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# ORIGINALS

# Hazards to Bladder and Intestinal Tissues from Intravesical Underwater Electrical Discharges from a Surgical Electronic Lithoclast

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Summary. Previous studies have shown that electronic lithoclast discharges produce effects resembling an underwater explosion. It was predicted that the shock wave produced by each discharge could damage nearby gas-containing gut through a mechanism known to be associated with underwater detonations. Effects associated with rapid oscillation of the vapour bubble produced could cause damage to the wall of the bladder. Investigation of lithoclast discharges in vivo on goat, and in vitro on sheep bladders demonstrated perforation of both. In vitro studies in the rabbit demonstrated the predicted greater susceptibility of air-filled gut over that filled with fluid. These hazards would be even greater in the ureter and caution in the use of electronic fragmentation of vesical and ureteric calculi is urged in the light of these findings.

Key words: Electronic lithoclast, Vesical calculus, Ureteric calculus.

The use of electronic methods of fracturing vesical calculi has been reported with increasing frequency since the first clinical description of the method by Büttger (6) in 1969. This technique may enable calculi which are either too hard or too large to be dealt with effectively by conventional mechanical instruments to be tackled without open operation. The first clinically useful instrument (Urat-1) was produced by Rese and Goligowsky who developed the initial research carried out by Yutkin (18). This apparatus produces repetitive bursts of electrical discharges, the energy, duration and frequency of which may be varied by the operator. The discharges are produced at a co-axial electrode which is applied to the target calculus under water by means of a modified cystoscope (4, 7, 8). More recently electronic lithotripsy has been applied to fragmentation of ureteric calculi (9, 11, 12). A further development of the principle occurred when special low inductance electrical components were used by Wallace et al. (16) to reduce the electrical discharge duration to a few microseconds in order to maximise the destructive effects on calculi.

In view of the extensive literature on electronic methods of calculus destruction which has appeared since 1970 (1, 2, 10, 13, 17) it appears that the technique could be finding increasing application. In the absence of information about the mode of action of the electrical discharges in achieving their effects it appeared advisable to investigate this in order to assess any potential hazards which might be involved.

High speed pressure-time and photographic studies (14) with an instrument of the type described by Wallace et al. (16) showed that each underwater electronic discharge was associated with the production of a shockwave and a rapid series of pressure pulses in a process strongly

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resembling the underwater detonation of a small explosive charge. The shockwave arose from the virtually instantaneous vapourisation of a small quantity of water by the spark producing an explosive rise in pressure. The subsequent pressure pulses arose from the rapid oscillatory expansion and contraction of the vapour bubble which was formed. These findings strongly suggested that tissue damage, particularly bladder rupture and damage to any nearby tissue containing gas, such as intestine, which is known to be at special risk in persons exposed to underwater explosions (15), could well arise from the use of electronic lithoclasts since the magnitude of the shockwaves and pressure pulses observed were similar to those known to be extremely hazardous. A direct investigation of the effects of electronic lithoclast discharges on tissues in vivo and in vitro was therefore desirable and this was performed as described below.

## MATERIALS AND METHODS

### Electronic Lithoclast

The instrument used was similar to that described by Wallace et al. (16). It consisted of a specially designed low inductance 0.25 $\mu$F capacitor which could be charged by means of a converter and voltage multiplier (independent of mains supply) to a selected voltage between 9 and 12 kV corresponding to stored electrical energy between 10 and 18 joules. On triggering, the capacitor was discharged through a flexible high voltage co-axial cable to a specially designed intravesical spark gap, about 7 mm in diameter, at the tip of a modified Riches-Kidd diathermy cystoscope. The assembly included a wide angle viewing system and fibre-optic illumination. Each discharge produced a single spark only, unlike the multiple discharges of the Urat-1 device.

### Sheep Bladder Experiments

1. First Series

Fresh sheep bladders were obtained from an abattoir and were placed in cold Ringer's solution immediately after slaughter. Each bladder was subsequently rinsed and distended with approximately 125 ml of the same solution. The lithoclast electrode and supporting cystoscope shaft were introduced into the bladder and were secured by a ligature around the urethral remnant. The lithoclast and attached bladder were mounted in a glass tank 45 cm long, 30 cm wide and 26 cm deep containing Ringer's solution, with the electrode tip 6-10 cm from the fluid surface. Difficulty was experienced initially in adjusting precisely the distance between the end face of the electrode and the bladder wall since the latter tended to float away. This was overcome by attaching a soft iron wire to the electrode (by means of epoxy cement) projecting forward towards the bladder wall. With the wire tip bent into a tight loop, to avoid damage to the bladder wall at the point of contact, this provided an adjustable spacer which could be bent to provide the gap required. The spacer was adjusted to give electrode-mucosa distances of 2.0, 1.0, 0.5, 0.3 and 0 cm. The lithoclast was discharged at selected voltages between 9 (setting 1) and 12 kV (setting 4). The site on the bladder nearest the electrode was marked prior to discharge by means of a colour coded cotton thread introduced by an atraumatic needle through as superficial a layer of serosa as possible. It was usually possible to effect several discharges at widely separated parts of the same bladder.

2. Second Series

This was designed to assess the effects of simulated bladder stones situated between the electrode and the bladder. Stones of both hard and soft consistency and of pre-selected dimensions were gently manipulated between the electrode and the mucosa where they were held by gentle pressure. No wire spacers were used. The dimensions of the stones selected varied between 4 x 5 x 3 mm to 10 x 10 x 7 mm in thickness. Otherwise the technique was similar to that used in the first series. Specimens from both series were placed in a formalin based fixative and sent for histological examination.

### Rabbit Intestine Experiments

A male New Zealand White rabbit weighing approximately 3.5 kg was anaesthetised with intravenous Nembutal. Anaesthesia was maintained by open Halothane and oxygen. The abdomen was opened and a suitable portion of the small intestine was delivered through the incision. By adjustment of the position of the animal it was possible to place intestinal loops into an adjacent tank of Ringer's solution. Keeping the blood supply intact, segments of gut about 4-6 cm in length were isolated by means of catgut ligatures. The lumen of each segment was filled either with a few ml of air or Ringer's solution by means of a fine hypodermic needle introduced obliquely through the wall. The submerged lithoclast electrode was discharged at various depths, power settings and distances from the gut. Following each discharge the gut was left for a few minutes before removal in order to allow acute tissue effects to become manifest.

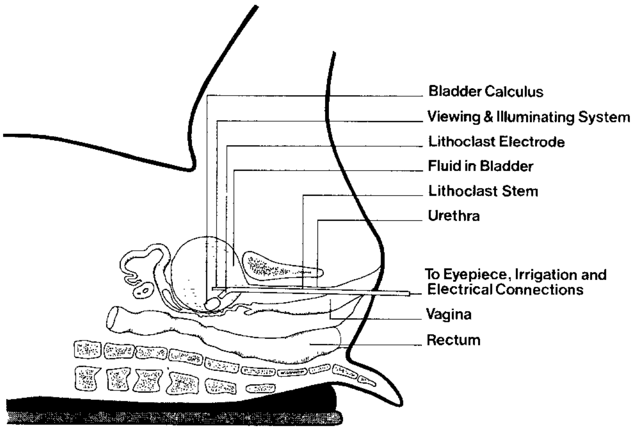


Fig. 1. Electronic lithoclast in use in a female goat. The angled electrode at the end of the modified cystoscope is placed in contact with the calculus under visual control.

Goat Bladder in vivo

A female goat weighing approximately 73 kg was premedicated with pentazocine and atropine. Anaesthesia was induced with Nembutal intravenously and maintained by closed circuit nitrous oxide, Halothane and oxygen. The animal was cystoscoped with the lithoclast and a faceted stone (from a sheep bladder) approximately 2.8 cm in its longest dimension, which had been inserted at open operation some weeks earlier, was located. With the lithoclast set at its lowest power level (1) a series of discharges was performed next to the stone or its fragments (see Figure 1 for details). Following this, an attempt was made to investigate the possible consequences of accidental discharge of the lithoclast in contact with the bladder mucosa. Five discharges were made on the ventral aspect of the bladder at various power settings. The abdomen was opened, the bladder inspected and removed with the urethra. The animal was then sacrificed and the specimen fixed for histological examination.

RESULTS

Sheep Bladder Experiments

1. First Series

No clear macroscopic or microscopic evidence of damage was seen at discharge distances of 2 cm and 1 cm at any of the power settings. Black specks (possibly damaged insulation) were seen on the mucosa after one discharge.

At 5 mm distance the mucosa was eroded and a bulge appeared in the serosal surface of the bladder at the lowest power setting. At power 2 the mucosa was again eroded. Mucosal splitting and serosal bulging occurred at power 3 and at power 4 (maximum) serosal bulging and marked stellate tears in the mucosa were seen.

A single discharge at the lowest power with the electrode in contact with the mucosa ruptured the bladder at the site of contact.

2. Second Series

With the hard stones the smallest (4 x 5 x 3 mm thick) was ejected through the bladder wall at the lowest power. A slightly larger stone 5 x 6 x 5 mm was not ejected at the same power but failed to protect the bladder wall from rupture. Otherwise, no obvious damage occurred at power 1 with larger stones. The bladder was again ruptured at power 2 (stone 7.5 x 5.5 x 5 mm thick). Slight damage to the mucosa and submucosa occurred at power 3 (stone 11 x 8 x 6 mm thick) and this progressed to a serosal bulge at power 4. No significant damage occurred with stones of larger dimensions although some soft stone fragments were driven superficially into the bladder mucosa but spared the muscularis.

Rabbit Intestine in vivo

Two segments of small intestine each approximately 4 cm long were prepared. One was filled with Ringer's solution; the other was inflated with air. The lithoclast was positioned 2 cm away from the antimesenteric border of the gut under 2-3 cm of fluid. A single discharge of maximum power was applied to each specimen.

The fluid-filled segment remained macroscopically intact. However, on microscopic examination although the mucosa and muscle coats appeared intact the lumen contained fresh blood and marked vascular congestion was visible.

The air-filled segment ruptured immediately with tears 1.0 and 1.5 cm in diameter adjacent to the isolating ligatures. In addition to gross vascular congestion many mucosal villi showed acute capillary haemorrhages and in one area the mucosal structure was markedly disrupted and was partly stripped from the underlying muscle with bleeding into the submucosa.

As a result of the striking rupture of the air-filled specimen the experiment was reproduced at the lowest power setting and with the electrode under 5 mm of fluid. No rupture occurred. A second discharge at 1 cm distance and 1 cm depth on the same specimen left it unruptured but with vascular congestion apparent. Microscopic examination showed occasional haemorrhages in the villi, marked vascular congestion with a disrupted, oedematous submucosa with perivascular petechial haemorrhages. Marked vascular congestion was seen.

A 6 cm segment of Ringer-filled gut was subjected to 2 discharges of the lowest power at approximately 2 cm and 1 cm depth respectively and 1 cm from the electrode, one each at one third of the distance between the ligatures. The gut remained unruptured but blood vessels in the wall became congested rapidly. The mucosa, submucosa and muscularis were intact but mesenteric and submucosal veins were congested. A petechial haemorrhage was present in the submucosa on the antimesenteric aspect of the bowel.

A discharge at maximum power 1 cm from a Ringer-filled segment produced slight haemorrhage in the mucosa but left the mucosa, submucosa and muscularis otherwise intact. A little fresh blood was found in the lumen.

The final discharge at maximum power 1 cm deep, 0.5 cm from a Ringer-filled segment failed to rupture it. A perivascular submucosal haemorrhage was present close to the discharge and another haemorrhage was present in the mesentery. Apart from small petechial haemorrhages in the mucosa the tissues appeared largely intact.

Goat Bladder in vivo

Seven discharges at minimum power completely fragmented the calculus without obvious evidence of injury to the bladder wall.

The lithoclast was then applied directly to widely separated ventral parts of the bladder mucosa, twice at power 1 and once at powers 2, 3 and 4. In each case (except with power 3 where the location of the discharge was in doubt) the bladder mucosa was seen to be split and bleeding. It was not thought that the bladder had been perforated. However, upon laparotomy, the abdomen was found to contain a substantial volume of bladder irrigating fluid and some stone fragments which had clearly been ejected earlier during stone fragmentation.

Microscopic examination showed the expected changes of acute injury and early inflammation. Vascular congestion, oedema and haemorrhage were visible with various degrees of physical disruption of the bladder layers. Fragments of calculus had been driven into and through the bladder wall.

## DISCUSSION

There are clearly limitations to the in vitro work with post-mortem sheep bladders. However those investigations were the only practical alternative to an extensive and less easily controlled series of in vivo experiments. The mechanical properties of the bladders may have altered after death but it seems unlikely that such changes in relatively fresh material would be large. The detection of very minor degrees of damage was made difficult in vitro by the absence of bleeding and the presence of early post-mortem changes. Nevertheless it is clear from the results that the bladder wall was protected from obvious damage by large stone fragments. However, as the stone fragments became smaller than about 1 cm in diameter the risk of major damage increased even at low power settings. An important in vitro finding was that fragments larger than those which could be evacuated via the irrigation channel of the cystoscope, and hence would need further fragmentation, failed to provide protection to the bladder wall even at the lowest power available and might even be ejected through the bladder wall.

It seems that in the fragmentation procedure in the goat such perforation of the bladder with ejection of fragments into the peritoneal cavity took place even though the lowest power was used. It was unrecognised until laparotomy demonstrated the unexpected finding of both fluid and stone particles in the peritoneal cavity. Even when the discharge was applied directly to the bladder wall in vivo the extent of the damage done was not appreciated at the time although slight bleeding was noted. There seems little doubt that there is a serious risk of perforation of the bladder under ordinary conditions of use and this finding confirms the predictions made from photographic and pressure-time investigations (14).

The previous photographic investigations showed that the spark produced a vapour bubble which reached a maximum diameter of up to about 3 cm in 1.25 milliseconds and it seems likely that it is the violence of this expansion (which reaches a maximum long after the shockwave has passed through the tissues) which ruptures the bladder. The oscillation of this vapour bubble results in a series of pressure or bubble pulses, each time it reaches a minimum volume, which are so short-lived that they behave like further shockwaves (14). Re-expansion of the vapour bubble after each minimum would add to the tissue disruption. Clearly spark discharges of the power used would present even greater hazards if they were applied within the ureter or by accident within the urethra.

The risk to gut is more difficult to assess particularly since the gut of the rabbit may be inherently less strong than that of man. In clinical conditions of use the lithoclast electrode would be separated from any gut nearby by tissue rather than water and the distance between the discharge and the gut might only occasionally approach 2 cm. Nevertheless, the marked susceptibility of air-filled gut and the relative resistance of fluid-filled gut to the effects of the discharge was striking and in accordance with predictions made both from previous observations and theory (14, 15). Shock waves pass through solid human tissues without substantial reflection or attenuation, other than that to be expected from fall-off with distance, since tissue density does not differ much from water. However, shock waves do not pass readily from water (or tissue) to gas and so are reflected. During the reflection the layer of water (or tissue) at the interface undergoes acceleration in the direction of the gas phase and the shockwave is reflected back as a wave of rarefaction. Since water under reduced pressure in a rarefaction wave vapourises, bubbles of vapour form almost instantaneously as the wave of rarefaction passes. The interface acceleration would occur in the mucosal layer of gas-filled gut and it seems probable that the stripping of the mucosa from the submucosa with rupture in the air-filled specimen may have resulted from this effect which would be analogous to the formation of a "spray dome" from the reflection of a shockwave from a depth charge at the air-water surface as described by Bebb (5). It is notable that the air-filled gut ruptured at 2 cm whilst a fluid-filled segment survived intact and relatively unharmed at 0.5 cm although the depth of the discharge was less in the latter case (vide infra).

The conditions of the rabbit gut experiments were such as to minimise rather than maximise damage. Both the lithoclast electrode and the gut were relatively near the surface. This resulted in energy which would otherwise have contributed to damaging bubble pulsation being wasted as turbulent motion of the water as the bubble broke the surface. Previous pressure measurements (14) have shown that the larger part of the energy of the spark appeared in the bubble pulses rather than the shockwave when conditions were such as to permit bubble oscillation.

In addition to loss of bubble pulse energy the shock wave was almost certainly substantially attenuated in terms of impulse (I)* due to destructive interference between the directly received shockwave in compression and the wave of opposite sign received by reflection from the surface via a slightly longer path (3, 5, 15). Since impulse is probably the important shock wave and bubble pulse parameter with respect to biological damage, effects of proximity to the surface cannot be neglected. When used in the bladder filled with fluid in the clinical state there would be no opportunity for attenuation effects from an air-fluid interface and the impulse (I) and probability of damage from a shockwave and unimpeded bubble pulsation would be greater. Further research has shown that it is possible to develop an electrode which produces a directional shockwave. This would reduce the electrical energy required and hence the vapour bubble volume and thereby some elements of the risk.

It may also be possible to develop an electrode in which the bubble is totally contained, thus almost certainly abolishing the risk of bladder perforation. However, until such improvements are made there seems little doubt that electronic lithotripsy at the energies involved in these experiments is a procedure which must be regarded as presenting real and previously unappreciated hazards.

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* The impulse (I) of a shockwave or bubble pulse is the integral of pressure with respect to time $(I)_t = \int_0^t p\,(t).\,dt$ and is represented by the area under the pressure time curve.

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