Lasers and lithotripsy

Lasers
Light amplification by stimulated emission of radiation
Lasers utilise energy (pumping) to get most electrons into a high energy state (population inversion). Change from high energy to lower electron energy state results in loss of a photon of light (emission).

Lasers (MCC)
- Monochromatic (depends on source material)
- Collimated (parallel, thus high energy density)
- Coherent (same wavelength)

Effects on tissue
- Thermal injury
  - Photothermal
    - Direct heating by energy absorption
    - Depending on temperature of tissue, coagulation (>42 degrees), ablation (>100 degrees) or vaporisation (>300 degrees)
Lasers and lithotripsy

degrees) e.g. Holmium works by vaporisation of stone

Photomechanical

Very high power density – rapid heating and formation of plasma bubble. Collapse leads microjet formation and fissuring of stone as for ESWL e.g. pulsed dye laser

Non-thermal

Photochemical

Absorbed energy directly converted into chemical reactions (i.e PDT)

Effects on tissue dependent on:

Wavelength
Tissue absorption
Pulse duration
Power density
Lasering technique

(i) Tissue penetration depends on wavelength

Pulsed dye 540nm Deepest
HeliumNeon 630nm
Nd:YAG 1060nm
Ho:YAG 2140nm
Erbium:YAG 3000nm
CO2 10600nm Shallowest (~50um)

Depth of penetration inversely proportional to wavelength
Depth of penetration of holmium laser 0.5mm

(ii) Absorption characteristics

Dependent on laser wavelength each tissue has an absorption coefficient

Colours of tissue play an important role

Haemoglobin (red) absorbs blue-green light.
Therefore argon used to treat port-wine stains
Green light laser used for TURP – utilises Nd:YAG laser and frequency doubling crystal to generate the green light wavelength (KTP low power 80W; lithium borate high power 120W)

(iii) Pulse duration

Lasers may be continuous or pulsed
Continuous laser on for > 0.25s

Strength of continuous lasers = energy per second
Energy per second (power) = energy (J) x frequency (Hz)
Most lasers pulsed – beam switched on and off, each pulse < 0.25s

Strength on pulsed lasers = energy per emitted pulse (energy x frequency)
Q-switched lasers only allow a pulse (very short high energy pulse) after near-complete population inversion

(iv) Power density

Power per unit area. Depends on fibre diameter
Typical fibre diameters are 200uM, 365uM and 550uM
(v) Laser technique
Some lasers cut on contact, vaporise on near contact, and coagulate in non-contact mode (effectively reduces power density)

Laser injury and legislation
Main injury to skin and eye
Highest skin absorption far UV and far IR
No medically useful UV lasers; CO2 lasers in far IR spectrum – used for skin ablation
Eye injury
Eyes absorb visible, near UV and near IR light
Near UV absorbed by aqueous humour and lens – cataracts
Visible light (400nm-700nm) retinal burn
IR light 700-1400nm (Nd:YAG) cataract, retinal burn
IR light 1400-3000nm (Ho:YAG) cataract, corneal burn
IR light 3000nm-10000nm (CO2) corneal burn

BS EN 60825 classification 2007 classed lasers into 4 types:
Class 1 safe
Class 2
Class 3
Class 4 dangerous
Most medical lasers class 3B or 4
Extracorporeal lithotripsy
Up to 85% of calculi treatable with ESWL
ESWL involves generation and transmission of shock waves onto calculi, resulting in fragmentation. Unintentional tissue damage always occurs, typically to blood vessels.

Physics and pathophysiology of SW:
- Initial positive then negative pressure
- Passes through stone in ~10us
- Effects directly due to shockwave itself or through cavitation
- Direct = Anterior and posterior fragmentation, shear and spalling
- Cavitation = requires fluid medium.
- Negative pressure causes dissolved gas in fluid around stone to expand into bubble. Collapse of bubbles cause microjets which pit the surface of the stone (and damage surrounding tissues)

ESWL machines
Original ESWL machine Dornier HM3 (spark gap generated under water; GA; water bath). Now three differing mechanisms for generation of shock wave
NB. Our machine is an Siemens Lithostar (EMG) / Storz modulith SLK (EMG)

All ESWL machines comprise 4 components:
(i) Shock wave generator
   - Electrohydraulic
   - Electromagnetic
   - Piezoelectric
(ii) Focussing device
   - Parabolic mirror
   - Acoustic lens
   - Focussing dish
(iii) Coupling mechanism
   - Water bath (Dornier HM3)
   - Water or gel-filled pads
(iv) Imaging system
   - Image intensifier
   - Ultrasound

First generation Dornier HM3
Second generation Non-water bath EHL machines
EMG lithotriptors (Siemens lithostar)
PZE lithotriptors

Third generation

As for second generation but portable, USS/fluoro
Non-renal use, endoscopic procedures

<table>
<thead>
<tr>
<th>SW generation</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td>Wide range of energy</td>
<td>Short lifespan (3,000–4,000 SW)</td>
</tr>
<tr>
<td></td>
<td>Twin-pulse technique</td>
<td>Renewal expensive</td>
</tr>
<tr>
<td></td>
<td>Flexible size of aperture (15–26 cm)</td>
<td>Minimal energy necessary for discharge</td>
</tr>
<tr>
<td>Piezoelectric elements</td>
<td>Very long lifespan (&gt; 1,000,000 SW)</td>
<td>Limited range of energy</td>
</tr>
<tr>
<td></td>
<td>Variation of frequency (1 – 100 Hz)</td>
<td>Large aperture necessary (&gt; 40 cm)</td>
</tr>
<tr>
<td></td>
<td>Target control</td>
<td></td>
</tr>
<tr>
<td>Electromagnetic elements</td>
<td>Wide range and continuous graduation of energy</td>
<td>Metal membrane must still be changed</td>
</tr>
<tr>
<td></td>
<td>Flexible size of aperture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long lifespan (200,000–400,000 SW)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiple focusing principles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– membrane + acoustic lens</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– cylinder + paraboloid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– spherical shape</td>
<td></td>
</tr>
</tbody>
</table>

Contraindications

- Obesity
- Coagulopathy
- UUT obstruction
- Sepsis or active UTI
- Pregnancy
- Renal artery aneurysm / AAA
- Cystine stone/monohydrate stone
- Anorexia nervosa (increased stone)
- Failure of localisation
- Women of child-bearing age & distal ureteric stones (ovary damage)
- Splenomegaly

Efficacy based on type of machine

Table 1. Recent publications evaluating different lithotriptors for shock wave lithotripsy of renal calculi. The most contemporary series were chosen to reflect the current practices regarding lithotripter employed, stone size, and stone location.

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Lithotriptor</th>
<th>Energy source</th>
<th>n</th>
<th>Overall stone free (%)</th>
<th>Retreatment rate (%)</th>
<th>Aux procedures (%)</th>
<th>Efficiency quotient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cope et al. [16]</td>
<td>1991</td>
<td>Wolf Pliolith</td>
<td>Piezoelectric</td>
<td>220</td>
<td>75</td>
<td>51</td>
<td>4</td>
<td>0.48</td>
</tr>
<tr>
<td>Mykalak et al. [22]</td>
<td>1992</td>
<td>Thera sonic</td>
<td>Piezoelectric</td>
<td>172</td>
<td>66</td>
<td>21</td>
<td>ND</td>
<td>0.67</td>
</tr>
<tr>
<td>Cass [24]</td>
<td>1995</td>
<td>Dornier HM3</td>
<td>Electrohydraulic</td>
<td>4 796</td>
<td>63</td>
<td>6</td>
<td>3</td>
<td>0.59</td>
</tr>
<tr>
<td>Cass [24]</td>
<td>1995</td>
<td>Medstone STS</td>
<td>Electrohydraulic</td>
<td>6 195</td>
<td>64</td>
<td>6</td>
<td>2</td>
<td>0.63</td>
</tr>
<tr>
<td>Eiblak et al. [20]</td>
<td>1998</td>
<td>Dornier Compact</td>
<td>Electromagnetic</td>
<td>191</td>
<td>73</td>
<td>13</td>
<td>2</td>
<td>0.63</td>
</tr>
<tr>
<td>Cot et al. [19]</td>
<td>2000</td>
<td>Modulith SL 20</td>
<td>Electromagnetic</td>
<td>849</td>
<td>87</td>
<td>21</td>
<td>ND</td>
<td>0.68</td>
</tr>
<tr>
<td>Lalak et al. [21]</td>
<td>2002</td>
<td>Dornier Compact Delta</td>
<td>Electromagnetic</td>
<td>500</td>
<td>63</td>
<td>ND</td>
<td>6</td>
<td>0.68</td>
</tr>
<tr>
<td>Johnson et al. [23]</td>
<td>2003</td>
<td>Dornier Doli S</td>
<td>Electromagnetic</td>
<td>204</td>
<td>74</td>
<td>6</td>
<td>7</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Focal volume = volume around F2 where pressure = 50% of peak
Power (energy per shock) = peak pressure (megaPa) x focal volume
Efficiency of a machine directed related to energy per shock
Pain related to energy density at skin
Explains why Dornier HM3 had highest power but GA was required
PZE machines have much higher peak pressures but focal zones low; thus pain reduced but retreatment rates increased
NB. No evidence for benefit of EMLA cream in 2 xRCTs
Efficacy based on stone location

Ureteric stones
- Proximal: 85%
- Middle: 90%
- Distal: 95%

Renal stones
- < 2 cm: 90%
- 2-3 cm: 60%

Lower pole renal calculi*
- < 2 cm: 33%
- > 2 cm: 20%

* depends on infundibular length, width, and infundibulopelvic angle

Horseshoe kidney: 55% (safer vs. PCNL but retreatment rate high)

Efficacy based on stone composition

Reduced with the following stones
- Cystine
- Calcium oxalate monohydrate
- Calcium hydrogen phosphate dihydrate (brushite)

Until recently no evidence that HU alone can predict response to ESWL. Recent evidence suggests that when body mass taken into account (Skin to stone distance) may predict response (<900 and <9 cm ~ 90% stone-free rate)

Efficacy based on shock-wave frequency

2 studies: between 70 and 90 shocks/min best

ESWL failure
- Stones > 15 mm
- Impacted
- Hard stones
- Unfavourable anatomy
- Failure after 2 treatments
- Localisation difficulties (mid-ureteric stones)

Complications

Early
- Renal colic
- Haematuria*
- Perirenal haematoma (?Page kidney)
- Infection
- Arrhythmia

Late
- Renal dysfunction?
- Hypertension?
- Impaired fertility?

*Risk factors for renal injury:
- Age > 60
- Child
Pre-existing hypertension
Pre-existing renal impairment

(i) Infection after ESWL
Overall sepsis seen in ~1% of cases and 3% staghorn calculi
Use of prophylactic antibiotics controversial
2 x RCTs showed no benefit for patients without positive UTI or infection stones. Pearle metaanalysis 2007 however showed reduced UTI rate and reduced hospitalisation in patients receiving prophylactic antibiotics at the time of ESWL (all patients negative MSU pre-Rx)
Current recommendations for prophylactic antibiotics
   Infection stones
   Positive UTI
   History of recurrent UTI
   Instrumentation at time of ESWL
   EUA recommends Abx for 4 days afterwards

(ii) Arrhythmia
Occurs in 11-59%
No increased risk of cardiac morbidity however
PPM should be checked and atrial sensing turned off (single chamber ventricular pacemakers should be fine)

(iii) Long-term renal dysfunction after ESWL
Animal studies, acute phase response and short term decrease in GFR, RPF and UO portend long-term renal damage.
Short-term effects disappear after ~7 days
Little conclusive evidence however. Janetschek et al (J Urol 1997) – increased RRI in patients with risk factors associated with new onset hypertension in 45% patients > 60 years
8% rate of new-onset hypertension after ESWL vs. 6% population
However patients with renal stones also overweight, and renal stones themselves a/w risk of hypertension

Advances in ESWL
Better prognostication of success
   Artificial neural networks
   HU and skin-to-stone distance
Adjuvant PDI therapy
Dual shock wave machines
Low shock-wave frequency (60 vs. 120)
Progressive voltage increase
Simultaneous chemolysis
Intracorporeal lithotripsy

<table>
<thead>
<tr>
<th></th>
<th>Fragmentation</th>
<th>Safety</th>
<th>Stone removal</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>EHL</td>
<td>+++</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>US</td>
<td>++</td>
<td>+++</td>
<td>+++++</td>
<td>+</td>
</tr>
<tr>
<td>Impact</td>
<td>++++</td>
<td>++++</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Pulsed-Dye</td>
<td>++</td>
<td>+++</td>
<td>0</td>
<td>+++++</td>
</tr>
<tr>
<td>Holmium</td>
<td>++++</td>
<td>++</td>
<td>++</td>
<td>+++</td>
</tr>
</tbody>
</table>

(i) EHL
Underwater spark plug
Plasma cavitation bubble – collapse leads to microjet and fissuring
Probe just off stone (1mm)
Ureteric damage and retropulsion problematic

(ii) USS
Energy from piezoelectric crystal transmitted longitudinally
Suction allows stone removal but inefficient for hard stones

(iii) Ballistic
Excellent fragmentation and safe, but retropulsion problematic

In general holmium laser most valuable. Although ballistic methods (Swiss lithoclast) cheap, reliable and safe, associated with significant retropulsion

Semi-rigid ureteroscopy
A/w high stone-free rates
Day case procedure
Lasers and lithotripsy

>95% single treatment

Complications
- bleeding (<1%)
- infection (2%)
- extravasation (3.7%)
- perforation (1.6%)
- stricture (<1%)
- streinstrasse (<1%)
- avulsion
- instrument damage

Technical considerations
- The migrated stone
  - Push-bang
  - Push-perc
- The impacted stone/stricture/urinary diversion
  - Percutaneous ureterolithotomy (antegrade approach: need flexible cystoscope/ FURS. If planning to use a FURS, advance 14F access sheath)
  - Laparoscopic ureterolithotomy

Flexible ureterorenoscopy

<table>
<thead>
<tr>
<th>Manufacturing company</th>
<th>Model</th>
<th>Working length (cm)</th>
<th>Deflection up/down (degrees)</th>
<th>Tip diameter (F)</th>
<th>Proximal diameter (F)</th>
<th>Channel diameter (F)</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyrus ACMI</td>
<td>DUR-D</td>
<td>65</td>
<td>250/250</td>
<td>8.7</td>
<td>9.3</td>
<td>3.6</td>
<td>Digital video ureteroscope; lightweight (1.18 lbs)</td>
</tr>
<tr>
<td>Gyrus ACMI</td>
<td>DUR-8E</td>
<td>64</td>
<td>170/180</td>
<td>6.75</td>
<td>10.1</td>
<td>3.6</td>
<td>Active secondary deflection of 130° gives total downward deflection of 310°</td>
</tr>
<tr>
<td>Olympus</td>
<td>URF-P5</td>
<td>70</td>
<td>275/275</td>
<td>5.4F</td>
<td>8.4</td>
<td>3.6</td>
<td>Bevelled “Evolution tip”; built-in moiré-effect reduction filter</td>
</tr>
<tr>
<td>Storz</td>
<td>Flex-X2</td>
<td>67.5</td>
<td>270/270</td>
<td>7.0</td>
<td>8.5</td>
<td>3.6</td>
<td>Laser resistant tip (Laserlite)</td>
</tr>
<tr>
<td>Stryker</td>
<td>FlexVision U-500</td>
<td>64</td>
<td>275/275</td>
<td>6.9</td>
<td>8.8</td>
<td>3.6</td>
<td>Locking mechanism during secondary deflection; high density fiber optic bundles for enhanced image resolution</td>
</tr>
<tr>
<td>Wolf</td>
<td>Viper</td>
<td>68</td>
<td>270/270</td>
<td>6.0</td>
<td>8.8</td>
<td>3.6</td>
<td>Slightly bevelled,atraumatic small tip</td>
</tr>
</tbody>
</table>

Instrument channel 3.6F across board. Flow rates:
- Empty channel 40 ml/min
- 2.2F basket 10 ml/min
- 3 F basket 4 ml/min

Cost and durability
- Expensive. Accounting for purchase cost, disposables and repairs, approximately 700 pounds per case. Expect 6-15 uses before repair
- Most sensitive part deflection unit
- ACMI DUR-8 (Now Storz) most reliable scope (Monga 2006)
- Damage prevention
  - Laser fibre in straight!
  - Avoid overtight coiling
  - Dedicated theatre table
Avoid back-feeding stiff wires
Lasering camera tip – dedicated laser bung

Pre-stenting a possibility to avoid PUJ stricturing. Some units (Norwich) pre-stent under local anaesthetic and USS/radiological screening
Pre-operative imaging should be mandatory (KUB on day, CT for radiolucent stones)
Unless a good anaesthetic reason, patient should be paralysed.
Access sheaths (12F or 14F; 28cm, 35cm or 46cm)
  Maintains low intrarenal pressure while operating
  Facilitates multiple entries/exits
  Protects instrument
  Passive egress of fragments
  Improved stone-free rates (Aude 2004)
Cook N-gage excellent for moving stones around kidney

Guidewires and JJ stents

What are the indications for stent insertion? ‘SPOILED’
  Solitary anatomical or functional kidney
  Perforation or suspected perforation
  Oedema
  Infection
  Large volume residual fragments
  Secondary elective procedure planned
  Dilatation >10F

What makes a perfect stent?
  Biocompatible
  Resists migration
  Good tensile strength
  Durable
  Easy insertion
  Inhibits biofilm
  Resists encrustation
  Radio-opaque
  Cheap

Perfect material not been found:
  Silicone
    Biocompatible and resists encrustation but insertion difficult due to high friction and low tensile strength (snaps easily)
  Polyurethane
    Strong and easily inserted but causes mucosal ulceration
  Polyethylene
    Biocompatible, but durability poor and crusts
  Copolymers
    Best combination. May be based on silicone (c flex or silitek) or other
  Percuflex stents (Boston Scientific) olefinicblock co-polymer strong and low friction but encrusts
Animal studies have shown that JJ stents a/w:
- Dilated ureter
- Impaired peristalsis
- Impaired stone passage

**Does a stent relieve obstruction?**
Controversial
- Urine refluxes up the centre of a stent
- Urine drains alongside stent
- JJ stent in an unobstructed ureter results in a rise in renal pelvic pressure
- JJ stents require significant pressure to drain compared with nephrostomy

**Does a stent impair stone passage?**
Controversial
- One meta-analysis (Abdel-Khalek 2003) of 938 pts shown that stone free rates after ESWL slightly lower in stented rather than non-stented patients
- AUA guidelines – stents do not improve outcome in patients with ESWL May actually impair outcome

**How bad are stent symptoms?**
Ureteric stent symptom questionnaire (Joshi 2002)
- 78% had bothersome LUTS
- >80% pain
- 32% sexual dysfunction
- 58% reduced work capacity
- No difference between standard stent, polaris, long loop, short loop (Lingeman 2005)
- No difference in stent size, but 4.8F stents appear to migrate more
- Reduced pain and readmission rate with overnight ureteric catheter vs. stent

**Guidewires**
4 main types
- PTFE coated steel core
  - Standard wire
  - Cheap £5
  - Low friction, reasonably stiff, but can kink
- Hydrophilic
  - Slippery and stiff
  - Mid-range £11
  - Migration problematic
- Hybrid wires
  - Sensor g/w
  - Hydrophilic tip, stiff nitinol core body
  - Difficult cases
  - Expensive £30
- Super stiff
  - Kink resistant
  - Mid-range