3 pulse. The leading positive-pressure phase of the HM3 pulse showed two peaks. We hypothesise that this structure is due to superposition of the portion of the SW focused by the main face of the ellipsoidal reflector and the edge wave derived from the reflector lip, enhanced by the cut-outs that accommodate the contrast pillows of the

fluoroscopy system. SWs from a hemi-ellipsoidal reflector that does not have these cut-outs have a leading positive-pressure wave that consists of a single peak [24,27]. Such a double-peak structure of HM3 SWs was evident for a radius of ≈ 2 mm off the acoustic axis and was not seen in SWs measured 5–10 mm off axis (middle and bottom panels).

The XX-ES waveforms shown in Fig. 5 were measured at the point (≈ 4 cm proximal to the geometric focus) used to target stones for clinical treatment with this lithotripter. At this position along the acoustic axis of the XX-ES, pulses fired at 9.3 kV did not have shock fronts. However, shock fronts formed at this target distance when pulses were fired at higher voltage settings of the lithotripter.

Under the similar but not equivalent conditions of acoustic output and SW exposure used in this study, stone breakage with the XX-ES lithotripter was more efficient than with the HM3. The XX-ES broke stones to complete fragmentation with significantly fewer shots than it took with the HM3, with means of 634 (42) and 831 (43) SW, respectively ($P < 0.01$).

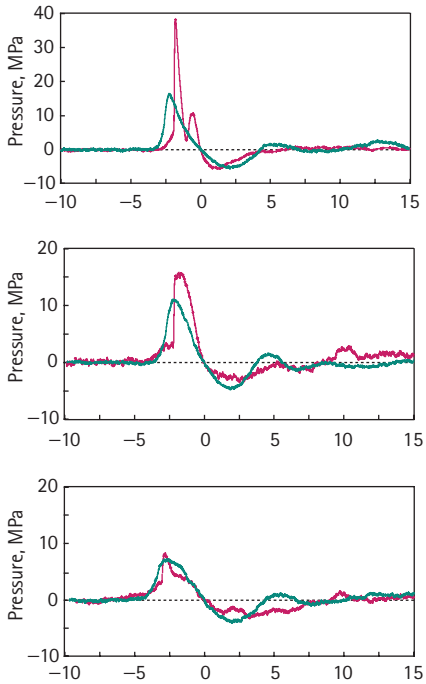
DISCUSSION

The dimensions of the focal zone produced by a lithotripter depend on many factors, including the focal length of the shock source (distance from source to focal point), the frequency content of the waveform, and the diameter of the source (aperture of the treatment head). As the diameter of the aperture is narrowed, the width of the focal zone increases [1]. A narrower aperture also decreases the area of skin surface intersected by the SW, raising the acoustic pressure at this interface and increasing the sensation of pain at the skin. One of the perceived drawbacks of the Dornier HM3, recognized soon after it was introduced, was that patients had too much discomfort at the skin and as such needed to be anaesthetized for treatment [28]. In an attempt to make lithotripsy anaesthesia-free, the aperture was widened, but this modification also narrowed the width of the focal zone. Before the introduction of the XX-ES lithotripter, all lithotripters have produced focal widths narrower than that of the Dornier HM3. It was reported that the XX-ES is used with no anaesthesia, but it has a relatively narrow region (≈ 5 cm) of acoustic intersection with the skin. If indeed patients tolerate treatment with this machine with no anaesthesia, it is probably because SWs are delivered at very low acoustic pressures (≈ 17 MPa).

The *in vitro* stone-breakage results, showing better fragmentation with the XX-ES operated at lower acoustic pressure than the HM3, suggests that the XX-ES fragments stones more efficiently than does the HM3. However, this result must be considered in the light of important differences in the experimental system with these two machines. The shock sources of these two lithotripters are orientated differently. The HM3 delivers SWs from below the focal point, while the treatment head of the XX-ES points downward. Thus, in the HM3, SWs hit the bottom of the stone basket from below, while with the XX-ES SWs hit the stone directly from above. It is possible that the orientation of the mesh might affect the acoustic field or cavitation field differently in the two conditions [29]. Also in the HM3, stone fragments and fine particulates released during breakage drift down toward the shock source, while in the XX-ES the path from source to target remains clear. We showed that at fast SW rates (120 SW/min) stone particles can serve as cavitation nuclei, acting to seed bubble activity along the acoustic axis, reducing the amplitude and duration of the negative pressure phase of the SW, and reducing stone breakage [27]. Further, a comparison such as we conducted must be interpreted with the understanding that there is no measure by which the acoustic output of different lithotripters can be compared directly, i.e. there is no agreed means to assure that two lithotripters can be operated to deliver equivalent output [1]. Even measurements showing the same pressure amplitude with different lithotripters do not show equivalency. With these caveats, our tests of stone breakage give a useful measure of the function of these lithotripters and show that the XX-ES breaks stones effectively at relatively low acoustic pressures.

Previous studies of lithotripsy injury in the juvenile pig model have shown that delivery of a typical clinical dose of SWs with the HM3 (2000 SWs, 24 kV, 120 SW/min) creates a vascular haemorrhagic lesion measuring ≈6% FRV [30]. Thus, the virtual absence of tissue injury with the XX-ES, using SW dose and settings (1500 SWs, 9.3 kV, 27 SW/min) typical of patient treatment, is an encouraging result. There was no vascular trauma detectable within the renal parenchyma of pigs treated with this lithotripter, and haemodynamic values were unaltered. However, this finding should not be interpreted to suggest that the XX-ES is, by design, a safe lithotripter, because tissue injury was also very low in the pigs treated with a comparable dose of SWs (1500 SWs, 18 kV, 30 SW/min) with the HM3. As previous studies with the HM3 showed significantly greater injury with a dose of SWs only 33% higher than was used in the current study, and as recent work with the HM3 showed that injury is significantly reduced

FIG. 5. Waveforms (mean of 300 SWs) from the XX-ES (red) (at 9.3 kV) and Dornier HM3 (blue) (18 kV) lithotripters collected on the acoustic axis (top), and at 5 mm (middle) and 10 mm (bottom) lateral to the acoustic axis. HM3 waveforms were collected in the plane of the geometric focal point, while XX-ES measurements were at the plane of focus used for clinical treatment (see text). Waveforms are aligned so that the transition from positive to negative pressure is at the zero point on the time scale (x axis). The double-spike structure of the positive pressure wave of the HM3 pulses on axis is probably caused by cut-outs of the reflector to accommodate the fluoroscopy contrast cushions. Comparing waveforms for the HM3 at X = 0 and X = 5 mm, the PPP declines quickly off-axis. The peak negative pressure is similar for the two machines, although the duration of the negative tail is longer for the HM3 than the XX-ES for waveforms collected off axis.



when the SW rate is slowed to 30 SW/min vs 120 SW/min [31], it might be that the lack of injury with the XX-ES in the present study shows the now well-established protective effect of a slow SW rate [32–37]. It would be valuable to test the effect of SW rate for a broad focal-zone lithotripter, but this could not be done using the XX-ES, as the acoustic output of this lithotripter is not stable at 120 SW/min (unpublished data).

In conclusion, that there was limited or no SW trauma in the kidneys of pigs treated with the XX-ES broad-focus low-pressure lithotripter is a positive finding, showing that the treatment conditions recommended for using this lithotripter are safe. *In vitro* stone breakage results are also encouraging, and show effective stone comminution at low acoustic pressure.

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CONFLICT OF INTEREST

None declared.

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Correspondence: Andrew P. Evan, Chancellor's Professor, Department of Anatomy and Cell Biology, Indiana University School of Medicine, 635 Barnhill Dr, MS 5035, Indianapolis, Indiana 46202–5120, USA.
e-mail: evan@anatomy.iupui.edu

Abbreviations: **SW**, shock wave; **RPF**, renal plasma flow, **(E)PAH**, (renal extraction of) para-aminohippuric acid; **FRV**, functional renal volume; **PPP**, peak positive pressure.