Exploration of Electro-Enhanced-Chemotherapy II.

Uptake of radioactive tracer in rat Muscle tissue at 6 and 24 hours after applied electric pulses of 1000 V/cm field-strength, 100 micro-s pulse-length, and various number of pulses.

Persson, Bertil R

Published in:
Acta Scientiarum Lundensia

2017

Document Version:
Publisher’s PDF, also known as Version of record

Link to publication

Citation for published version (APA):

Creative Commons License:
Unspecified
Citation: (Acta Scientiarum Lundensia)
Uptake of radioactive tracer in rat Muscle tissue at 6 and 24 hours after applied electric pulses of 1000 V/cm field-strength, 100 μs pulse-length, and various number of pulses.
Acta Scientiarum Lundensia, Vol. 2017-003, pp. 1-21, ISSN 1651-5013

Corresponding address:
Bertil RR Persson prof.em
Medical Radiation Physics
Barngatan 2
SE-221 85 LUND, Sweden
e-mail: bertil_r.persson@med.lu.se,
e-mail: bertilrrpersson@gmail.com
Mobile: +4672 009 9122
Research paper:

Exploration of Electro-Enhanced-Chemotherapy II

Uptake of radioactive tracer in rat Muscle tissue at 6 and 24 hours after applied electric pulses of 1000 V/cm field-strength, 100μs pulse-length, and various number of pulses. (ver. 1.0)

Bertil R.R. Persson,
PhD, MDhc, professor emeritus
Lund University, Faculty of Medicine, Department of Clinical Sciences Lund,
Medical Radiation Physics, 22185 Lund, Sweden

Executive Summary

The aim of the study is to explore the enhanced uptake of the radioactive tracer Technetium-99m-DTPA ($^{99m}$Tc-DTPA) in rat Muscle tissue in Fischer 344 rats after applied electric pulses of 1000 V/cm field-strength, 100μs pulse-length, and various number of pulses.

Methods: $^{99m}$Tc-DTPA (total, 150 MBq) was administered intramuscularly (i.m.) at the shoulder as a bolus in several fractions of 50 μl each in 1 minute intervals. Images of the radioactivity distribution in the rats was recorded with a gamma-camera at 6 and 24 hours after electroporation. EP treatment was performed with 2 needle electrodes separated 8 mm inserted in the right back thigh muscle, through which electric pulses of 600;800;1000;1200 V/cm field-strength, and 100;250;500 μs pulse-length were applied. Bioimpedance measurements were performed at 2 and 20 kHz through the needle electrodes in the right back thigh muscle. Before applying the EP treatment pulse, two measurements established the reference level $R_{before}$. Then $N_p$ consecutive pulses ($N_p = 2,4,6,10,12$) of field strength amplitude,1000V/cm and pulse-length 100μs were applied in 1 s interval and the impedance was recorded between each pulse. In order to study the relaxation of the poration the conductance measurements were continued 15 times after the last pulse in 1 s interval.

Statistical analysis and modelling of the data is performed using multivariate data processing methods such as Principal Component Analysis PCA, and modelled with the method of Projection to Latent Structures, PLS, also called PLSR Partial Least Square Regression.

Results: The f the uptake ratios was predicted by tissue impedance measurements at various frequencies 2-50 kHz. This is shown by the outcome of the PLS-modelling equations of Uptake ratio at 6 and 24 h versus tissue Conductance change Index at 2 and 50 kHz after the last pulse:

- $UR_{6h} = 4.22 + 0.027*CCI(2); UR_{6h} = 4.45 + 0.040*CCI(50)$
- $UR_{24h} = 3.77 + 0.07*CCI(2); UR_{24h} = 0.44 + 0.24*CCI(50)$

Conclusion: The most optimal scenario to predict the outcome of the electrochemotherapy session i.e. to achieve highest uptake ratio of bleomycin would be to use the relaxation time (T1/s) of the tissue conductivity after treatment and the delivered absorbed energy (W J/kg).

- $UR_{6h} = -8.097+2.04*(T1/s)+1.88\cdot10^{-3}*(W J/kg^{-1})$
- $UR_{24h} = -25.78+7.63*(T1/s)-1.36\cdot10^{-3}*(W J/kg^{-1})$
1. Introduction
The principles for application of high voltage impulses in vivo for tumor therapy and gene therapy has previously been described in detail (Persson 2000). The aim of the present study is to explore the enhanced uptake of the radioactive tracer Technetium-99m-DTPA (\(^{99m}\text{Tc-DTPA}\)) in rat Muscle tissue in Fischer 344 rats after applied electric pulses of 1000 V/cm field-strength, 100\(\mu\)s pulse-length, and various number of pulses.

2. Exploration of Radioactivity Uptake

Animals
Healthy Fischer-344 rats (B&K; Stockholm, Sweden) and Wistar rats (Taconic M&B; Ry, Denmark) were used in the experiments. The animals were housed in polycarbonate cages with access to food and fresh water \textit{ad libitum}. Both male and female rats were used, weighing 300–400 and 150–200 g, respectively. Before electric pulse treatment, the animals were anesthetized with either chloral hydrate or isoflurane (Forene; Abbott Scandinavia AB, Solna, Sweden) by applying “Univentor 400 anesthesia unit.”

The Animal Ethical Committee in Malmö/Lund (Permit M171-04; Lund, Sweden) approved all experimental animal procedures.

Radiopharmaceutical
Technetium-99m (\(^{99m}\text{Tc}\)) is a radioisotope with physical characteristics suitable for \textit{in vivo} tracer experiments. It has a half-life of 6.0 hours and emits gamma photons of 140 keV (87% per decay), which results in a low absorbed dose per activity unit (Bq) and high detection efficiency in thin NaI(Tl) crystals used in gamma cameras.

The radiopharmaceutical \(^{99m}\text{Tc-DTPA}\) is a stable, water-soluble compound (MW 416) used clinically in radionuclide angiography, static brain imaging, and kidney and urinary tract studies. \(^{99m}\text{Tc-DTPA}\) was chosen as the tracer in this study because its pharmacokinetic behavior is very similar to bleomycin (MW 1400).

\(^{99m}\text{Tc-DTPA}\) is prepared from a kit of TechneScan® (Mallinckrodt Medical B.V.; Petten, Holland). This kit is a freeze-dried sterile mixture of 25 mg Ca-Na-3-diethylene-triamine-pentaacetate (DTPA), 0.21 mg stannous-chloride-dihydrate (SnCl\(_2\cdot\text{H}_2\text{O}\)), 0.25 g Gentisic acid that is a di-hydroxy-benzoic acid, used as an antioxidant excipient, and 12 mg sodium chloride. By adding 300 MBq \(^{99m}\text{Tc-sodiumpertechnetate}\) in 0.75 mL of sterile, pyrogen-free physiological saline, mixed until the powder is dissolved, \(^{99m}\text{Tc-DTPA}\) is formed. After 15 minutes at room temperature, the \(^{99m}\text{Tc-DTPA}\) solution is ready for injection and is stable for 8 hours. The labeled compound is a slightly opalescent and colorless aqueous solution with a pH of 4.0–5.0, with a labeling efficiency 95%. In the present study the \(^{99m}\text{Tc-DTPA}\) (total, 150 MBq) was administered intramuscularly (i.m.) at the shoulder as a bolus in several fractions of 50 \(\mu\)l each in 1 minute intervals.
Radioactivity measurement

Images of the radioactivity distribution in a typical rat under the gamma-camera (GK) is shown in Figure 1 at 6 hours after electroporation in Figure 2 after 24 hours. The administration site at the shoulder appears as a dark spot and the uptake in the electric pulse treated region at the thigh is seen as a dark spot. The corresponding area at the opposite untreated side is used as reference for extracellular activity. Kidney(K), bladder(B) with urine activity are seen as dark areas in the picture.

The present study investigates the effect of applied electric pulses of 600; 800; 1000; 1200 V/cm; 100 and 500 μs pulse length, and 2, 4, 6 or 12 pulses, on the accumulation of the radiolabeled pharmaceutical $^{99m}$Tc-DTPA that mimics the Bleomycin, in rat muscular tissue after in vivo electroporation. Gamma camera measurements are applied to noninvasively quantify the accumulation of $^{99m}$Tc-DTPA in the region treated with electrical pulses as previously described.

![Figure 1](image1.png) GK-image of a rat at 6 h after electroporation treatment with 800 V/m; 0.25 ms; 12 pulses; K= kidney, B= bladder

![Figure 2](image2.png) GK-image of the same rat as in 1a at 24 h after electroporation treatment with 800 V/m; 0.25 ms 12 pulses. K= kidney, B= bladder

In Table 1 is displayed for each rat: applied field strength (V/cm), pulse-length (μs), number of applied pulses N, and uptake-ratio of $^{99m}$Tc-DTPA in the target region after 6 h (UR6h) and after 24 hours (UR24h).

<table>
<thead>
<tr>
<th>Rat ID</th>
<th>E V/cm</th>
<th>PL μs</th>
<th>N pulses</th>
<th>TcUR6h</th>
<th>±Sd</th>
<th>TcUR24h</th>
<th>±Sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>1000</td>
<td>100</td>
<td>6</td>
<td>1.45</td>
<td>0.07</td>
<td>1.61</td>
<td>0.36</td>
</tr>
<tr>
<td>1002</td>
<td>1000</td>
<td>100</td>
<td>6</td>
<td>3.50</td>
<td>0.16</td>
<td>4.44</td>
<td>0.39</td>
</tr>
<tr>
<td>1003</td>
<td>1000</td>
<td>100</td>
<td>6</td>
<td>3.26</td>
<td>0.16</td>
<td>11.59</td>
<td>4.27</td>
</tr>
<tr>
<td>1004</td>
<td>1000</td>
<td>100</td>
<td>12</td>
<td>9.72</td>
<td>0.56</td>
<td>5.77</td>
<td>0.83</td>
</tr>
<tr>
<td>1005</td>
<td>1000</td>
<td>100</td>
<td>12</td>
<td>10.63</td>
<td>0.72</td>
<td>12.84</td>
<td>1.23</td>
</tr>
<tr>
<td>1006</td>
<td>1000</td>
<td>100</td>
<td>12</td>
<td>6.66</td>
<td>0.40</td>
<td>11.99</td>
<td>2.79</td>
</tr>
</tbody>
</table>

Statistical analysis and modelling of the data is performed using multivariate data processing methods such as Principal Component Analysis PCA, and modelled with the method of Projection to Latent Structures, PLS, also called PLSR Partial Least Square Regression. Herman Wold introduced the method of Partial least squares (Wold, 1982). His son Svante Wold, who
was a chemist has then developed the method to be used in chemometrics, and according to him, the projection to latent structures should be the correct name of the method (Wold et al., 2001). These methods are nowadays commonly used in chemometrics, bio-pharmacology and related areas. Principal component analyses PCA and clustering are used to study the quality and structure of the original database. PCA can also be used to find outliers and to find out if the data can be divided into various classes. In order to find an equation to predict the dependent variables from the descriptors, the model of Projection to Latent Structure regression (PLSR) was used (XLSTAT, 2015).

3. Exploration of conductance measurements

Electrical Impedance and Admittance

Tissue can be considered as a dielectric with losses, modeled as a parallel RC-circuit with admittance \( Y = \frac{1}{\text{abs}(Z)} \).

\[
Y = G + j \cdot \omega \cdot C \quad \text{where} \quad G = \frac{A}{d} \cdot \sigma = k \cdot \sigma \quad \text{and} \quad C = \frac{A}{d} \cdot \varepsilon = k \cdot \varepsilon
\]

where

\( Z \) is the impedance;
\( Y \) is the admittance = \( \frac{1}{\text{abs}(Z)} \);
\( G \) is the conductance (\( \Omega^{-1} \));
\( \sigma \) is the conductivity (S);
\( C \) is the capacitance (F);
\( \varepsilon \) is the permittivity;
\( A \) is the cross section of the tissue (m\(^2\));
\( d \) is the thickness of tissue (m);
\( k \) is the geometric constant of the electrode arrangement in question.

Impedance Powering Parameters of electroporation

Various parameters derived from the impedance or admittance data are used for prediction the outcome of electroporation in terms of uptake of \(^{99m}\text{Tc-DTPA} \) and DNA expression in the treated tissue volume.

Conductance measurements were performed in 3 Fischer 344 rats with 2 needle electrodes separated 8 mm inserted in the right back thigh muscle. Before applying the EP treatment pulse, two measurements were performed to establish the reference level. Then 6 or 12 consecutive voltage pulses of field strength amplitude 1000 V/cm and pulse-length 100 \( \mu \)s were applied in 1 s interval and the impedance was recorded between each pulse. In order to study the relaxation of the poration the conductance measurements were continued 15 times after the last pulse in 1 s interval.
6 pulses 1000 V/cm and pulse-length 100 μs

The results of a selected rat (R001) are displayed in Figure 2.

![Graph showing conductance ratio before, during and after 6 consecutive pulses of 1000 V/cm amplitude and 100 μs pulse length for Rat No. R001.]

The Conductance change index GCI

The Conductance change index GCI is equal to the ratio between difference in admittance between each pulse and the admittance before the first pulse and the admittance before the first pulse.

\[
G_{CI_p} = \left(\frac{G_p}{G_0} - 1 \right)
\]

- \(G_0\) is the conductance (Ω\(^{-1}\)) before the first pulse.
- \(G_p\) is the conductance after pulse no. \(p\)

![Graph showing conductance change index after each EP pulse measured at 2, 5, 10, 20, 30, 50 kHz for Rat 001.]

Figure 3
Conductance ratio before, during and after 6 consecutive pulses of 1000 V/cm amplitude and 100 μs pulse length Rat No. R001.

Figure 4
Conductance change index after each EP pulse measured at 2, 5, 10, 20, 30, 50 kHz.
Table 2
Conductance change Index in % after 6 pulses

<table>
<thead>
<tr>
<th>Rat</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>R001</td>
<td>74,1</td>
<td>65,0</td>
<td>58,2</td>
<td>50,0</td>
<td>44,1</td>
<td>35,8</td>
</tr>
<tr>
<td>R002</td>
<td>29,7</td>
<td>26,2</td>
<td>23,2</td>
<td>20,1</td>
<td>18,0</td>
<td>14,7</td>
</tr>
<tr>
<td>R003</td>
<td>46,7</td>
<td>44,3</td>
<td>43,7</td>
<td>43,5</td>
<td>43,9</td>
<td>42,8</td>
</tr>
</tbody>
</table>

Conductance difference between consecutive pulses

Conductance difference between consecutive pulses

\[ \Delta G = G_{i+1} - G_i \]

Where \( i \) is the pulse number \( i = 0, 1, 2, 3, 4, 5, 6 \)

Figure 5
Conductance difference at 2 kHz between consecutive 6 pulses: 1000 V/cm, 100 μs.

Table 3
Conductivity change between the first 3 pulses and the declination

<table>
<thead>
<tr>
<th>Rat</th>
<th>Δσ1 %</th>
<th>Δσ2 %</th>
<th>Δσ3 %</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>R001</td>
<td>33,89</td>
<td>8,38</td>
<td>1,76</td>
<td>-3,83</td>
</tr>
<tr>
<td>R002</td>
<td>20,09</td>
<td>7,23</td>
<td>1,21</td>
<td>-2,61</td>
</tr>
<tr>
<td>R003</td>
<td>19,34</td>
<td>8,15</td>
<td>4,36</td>
<td>-1,84</td>
</tr>
</tbody>
</table>
12 pulses 1000 V/cm and pulse-length 100 μs

Conductance measurements was performed with 2 needle electrodes separated 10 mm inserted in the right back thigh muscle in Fisher 344 rats. Consecutive voltage pulses of amplitude 1000 V and pulse length 100 μs were applied and the conductance was recorded between each pulse and 15 times after the last pulse.

Figure 6
Conductance ratio before, during and after 12 consecutive EP pulses of 1000 V/cm amplitude and 100 μs pulse length. Rat No. R004

Figure 7
Conductance change index after each EP pulse Rat No. R004
Table 4
Conductance change Index in % after 12 pulses

<table>
<thead>
<tr>
<th>Rat</th>
<th>2 kHz</th>
<th>5 kHz</th>
<th>10 kHz</th>
<th>20 kHz</th>
<th>30 kHz</th>
<th>50 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>R004</td>
<td>46,9</td>
<td>42,9</td>
<td>39,3</td>
<td>33,6</td>
<td>29,5</td>
<td>24,3</td>
</tr>
<tr>
<td>R005</td>
<td>73,3</td>
<td>69,2</td>
<td>64,5</td>
<td>57,5</td>
<td>52,7</td>
<td>44,3</td>
</tr>
<tr>
<td>R006</td>
<td>99,8</td>
<td>92,2</td>
<td>85,1</td>
<td>73,8</td>
<td>64,8</td>
<td>53,1</td>
</tr>
</tbody>
</table>

Conductance difference between consecutive pulses

Conductance difference between consecutive pulses

\[ \Delta G = G_{i+1} - G_i \]

Where \( i \) is the pulse number: \( i = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 \)

Figure 8
Conductance difference between consecutive measurements. Rat No. R004

Table 5
Conductivity change between the first 3 pulses and the declination \( k \).

<table>
<thead>
<tr>
<th>Rat</th>
<th>( \Delta \sigma_1 ) %</th>
<th>( \Delta \sigma_2 ) %</th>
<th>( \Delta \sigma_3 ) %</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R004</td>
<td>17,64</td>
<td>7,36</td>
<td>2,66</td>
<td>-2,03</td>
</tr>
<tr>
<td>R005</td>
<td>21,20</td>
<td>10,12</td>
<td>2,18</td>
<td>-1,88</td>
</tr>
<tr>
<td>R006</td>
<td>38,90</td>
<td>10,70</td>
<td>4,78</td>
<td>-3,19</td>
</tr>
</tbody>
</table>
Summary of uptake prediction from conductance measurements

The main effect on the conductance is achieved already after the first EP-pulse as shown in the diagrams of Figures 5 and 8. The effect of the following pulses varies a lot from animal to animal. In some cases there is a steadily increase and in some case there is even a decrease. The correlation of the radioactivity uptake ratio and the conductance change index after the last pulse indicate a slight positive correlation coefficient for the 24 h uptake ratio.

**Figure 9a**
Uptake ratio at 6 h versus Conductance change Index at 2 kHz after the last pulse

\[ UR_{6h} = 4.22 + 0.027 \times CCI(2) \]

**Figure 9b**
Uptake ratio at 6 h versus Conductance change Index at 50 kHz after the last pulse

\[ UR_{6h} = 4.45 + 0.040 \times CCI(50) \]

**Figure 10a**
Uptake ratio at 24 h versus Conductance change Index at 2 kHz after the last pulse

\[ UR_{24h} = 3.77 + 0.07 \times CCI(2) \]

**Figure 10b**
Uptake ratio at 24 h versus Conductance change Index at 50 kHz after the last pulse

\[ UR_{24h} = 0.44 + 0.24 \times CCI(50) \]
Uptake ratio at 6 and 24 h versus tissue Conductance change Index at 2 and 50 kHz after the last pulse

\[ UR_{6h} = 4.22 + 0.027 \times \text{CCI(2)}; \quad UR_{6h} = 4.45 + 0.040 \times \text{CCI(50)} \]

\[ UR_{24h} = 3.77 + 0.07 \times \text{CCI(2)}; \quad UR_{24h} = 0.44 + 0.24 \times \text{CCI(50)} \]

**Figure 11a**
Uptake ratio at 6 h versus conductance change of the first EP pulse

**Figure 11b**
Uptake ratio at 24 h versus conductance change of the first EP pulse

\[ UR_{6h} = 9.0 - 0.12 \times \text{DC01 Intercept} \]

\[ UR_{24h} = 8.4 - 0.016 \times \text{DC01} \]

### 4. Exploration of the phase angle in tissue before and after EP

**Impedance Phase angle measurements**

**The ratio of the phase before and immediately after electroporation:**

Tissue can be considered as a dielectric with losses, that is modelled as a parallel RC circuit with phase angle \( \phi \), that is derived from recorded data of the phase angle between the real and imaginary part of impedance. Since the tangent (tg) of the phase-angle \( \phi \), (in radians) is equal to the ratio between the imaginary and real part of the impedance \( \text{tg} \phi = \frac{\text{im}Z}{\text{re}Z} \) this is a more relevant measure than the direct phase in degrees.

**Loss Change Index value immediately after electroporation LCI-End.**

The loss angle \( \delta \) of a capacitor is defined so that the ideal capacitor with zero losses has zero loss angle. This means that the loss angle \( \delta = 90^\circ - \phi \), where \( \phi \) is the recorded phase angle. The loss tangent \( \text{tg} \delta \) is also called the dissipation factor that is equivalent to the energy loss per cycle divided by the energy stored per cycle (rms or peakvalue). The impedance of the equivalent circuit \( Z^* = |Z| \cdot \cos \phi + j |Z| \cdot \sin \phi \) and thus:
The power loss in the circuit only takes place in the resistive part \( \text{re}[Z] \) if the capacitive part is considered as an ideal capacitor. The frequency dependence of the power loss is dependent on how the circuit is driven. With constant amplitude voltage \( U \) the power loss goes from zero level at very low frequencies to a defined value \( U^2/R \) at high frequencies. With constant amplitude current, the power level goes from a constant value at very low frequencies through a maximum at the frequency determined by the time constant \( \tau = RC \) and to zero at high frequency. The “Loss Change Index” LCI at a specific frequency LCI is evaluated as follow:

\[
\text{Loss Change Index}_{\text{LCI}} = \left( 1 - \frac{\cot\phi_{\text{before}}}{\cot\phi_{\text{after}}} \right) = \left( 1 - \frac{\text{Re}[Z]/\text{Im}[Z]_{\text{before}}}{\text{Re}[Z]/\text{Im}[Z]_{\text{after}}} \right)
\]

The Loss Change Index is zero if there is no change in the phase angle and approach 1 as \( \text{Im}[Z]_{\text{after}} \) goes to zero after heavy exposure.

**Impedance measurements.**

Bio-impedance measurements were performed at a frequency of 2-5-10-30-50 kHz. The electrical impedance was measured by applying a 1 mV pulse:
- Twice before the EP pulse
- After each EP pulse
- and after the last electroporation pulse in 1 s intervals.

In all experiments the applied electric field is given as applied voltage over the needle electrodes divided by their distance. The actual field strength in the tissue is, however, quite inhomogeneous in this setting.

**Phase angle loss tangent \( \tan\delta \) measurements \( E=1000 \text{ V/cm}, 100 \mu\text{s}, 6 \text{ pulses} \)**

![Figure 12](image)

Tangent of phase angles recorded at 2 and 50 kHz after 6 consecutive pulses 1000 V/cm 100 \( \mu\text{s} \). Rat R001
The Loss change index after each pulse is defined as

\[ LCI(i) = \left(1 - \frac{\cot \phi_0}{\cot \phi_i}\right) \]

where

\( \phi_0 \) is the phase angle of the tissue before any electroporation

\( \phi_i \) is the phase angle of the tissue after the \( i^{th} \) electroporation pulse

LCI is an index that indicates the change of the dielectric properties of the tissue after each electroporation pulse.

**Figure 13**
The Loss change index after each pulse defined as

\[ LCI(i) = \left(1 - \frac{\cot \phi_0}{\cot \phi_i}\right) \]

**Phase angle loss tangent \( \tan \delta \) measurements**

The loss tangent \( \tan \delta \) is also called the *dissipation factor* that is equivalent to the energy loss per cycle divided by the energy stored per cycle (rms or peak value). The impedance of the equivalent circuit

\[ Z = |Z| \cdot \cos \phi + j|Z| \cdot \sin \phi \]

and thus:

\[ \tan \phi = \frac{\text{im}[Z]}{\text{re}[Z]} = \frac{\varepsilon'}{\varepsilon} \quad \text{and} \quad \tan \delta = \frac{\text{re}[Z]}{\text{im}[Z]} = \cot \phi \]
The Loss change index after each pulse is defined as

$$LCI(i) = \left(1 - \frac{\cot \phi_0}{\cot \phi_i}\right)$$

where

- $\phi_0$ is the phase angle of the tissue before any electroporation
- $\phi_i$ is the phase angle of the tissue after the $i^{th}$ electroporation pulse

$LCI$ is an index that indicates the change of the dielectric properties of the tissue after each electroporation pulse.

<table>
<thead>
<tr>
<th>Rat</th>
<th>2 kHz</th>
<th>50 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>R004</td>
<td>34,3</td>
<td>21,6</td>
</tr>
<tr>
<td>R005</td>
<td>39,9</td>
<td>36,2</td>
</tr>
<tr>
<td>R006</td>
<td>40,6</td>
<td>47,0</td>
</tr>
</tbody>
</table>

**Figure 14**
Tangent of phase-angle measured at 2 kHz and 50 kHz after each 12 Pulses 1000 V; 100 μs pulse

**Figure 15**
The Loss Change Index measured at 2 kHz after each 1000 V; 100 μs pulse

**Table 6**
Loss change Index in % after 12 pulses
5. Specific absorbed energy and temperature increase

Specific absorbed energy from electric pulses and temperature increase

The specific absorbed energy $W$ is calculated from the following expression

$$W = \frac{\sigma E^2}{\rho} \cdot t_p \cdot N \; [J.kg^{-1}]$$

where

- $\sigma$ is the tissue conductivity for the tissue [S/m]
- $\sigma = \sigma_{ini} \cdot G_{rel(i-1)}$
- $\sigma_{ini}$ is tissue conductivity 0.17 S/m
- $G_{rel(i-1)}$ is relative conductivity recorded after each pulse $i$
- $\rho$ is the density of the tissue (muscle 1060 kg/m$^3$)
- $E$ is the electric field strength [V/m]
- $t_p$ is the pulse length [s]
- $N$ is the number of applied pulses

For the experimental case the cumulative absorbed power is derived from the following equation

$$W = \sum_{i=1}^{n} \frac{\sigma_{ini} G_{rel(i-1)} E^2 t_p}{\rho} \cdot N(i) \; [J.kg^{-1}]$$

where

- $\sigma_{ini}$ the tissue conductivity before EP-pulses
- $G_{rel(i-1)}$ the relative conductance recorded between each pulse

The specific heat capacities $c_p$ in the relevant temperature region from 20°C to 40°C, of muscles, skin and organs appear to be nearly independent of species and range mostly between 3.2 and 3.9 kJ.kg$^{-1}$.K$^{-1}$. Due to the variation in different measuring methods and biological variability of tissues no significant differences seems to occur between organs. The values of fat are distinctly lower; they range from 1.6 to 3.0 kJ.kg$^{-1}$.K$^{-1}$.

Due to the decrease in blood flow in the target volume treated with Electric pulses, the temperature increase is about $\Delta T = W/c_p$ degree.
Table 7
Estimated absorbed energy (J.kg⁻¹) per pulse, and corresponding sum of the 6 pulses.

<table>
<thead>
<tr>
<th>No. Pulses</th>
<th>R001</th>
<th>R002</th>
<th>R003</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>227</td>
<td>196</td>
<td>195</td>
</tr>
<tr>
<td>2</td>
<td>247</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>3</td>
<td>251</td>
<td>213</td>
<td>221</td>
</tr>
<tr>
<td>4</td>
<td>265</td>
<td>214</td>
<td>228</td>
</tr>
<tr>
<td>5</td>
<td>280</td>
<td>214</td>
<td>236</td>
</tr>
<tr>
<td>6</td>
<td>279</td>
<td>208</td>
<td>235</td>
</tr>
<tr>
<td>Sum</td>
<td>1549</td>
<td>1256</td>
<td>1326</td>
</tr>
<tr>
<td>ΔT °C</td>
<td>0.45</td>
<td>0.37</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 8
Estimated Absorbed power (J.kg⁻¹) per pulse and corresponding sum of the 12 pulses and final temperature increase (σ\text{tiss} = 0.17 S/m).

<table>
<thead>
<tr>
<th>No. Pulses</th>
<th>W / J.kg⁻¹</th>
<th>R004</th>
<th>W / J.kg⁻¹</th>
<th>R005</th>
<th>W / J.kg⁻¹</th>
<th>R006</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>191</td>
<td>197</td>
<td>238</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>206</td>
<td>218</td>
<td>265</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>212</td>
<td>223</td>
<td>278</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>213</td>
<td>231</td>
<td>284</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>215</td>
<td>242</td>
<td>289</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>217</td>
<td>250</td>
<td>296</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>221</td>
<td>258</td>
<td>302</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>224</td>
<td>263</td>
<td>306</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>229</td>
<td>269</td>
<td>311</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>232</td>
<td>274</td>
<td>317</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>236</td>
<td>279</td>
<td>322</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>236</td>
<td>278</td>
<td>320</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum W</td>
<td>2632</td>
<td>2983</td>
<td>3529</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔT °C</td>
<td>0.77</td>
<td>0.87</td>
<td>1.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 16a
Estimated Absorbed energy (J.kg⁻¹) per pulse

Figure 16b
Consecutive difference in Absorbed energy (J.kg⁻¹) per pulse

In the case of 12 pulses 1000V/cm 0.1 ms and an initial tissue conductivity of 0.17 S/m the temperature increase is about 0.7 – 1 degree °C.
Figure 17 Estimated Absorbed power (J.kg\(^{-1}\)) per pulse with a corresponding sum of the 12 pulses 2632 J.kg\(^{-1}\) (\(\sigma_{ini} = 0.17 \text{ S/m}\)), and the difference of consecutive pulses (red curve)

**The Current density (A/cm\(^2\))**

For the experimental case the average current density is derived from the following equation

\[
J = \sum_{i=1}^{n} \sigma_{ini} \cdot G_{rel(i-1)} \cdot E \cdot 10^{-4} \cdot N(i) \quad [\text{A.cm}^{-2}] 
\]

Figure 18

Derived current density after each of 12 consecutive voltage pulses of field strength amplitude 1000 V/cm and pulse-length 100 \(\mu\)s applied in 1 s interval. The conductance was recorded at 2 kHz between each pulse to estimate \(G_{GG} = 0.17 \text{ S/m}\).
The current density $J$ (A.cm$^{-2}$) corresponds to the current $I$ (A) recorded in each pulse with needle electrodes. The average corresponding to the values of Figure 18 is $2.34 \pm 0.13$ A.cm$^{-2}$.

### Table 9

<table>
<thead>
<tr>
<th>No. pulses</th>
<th>R001</th>
<th>R002</th>
<th>R003</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.40</td>
<td>2.08</td>
<td>2.06</td>
</tr>
<tr>
<td>2</td>
<td>2.61</td>
<td>2.23</td>
<td>2.24</td>
</tr>
<tr>
<td>3</td>
<td>2.66</td>
<td>2.26</td>
<td>2.34</td>
</tr>
<tr>
<td>4</td>
<td>2.81</td>
<td>2.27</td>
<td>2.42</td>
</tr>
<tr>
<td>5</td>
<td>2.97</td>
<td>2.27</td>
<td>2.50</td>
</tr>
<tr>
<td>6</td>
<td>2.96</td>
<td>2.20</td>
<td>2.49</td>
</tr>
</tbody>
</table>

Average $\pm$ SD $2.7 \pm 0.2$ $2.22 \pm 0.07$ $2.34 \pm 0.15$

### Table 10

<table>
<thead>
<tr>
<th>No. Pulses</th>
<th>R004</th>
<th>R005</th>
<th>R006</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>2.03</td>
<td>2.09</td>
<td>2.52</td>
</tr>
<tr>
<td>2</td>
<td>2.18</td>
<td>2.32</td>
<td>2.81</td>
</tr>
<tr>
<td>3</td>
<td>2.24</td>
<td>2.37</td>
<td>2.94</td>
</tr>
<tr>
<td>4</td>
<td>2.26</td>
<td>2.45</td>
<td>3.01</td>
</tr>
<tr>
<td>5</td>
<td>2.28</td>
<td>2.56</td>
<td>3.07</td>
</tr>
<tr>
<td>6</td>
<td>2.30</td>
<td>2.65</td>
<td>3.14</td>
</tr>
<tr>
<td>7</td>
<td>2.34</td>
<td>2.73</td>
<td>3.20</td>
</tr>
<tr>
<td>8</td>
<td>2.38</td>
<td>2.79</td>
<td>3.25</td>
</tr>
<tr>
<td>9</td>
<td>2.42</td>
<td>2.85</td>
<td>3.30</td>
</tr>
<tr>
<td>10</td>
<td>2.46</td>
<td>2.90</td>
<td>3.37</td>
</tr>
<tr>
<td>11</td>
<td>2.50</td>
<td>2.95</td>
<td>3.41</td>
</tr>
<tr>
<td>12</td>
<td>2.50</td>
<td>2.95</td>
<td>3.40</td>
</tr>
</tbody>
</table>

Average $\pm$ SD $2.32 \pm 0.13$ $2.63 \pm 0.27$ $3.12 \pm 0.26$

### 6. Conductance relaxation

After the applied electro-permeabilization pulse the conductivity start to decrease and approach a plateau value. The fraction of the plateau value relative to the initial conductivity is a measure of the fraction of reversible electropermeabilized cells. This value is of importance for the long term transfer of exogenous substances to the cell and outflow of immunogenic substances from the cell. The relaxation curves for each rat was fitted to a single exponential decay

$$\sigma_{rlp} = A_0 + f_{rev} \cdot \exp(-t/T1)$$  \hspace{1cm} (eq. 6)

where $f_{rev}$ is the fraction of reversible electroporation

$A_0 = 1 - f_{rev}$ is the fraction of irreversible electroporation
The mean relaxation curve of the conductivity relative to that after the last pulse $G$ is fitted to an exponential equation

$$G = 0.885 + 0.111 \cdot \exp \left( -0.2 \cdot t \right) \quad \text{(eq. 7)}$$

The relaxation rate constant is 0.2 s$^{-1}$ corresponding to a mean relaxation time of 5 s the fraction of reversible electropermeabilized cells is 0.11 (11%)

### Table 11
Mean relaxation time $T_1$ (s) and the fraction of Reversible electropermeabilized tissue ($f_{rev}$) are given in the table

<table>
<thead>
<tr>
<th>Rat No.</th>
<th>$T_1$ (s)</th>
<th>sd</th>
<th>$f_{rev}$</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>R001</td>
<td>3.9</td>
<td>0.3</td>
<td>0.101</td>
<td>0.003</td>
</tr>
<tr>
<td>R002</td>
<td>4.0</td>
<td>0.3</td>
<td>0.120</td>
<td>0.003</td>
</tr>
<tr>
<td>R003</td>
<td>5.1</td>
<td>0.3</td>
<td>0.135</td>
<td>0.003</td>
</tr>
</tbody>
</table>

### Table 12
Mean relaxation time $T_1$ (s) and the fraction of reversible electropermeabilized tissue ($f_{rev}$).

<table>
<thead>
<tr>
<th>Rat No.</th>
<th>$T_1$ (s)</th>
<th>se</th>
<th>$f_{rev}$</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>R004</td>
<td>4.90</td>
<td>0.29</td>
<td>0.111</td>
<td>0.002</td>
</tr>
<tr>
<td>R005</td>
<td>5.61</td>
<td>0.44</td>
<td>0.133</td>
<td>0.004</td>
</tr>
<tr>
<td>R006</td>
<td>5.36</td>
<td>0.49</td>
<td>0.106</td>
<td>0.003</td>
</tr>
</tbody>
</table>
7. Conclusion

PLS modelling of the uptake ratios with all predictor variables resulted in the distribution of “Variable Importance in the Projection” (VIP) shown in Figure 20.

![Figure 20](image)

**Figure 20** Distribution of “Variable Importance in the Projection” (VIP) when all predictor parameters were applied in the PLS model.

The model equations of the uptake ratios when the 2 most important predictor parameters were applied in the PLS model:

\[
UR_{6h} = -8,097 + 2,04 \times (T1/s) + 1,88 \times 10^{-3} \times W \ J.kg^{-1}
\]

\[
UR_{24h} = -25,78 + 7,63 \times T1/s + 1,36 \times 10^{-3} \times W \ J.kg^{-1}
\]

Such equations can be used to predict the outcome of the Electro Enhanced Chemotherapy treatment.
References


