**Problem: Shock-Wave Lithotripsy (SWL)**

In SWL, a very common, non-invasive method to destroy kidney stones, the kidney is blasted with high intensity sound waves generated outside the patient and focused on the stone.

- **Focused (direct) shock waves:**
  - Compression induced cracks
  - Stone spallation by reflection
  - Tissue shearing
  - Tension "tail" of the pressure impulse

- **Indirect shock waves:**
  - Cavitation - bubble expansion and collapse
  - Pitting by "jets" of collapsing bubbles
  - Tension waves by reflection – dilatation of vessels and capillaries

Our numerical simulations of stone spallation use a fragmentation technique of [Pandolfi & Ortiz, 2002] with special cohesive elements.

**Journal of Urology (1992):**
"SWL is a form of renal trauma"
Shock waves focus at stone but damage tissue!

**Material Model: Kidney Tissue**

The elastic behavior of the soft tissue is constrained by a deviatoric stress measure corresponding to a shear stress.

**Logarithmic plastic strain:** $\varepsilon^p$

The volumetric expansion of the body $V = JV_0$ with $J = \det(F)$ is induced by hydrostatic tension.

**Logarithmic plastic dilatation:** $\vartheta^p$

The tissue material is incompressible, irreversible volumetric expansion is only induced by cavitation of (empty) bubbles:

$$\frac{d}{dt} \left( r^3 - a^3 \right) = 0 \quad \rightarrow \quad \dot{\vartheta}^p = \frac{dr}{dt}$$

Formulate the corresponding energy of dissipated volumetric work and the kinetic energy of expanding bubbles.

The plastic dilation relates to micro-mechanic via the volume of the cavities, e.g., for $N$ cavities with radius $a$:

$$\vartheta^p = \log \left( 1 + \frac{2}{r^3} N(a^3 - a_i^3) \right)$$

Use an incremental solution procedure and define in every time interval an update-energy function in terms of logarithmic plastic variables.

$$f_i(F_{i+1}, e_{i+1}, M, \theta_{i+1}^p) = W^c(F_{i+1}, \theta_{i+1}^p) + W^v(e_{i+1}, \theta_{i+1}^p) + K(\vartheta^p, \theta_{i+1}^p) + \Delta W(\Delta \vartheta^p, \Delta e^{i+1}, \Delta \theta_{i+1}^p)$$

Compute the updated internal variables by:

$$W_u = \min_{e_i, M, \theta_{i+1}^p} f_i$$

**Numerical Simulation**

- Elastic material data (elastic modulus $0.05 \ldots 0.3$ MPa, viscosity $0.001 \ldots 0.007$ Pa s) are known, but only few experiments determine inelastic properties.
- Different parameters for different regions of the kidney are not available, all data are homogenized for “the kidney”.
- Parametric studies on the effect of varying material data (uniaxial strain):
  - Body tissue
  - Kidney tissue
  - Fat

- Propagation of (damage inducing) stress waves
- First finite element mesh based on geometrical data purchased from a company.
- Functional tissue (renal cortex, medulla, …) : new material model
- Non-functional tissue (ureter, main arteries and veins) : non-linear elastic material

- Damage in a pig kidney experiments by [Cleveland et al., 2000]
- Color: irreversible volumetric expansion (damage)