Future Implantable Systems

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Real Time, Distributed In Vivo Diagnostics

- Moving implants
- Wireless endocardial pacing and sensing
- Multielectrode epicardial mapping for EP study
- Chip in cell for cellular-level monitoring and therapeutic treatments

1 mm  100 μm  10 μm

Implant Dimension
Current Autonomous Implants

- Use remote power source to remove the battery partially or completely.
- Power transmission is like a transformer – **inductive coupling**.
- Power receiver is large – 1 to a few cm.
- Extremely short distance (almost touching)
- Coil alignment is critical.
- **Still, we haven’t solved the problem of miniaturization.**

[Lenaerts 07]  [Wang 06]
Can we do better than inductive coupling?

Back to Physics …

\[ \nabla \times \mathbf{H} = -i\omega \varepsilon_0 \varepsilon_r \mathbf{E} + \sigma \mathbf{E} \]
\[ \nabla \times \mathbf{E} = i\omega \mu_0 \mathbf{H} \]

In the past 50 years, analyses on wireless power transmission within biological tissues omit the displacement current – the term Maxwell added to Ampere’s Law and resulted in the Maxwell equations.

- Lower frequency is better!
- Most systems operate at 10 MHz or lower.

YES when we take into account the displacement current.
Optimal frequency

\[
\omega_{\text{opt}} = \sqrt{\frac{c \sqrt{\varepsilon_r}}{d \tau (\varepsilon_r - \varepsilon_{\infty})}} \cdot \sqrt{1 - \frac{4 a_\perp^2 + \left( \sigma d \sqrt{\frac{\mu_r}{\varepsilon_0 \varepsilon_r}} - 1 \right) a_\parallel^2}{\frac{d \varepsilon_r^{3/2}}{c \tau (\varepsilon_r - \varepsilon_{\infty})} + 1}} \, a_\parallel^2
\]

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Freq (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood</td>
<td>3.54</td>
</tr>
<tr>
<td>Bone (cancellous)</td>
<td>3.80</td>
</tr>
<tr>
<td>Bone (cortical)</td>
<td>4.50</td>
</tr>
<tr>
<td>Brain (grey)</td>
<td>3.85</td>
</tr>
<tr>
<td>Brain (white)</td>
<td>4.23</td>
</tr>
<tr>
<td>Fat (infiltrated)</td>
<td>6.00</td>
</tr>
<tr>
<td>Fat (not infiltrated)</td>
<td>8.64</td>
</tr>
<tr>
<td>Heart</td>
<td>3.75</td>
</tr>
<tr>
<td>Kidney</td>
<td>3.81</td>
</tr>
<tr>
<td>Lens cortex</td>
<td>3.93</td>
</tr>
<tr>
<td>Liver</td>
<td>3.80</td>
</tr>
<tr>
<td>Lung</td>
<td>4.90</td>
</tr>
<tr>
<td>Muscle</td>
<td>3.93</td>
</tr>
<tr>
<td>Skin</td>
<td>4.44</td>
</tr>
<tr>
<td>Spleen</td>
<td>3.79</td>
</tr>
<tr>
<td>Tendon</td>
<td>3.71</td>
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</tbody>
</table>
Prototype Receiver at .13 μm CMOS

- Operating frequency: 915 MHz or 1 GHz
- TX antenna size: 20 mm × 20 mm
- RX antenna size: 2 mm × 2 mm
- Inter-antenna dielectric: 15 mm, bovine muscle tissue
- Startup time: 4 μs
- Rectifier efficiency: 65%
- Regulator efficiency: 70%
- Gain of link + rectifier + regulator: -33.2 dB (theoretical 31.0 dB)
- DC output power: 140 μW @ 1.2 V regulated

- Unique features
  - Adaptive conjugate matching
  - Highly efficient rectifier

- Coil dimension is 2 mm × 2 mm which is 100 times smaller than previous designs in the literature at the same power transfer efficiency and range.
1959, Richard Feynman, *Plenty of Room at the Bottom*:

A friend of mine (Albert R. Hibbs) suggests a very interesting possibility for relatively small machines. He says that, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and “looks” around. (Of course the information has to be fed out.) It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately-functioning organ.
Translating Torques into Motion

- Idea is similar to the paddle in kayaking.
- Asymmetrical shape produces asymmetrical drag forces.
- Alternate direction of EM torque results in net forward force.
- Device can be optimized in terms of shape, frequency of current switching, and magnitudes of currents.
Preliminary Experiments
- Power and data are transmitted from same antenna
- Propulsion dominates power consumption, and must be efficient.
- Plan to tape out in mid June
In the United States, about half of the cardiac mortality is due to ventricular arrhythmia, which accounts for approximately 300,000 deaths per year.
CHIC (CHip In Cell)

- Autonomous, wireless, implantable sensor
- Active, continuous-time monitor of cellular activity

Lung cancer cell

Source: T. Johnson, B. Reutter

25 \mu m^2 chip

50 \mu m
Sensors and Resonantors

CMFET chemical sensor

Pressure sensor on flexible substrate

Micro resonantor
## Choice of Cells

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Cell Size</th>
<th>Device Size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Xenopus Oocytes</strong></td>
<td>1.0 mm (spherical)</td>
<td>50 μm</td>
</tr>
<tr>
<td><strong>Plant Protoplasts</strong></td>
<td>60 μm (spherical)</td>
<td>10-15 μm</td>
</tr>
<tr>
<td><strong>Chinese Hamster Ovary (CHO)</strong></td>
<td>2x 25x 100 μm (spread on surface)</td>
<td>~ 5 μm</td>
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