Investigation of Differences Between Nanosecond Electropulse and Electrohydraulic Methods of Lithotripsy: A Comparative In Vitro Study of Efficacy

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Abstract

Purpose: To compare the effectiveness of novel nanosecond electropulse lithotripsy with standard electrohydraulic lithotripsy to demonstrate and authenticate their differences because both modalities appear to be similar.

Materials and Methods: An in vitro fragmentation study was conducted using cuboid BegoStone phantoms, which mimic hard and soft stones, based on an established model. Three different stone sizes were used in the testing having volumes of 100, 256, and 320 mm³. A nanosecond electropulse lithotripter (NEPL) and an electrohydraulic lithotripter (EHL) were operated using a range of probe sizes at comparable energy settings and pulse rates with the objective of obtaining a stone fragment <2 mm. To compare the efficacy of these two lithotripters, the number of pulses needed for stone phantom fragmentation was recorded according to probe size and energy setting, which were then converted into units of cumulative energy.

Results: The results clearly demonstrated that, for all operating modes and stone phantom types, the NEPL device needs much less cumulative energy and thus fewer pulses and consequently less time to achieve stone fragmentation than the EHL device. The disparity in the results is explained by the dissimilar mechanisms at work in the compared lithotripters during destruction of the stone. The electropulse stone disintegration mechanism transfers energy directly into the stone because of discharge penetration into a solid body. This contrasts with the electrohydraulic mechanism in EHL in which energy is transferred through the liquid medium, which also creates a damaging shockwave.

Conclusions: The findings demonstrate that, for all operating modes and stone types, the NEPL device needs much less cumulative energy and thus fewer pulses for stone fragmentation than the EHL device. The disparity in the results is explained by the dissimilar mechanisms at work in the compared lithotripters during destruction of the stone.

Introduction

A variety of conservative and surgical treatment modalities are currently being used to remove urinary tract stones from patients. Until the late 1970s, classic open surgery was the most common method of treating patients with urolithiasis. In the 1980s, extracorporeal shockwave lithotripsy (SWL) was invented as a totally noninvasive method to fragment urinary stones. Up to 30% of urinary stones, however, cannot be treated with SWL, which necessitate an endoscopic approach for fragmentation and removal. The search for effective lithotripters with minimum tissue trauma potential has resulted in the development of various contact and noncontact lithotripters for treating stones that work in the kidney via percutaneous access, through the ureter to the renal pelvis via retrograde transurethral access, or in the bladder via transurethral access.1-3

Endoscopic fragmentation of urinary stones can be achieved with the use of ultrasonic, pneumatic, electrokinetic, electrohydraulic, and laser lithotripters, sometimes in combination. Each lithotripsy method, however, has its advantages and disadvantages. Thus, ultrasonic lithotripsy is limited to rigid probes and endoscopes but has the advantage of simultaneous suction of fragments through hollow probes. Impact lithotripsy (with the use of pneumatic and electrokinetic lithotripters) is an effective method of contact lithotripsy; however, the use of such lithotripters is also restricted to rigid endoscopes, and retrograde propulsion of the stone in the ureter is considered to

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be a disadvantage of this mode. Electrohydraulic and laser lithotripsy can be used as effective contact or "near object" fragmentation methods with both rigid and flexible endoscopes, which considerably broaden their range of use in modern urology. When compared with other methods, however, electrohydraulic lithotripsy is associated with a high complication rate because the shockwave that it generates damages surrounding tissues. Laser lithotripsy is less traumatic, but the equipment is still expensive and the stone fragmentation process is quite slow. The laser also necessitates a protected environment for operation because of the hazard potential of laser radiation and carries a high potential risk of damage to expensive flexible endoscopes from laser fiber breakage inside the flexed instrument.

To overcome the shortcomings of the currently available intracorporeal lithotripters, Lithotech Medical, Ltd. (Israel) has developed a novel nanosecond electropulse lithotripter (NEPL) that is compatible with both rigid and flexible endoscopes and can safely fragment calculi in the entire urinary tract using probes of various diameters. This lithotripsy method differs considerably in operating principle from existing devices because it uses nanosecond duration electric pulses with a very short rise time to fragment stones.

While both the NEPL and the electrohydraulic lithotripter (EHL) appear to be similar in principle (they both use probes with two electrodes at the distal end to which an electrical pulse is applied), their characteristics are fundamentally different.

The purpose of this study is to compare the effectiveness of NEPL and standard EHL on the fragmentation of artificial stones to demonstrate and authenticate the differences between these methods.

Electrohydraulic lithotripsy was the first method used for intracorporeal fragmentation of urinary stones using a probe that is brought into contact with the target stone. When an electrical pulse is supplied to the probe, an electric arc is discharged between its electrodes that vaporizes the liquid surrounding the distal end of the probe. The electrical breakdown within the liquid generates cavitation bubbles that expand and produce an initial shockwave. When the cavitation bubble collapses, a secondary shockwave builds up that is transmitted to the nearby stone, producing compressive and tensile mechanical stresses in the stone that result in its disintegration.

In contrast with the EHL, the new NEPL technology uses a different phenomenon discovered in the 1960s for disintegrating solid body concrements. It was demonstrated at that time that, under the influence of a high voltage pulse of short duration, an electrical discharge channel will penetrate a solid dielectric such as a geological material placed in an insulating liquid (including water). Because the solid dielectric has a lower breakdown voltage than the liquid medium, voltage breakdown occurs when such a high-voltage nanosecond pulse with a very short rise time is transferred to a urinary stone (which is basically a solid inorganic dielectric) and current then starts flowing through plasma channels forming within the dielectric medium. This induces tensile thermomechanical stress in the stone, resulting in cracks and ultimately in its destruction. The conceptual basis for the electropulse method of material destruction is stated in three reports and is illustrated by experimental data pointing to its potential significance.

Figure 1 schematically compares breakdown voltage-time curves at an equal discharge gap for a solid body and a liquid medium. The intersection point on the voltage-time curves...
Ac corresponds to parity with respect to the dielectric strengths of the compared media. When pulse voltage exposure is less than $2 - 3 \times 10^{-7}$ seconds (to the left of Ac in the diagram), the solid body has a lower dielectric resistance than the liquid, leading to its electrical breakdown and causing its destruction.\(^9\)\(^,\)\(^18\)

In electrohydraulic lithotripsy, electrical discharge and breakdown always occurs through the liquid (diagram areas to the right of Ac), which produces a shockwave in the liquid from the much longer pulses and lower voltage used in comparison with the NEPL. The shockwave induced by the EHL can cause serious damage to surrounding tissues, which is the reason the use of EHL has been virtually abandoned in endoscopic stone fragmentation, especially in the ureter where the safe distance to the urothelium is negligible.

In contrast to the EHL, the energy produced by the electrical pulse used in the NEPL is released directly within the volume of the target body rather than in the liquid, needing less energy for disintegration of the stone.

Figure 2 schematically demonstrates the operating principle of the NEPL based on observations of the inverse dielectric strength of liquids and solid bodies.\(^18\) In nanosecond electro-pulse lithotripsy, a voltage pulse $U(t)$ with parameters corresponding to the diagram area left of the Ac point (Fig. 1) is fed to the electrodes attached to the surface of the solid body (Fig. 2a). The breakdown subsequently occurs in the gap within the solid body and not through the shortest path on its surface (Fig. 2b). The effect demonstrated in Fig. 2b is known as “discharge penetration into a solid body”\(^9\) and is characterized by the pulse current flowing through the discharge channel $I(t)$ and by the release of energy. If the energy is released rapidly enough, a microexplosion occurs in the solid body, resulting in the formation of a pit in the electrode contact area (Fig. 3a). Microcracks caused by the electrical discharges then accumulate within the stone, resulting in a main crack connected with the initial pitted area between the electrodes and leading to subsequent splitting of the stone (Fig. 3b).

Figure 4 schematically demonstrates the principle of the EHL operation. In electrohydraulic lithotripsy, a voltage pulse $U(t)$ with parameters corresponding to the diagram area right of point Ac (Fig. 1) is fed to the electrodes that are in close proximity to the solid body surface. When the voltage level reaches $U_{eh}(t)$, the liquid breaks down near the surface. This phase is characterized by pulse current flowing through the discharge channel $I(t)$ and by the release of energy (Fig. 4a). At this time and as noted above, the electrical breakdown of the liquid generates cavitation bubbles (Fig. 4b), resulting in the initiation of a shockwave and the creation of a pressure zone acting on the solid body, leading to its subsequent destruction (Fig. 4c).\(^20\)\(^,\)\(^21\) Thus, crater formation in the initial phase is not observed experimentally with the EHL (Fig. 5a). The shockwave passing through the uroliths causes mechanical stresses that accumulate in the stone and ultimately results in its fragmentation (Fig. 5b).

The NEPL is currently used clinically in dozens of Russian hospitals and has been proven to be an efficient and safe lithotripter.\(^10\)\(^–\)\(^12\) The basic characteristic of the device is that it produces a nanosecond pulse with a rise time of less than 50 nanoseconds, duration of 250 to 500 nanoseconds, and voltage of 10 kV when the energy applied to the object is between 0.3 and 1.0 J.

If the NEPL probe is located solely in a liquid and is not in direct contact with the stone, a discharge will occur in the liquid, and a pressure wave will be produced when the pulse is released. To establish tissue safety of the NEPL in such a scenario, safety studies have been conducted on canine and on human ex-vivo tissue samples harvested after nephrectomy, ureterectomy, and cystectomy procedures. In these studies, the NEPL probe tip was positioned close to or in direct contact with the tissue when the pulses were released. These studies demonstrated the low-trauma profile of the NEPL.\(^22\) A further study demonstrated that a direct electropulse exposure of 1.0 J
Materials and Methods

To simulate “hard” and “soft” uroliths, we used two types of BegoStone24 phantom stones. Their physical properties are presented in Table 1.

The procedure for preparing the samples was performed according to instructions.25 Two different powder-to-water mixing ratios were used to produce stone phantoms that mimic hard and soft stones (Table 1). Density of the stone phantoms was measured using the Hounsfield units (HU) scale, and hardness was measured using the Vickers hardness (HV) test. Measured average density was 2530 HU for hard samples, and 1400 HU for soft samples. Hardness based on the Vickers test was measured with an applied 100 g load for 10 seconds of dwell time. The averaged microhardness value was 90 HV for hard samples and 60 HV for soft samples.

Three typical sizes of cuboid samples were prepared for the test procedure. Each stone size corresponded to a specific lithotripter probe size. For the EHL tests, the following three typical probe sizes were used: 3.0 Fr, 4.5 Fr, and 7.0 Fr. For the NEPL tests, corresponding probe sizes of 2.7 Fr, 4.5 Fr, and 6.0 Fr were selected from a probe range of 2.0 Fr to 8.0 Fr. The stone sizes for the probes were chosen so that solid stones would be destroyed by the NEPL within approximately one-third of the probe’s service life at maximum pulse energy. For each lithotripsy method, probes of similar or identical size were allocated for the comparison (Table 2). One probe was used per stone phantom, and the test was repeated six times for each probe size and energy setting.

Comparative trials were conducted in physiologic saline (0.9% NaCl) at room temperature. The stones specifically sized for each lithotripter probe were placed on a stainless steel grid with 2 × 2 mm openings and immersed in the saline. The distal part of the probe was positioned at a 90-degree angle to the horizontal surface of the stone and brought into contact with the stone surface (for NEPL) or positioned in close proximity to it (for EHL). An electric pulse was then supplied to the probe from the respective lithotripter. Examinations of the stones that were performed periodically during the tests did not constitute official evaluation criteria. The probe was repositioned after each loss of contact with the target stone. The experiment was terminated when the test objective of clearing the complete stone phantom through the 2 mm mesh of the grid was achieved. To prevent stone repulsion from having an impact on the results of the experiment, the stones or stone fragments were held with tweezers during the fragmentation process. The number of pulses needed for clearing each stone phantom were recorded per probe size and energy setting. The closest possible corresponding NEPL and EHL energy settings and probe sizes were used for the comparison. The number of pulses needed to clear the stone phantom were converted into cumulative energy (number of pulses × energy per pulse).

The following devices were used for the testing:

1. NEPL: Urolit-105M nanosecond electropulse lithotripter (Lithotech Medical Ltd., Israel) with a 0.3 to 1.0 J pulse energy range (divided into eight parts in 0.1 J increments), operating in single-pulse mode and in 1 to 5 Hz multiple pulse mode (in 1 Hz increments).
2. EHL: Lithotron EL 25 Combilith electrohydraulic lithotripter (Walz Electronic GmbH, Germany) with 0.36 and 0.96 J pulse energy, operating in both single-pulse mode and multiple pulse modes.

The test settings for both lithotripters are provided in Table 3.

Table 1. Properties of BegoStone Phantom Stones

| BegoStone powder-to-water ratio | 15:3/15:6 | Tested sample volumes | 100, 256, and 320 mm³ | Tensile strength | 7 MPa/3.2 MPa | Longitudinal acoustic impedance | 8.2 × 10⁶ kg/m² sec/4.9 × 10⁶ kg/m² sec | Transverse acoustic impedance | 4.6 × 10⁶ kg/m² sec/2.8 × 10⁶ kg/m² sec |

Table 2. Probes and Stones Selected to Compare Lithotripter Effectiveness

<table>
<thead>
<tr>
<th>Comparison #</th>
<th>NEPL probe</th>
<th>EHL probe</th>
<th>Stone size, mm</th>
<th>Main clinical application (stone location)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7 Fr</td>
<td>3.0 Fr</td>
<td>5 × 5 × 4</td>
<td>Ureter, kidney (t.a.*)</td>
</tr>
<tr>
<td>2</td>
<td>4.5 Fr</td>
<td>4.5 Fr</td>
<td>8 × 8 × 4</td>
<td>Ureter, bladder</td>
</tr>
<tr>
<td>3</td>
<td>6.0 Fr</td>
<td>7.0 Fr</td>
<td>8 × 8 × 5</td>
<td>Bladder, kidney (p.a.**)</td>
</tr>
</tbody>
</table>

* t.a. = transurethral access; ** p.a. = percutaneous access.
NEPL = nanosecond electropulse lithotripter; EHL = electrohydraulic lithotripter.
### Table 3. Experimental Conditions for the Lithotripters Under Examination

<table>
<thead>
<tr>
<th></th>
<th>NEPL</th>
<th></th>
<th>EHL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy, J</td>
<td></td>
<td>E min 0.4</td>
<td></td>
<td>E min 0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E max 1</td>
<td></td>
<td>E max 0.96</td>
</tr>
<tr>
<td>Frequency mode</td>
<td>Single pulse mode</td>
<td></td>
<td>Single pulse mode</td>
<td></td>
</tr>
<tr>
<td>Number of consecutive pulses applied to the stone</td>
<td>Variable</td>
<td></td>
<td>Variable</td>
<td></td>
</tr>
</tbody>
</table>

**FIG. 6.** Comparison of the total energy spent on stone fragmentation for selected probe pairs. (a) 6.0 Fr and 7.0 Fr probes, hard stone; (b) 4.5 Fr and 4.5 Fr probes, hard stone; (c) 2.7 Fr and 3.0 Fr probes, hard stone; (d) 6.0 Fr and 7.0 Fr probes, soft stone; (e) 4.5 Fr and 4.5 Fr probes, soft stone; (f) 2.7 Fr and 3.0 Fr probes, soft stone.
The results were statistically evaluated for distinctive differences between the tested devices by paired samples t-test using a P value criterion equal to 5% level of statistical significance (P ≤ 0.05). The statistical analysis was performed for both hard and soft stones using SPSS Statistics software on the results obtained for both devices (12 pairs) according to the selected probe pairs and stone sizes (Table 2) at the specified energy (Table 3).

Results

The cumulative energy needed to clear the stone phantom through the grid was chosen as the criterion for comparing the efficacy of the two devices. A graphic comparison of the data is shown in Figure 6. Data regarding the cumulative energy (Esum) and number of pulses needed for the two compared lithotripters to clear a stone of a specified type and size are presented in Appendix 1.

Stone clearance was achieved with the NEPL in 100% of the tests, while the EHL had a success rate of 83% (2 failures in 12 tests). The EHL failed to fragment hard stones phantoms with 0.36 J of energy using the 3 Fr and 7 Fr probes (Figs. 6a, c). The estimated P value for successful tests was less than 0.04 (P < 0.04). With the exception of soft stones treated with 2.7/3 Fr probes at 0.36 to 0.4 J (P > 0.05), the results in terms of successful disintegration were significantly better with the NEPL than with the EHL (P < 0.04) (Fig. 6f).

In general, the standard deviation of the test series is considerably smaller for the NEPL compared with the EHL, which demonstrates a more consistent output from the NEPL device.

Discussion

The test results (Fig. 6, Appendix 1) clearly demonstrate that the NEPL in all cases investigated in the given work needs significantly less cumulative energy to destroy artificial stone phantoms than the EHL and is therefore more effective, because energy is transferred directly to the stone. The disparity in cumulative energy and number of pulses needed by the devices to clear stone phantoms increases with stone hardness and pulse energy.

Another interesting conclusion can be drawn from the investigation regarding the dependence of the cumulative specific volumetric energy (Ev) needed for fragmenting stone phantoms on phantom hardness and probe size (Ev = Esum/V where V is the stone volume). Calculated cumulative specific Ev needed for stone fragmentation for each lithotripter is given in Figures 7 a, b.

The results demonstrate entirely different dependencies between the specific Ev needed for clearing stone phantoms according to both sample density and probe diameter. For the EHL, there is no explicit correlation between the specific pulse energy applied to the stone and the density of the sample material or diameter of the probe. Much greater specific energies are required, however, for the destruction of hard stones compared with soft stones (Fig. 7a). For the NEPL, on the other hand, an explicit correlation exists between the specific energy needed for stone destruction and the density of the target material, with a clear decrease in the specific energy needed as probe size is increased (Fig. 7b).

At the same time, the average total specific Ev needed for stone fragmentation for the NEPL is four times less than for the EHL (Fig. 8). Thus, at comparable pulse parameters, NEPL needs substantially lower cumulative energy values and, accordingly, less time for stone destruction.

FIG. 7. Dependence of the specific energy needed for stone fragmentation on stone density and probe size. (a) EHL; (b) NEPL.

FIG. 8. Total specific energy needed for clearing stone phantoms during testing.
As described above, the operating principles of the compared lithotripters differ in how they destroy stones and, primarily, in the way they transfer energy to the stone. It has thus now been proven experimentally that the NEPL needs considerably less cumulative energy for stone destruction than the EHL because the energy is directly loaded into the stone.

At the same time, NEPL efficacy depends on the discharge distance between the probe electrodes. This distance is related to probe diameter—as probe diameter increases, less specific energy is needed for stone destruction. Thus, a greater distance between electrodes will create a larger plasma channel in the stone during discharge and, as a consequence, will cause an increase in thermomechanical stresses.

Explicit differences in the results (Figs. 6–8, Appendix 1) confirm the fact that, despite the similarity of the two methods (an electrical discharge between electrodes at the probe tip), different mechanisms of solid body disintegration are in place that account for the considerable differences in the results.

**Conclusion**

This study compares the efficacy of the nanosecond electropulse and electrohydraulic methods of lithotripsy. The findings demonstrate that, for all operating modes and stone phantom types, the NEPL needs much less cumulative energy and thus fewer pulses and correspondingly less time for stone fragmentation than the EHL. It is therefore concluded that NEPL is, by any definition, a more effective means for stone fragmentation than EHL. The results have ascertained various dependences between stone density (or hardness) and fragmentation than EHL. The results have ascertained various dependences between stone density (or hardness) and probe size for the specific volumetric energy needed for stone fragmentation.

The disparity in the results is explained by the dissimilar mechanisms at work in the compared lithotripters during stone destruction. The electropulse stone destruction mechanism applied in the NEPL transfers energy directly into the stone from discharge penetration into a solid body. This is in contrast with the electrohydraulic mechanism in the EHL, wherein energy is transferred through the liquid, which also creates a damaging shockwave.

**Disclosure Statement**

No competing financial interests exist.

**References**


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**Abbreviations Used**

- Ac: the point at which the breakdown probabilities of liquid and solid body are equal
- EHL: electrohydraulic lithotripter
- Ev: volumetric energy
- I(t): current pulse
- NEPL: nanosecond electropulse lithotripter
- SWL: shockwave lithotripsy
- Ueh(t): voltage pulse during breakdown of a liquid
- U(t): voltage pulse applied to the solid body

(Appendix follows →)
### Appendix 1. Test Data

#### Hard “stone,” NEPL, Pulse energy of 1 J

<table>
<thead>
<tr>
<th>Esum, J</th>
<th>Number of pulses</th>
<th>Esum, J</th>
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<tbody>
<tr>
<td>141</td>
<td>(±40)</td>
<td>141</td>
<td>(±40)</td>
<td>222</td>
<td>(±22)</td>
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#### Hard “stone,” EHL, Pulse energy of 0.96 J

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<td>557</td>
<td>(±148)</td>
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#### Hard “stone,” NEPL, Pulse energy of 0.4 J

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<td>186</td>
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#### Hard “stone,” EHL, Pulse energy of 0.36 J

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<td>(±238)</td>
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#### Soft “stone,” NEPL, Pulse energy of 1 J

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#### Soft “stone,” EHL, Pulse energy of 0.96 J

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<td>80</td>
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<td>83</td>
<td>(±18)</td>
<td>201</td>
<td>(±63)</td>
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#### Soft “stone,” NEPL, Pulse energy of 0.4 J

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<tr>
<td>38</td>
<td>(±5)</td>
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<td>90</td>
<td>(±24)</td>
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#### Soft “stone,” EHL, Pulse energy of 0.36 J

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<tr>
<td>41</td>
<td>(±12)</td>
<td>113</td>
<td>(±33)</td>
<td>140</td>
<td>(±36)</td>
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