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Thermal Ablation: A Comparison of Thermal Dose Required for Radiofrequency-, Microwave- and Laser-induced Coagulation in an *Ex-vivo* Bovine Liver Model

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Introduction

The past decade has witnessed a widespread expansion into the clinical setting of image-guided minimally-invasive ablation techniques using various thermal energy sources, such as radiofrequency, microwave, high intensity focused ultrasound, and laser to destroy focal tumors in multiple organ sites [1]. In many cases, these techniques allow one to avoid major surgery, that otherwise would have been required for removal of malignancy or enable treatment for non-surgical candidates [2,3]. Owing to advancements in both imaging modalities used for visualization and percutaneous devices used for delivery of energy into tumor tissue, these techniques have established themselves as viable treatment options for eradication of solid tumors in locations such as the liver [4,5,6], kidney [7], bone [8], lung [9], with ever expanding utility to additional locations including head and neck [10], adrenals, prostate and others [11,12].

Based upon conventional wisdom, current clinical algorithms for thermal ablation have used tissue heating $>50^{\circ}\text{C}$ for > 5 min as a paradigm end point denoting induced coagulation for all tissue types [13]. Yet, more recently obtained experimental data [14] has shown that using a 50°C isotherm as the main surrogate treatment endpoint is likely overly simplistic and that the actual critical thermal dosimetry (i.e. at the margin of the coagulation zone) is quite variable and tissue-specific in as of yet incompletely uncharacterized ways. This propels the need for a tissue specific understanding of heat – tissue interactions. Moreover the “*high temperature*” dosimetry of thermal ablation does not necessarily follow classical *hyperthermia* dosimetry that is based on a paradigm of prolonged, uniform heating of entire volume of tissue after achieving thermal steady state. For example, we have shown, that thermal dosimetry of a single

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internally-cooled radiofrequency ablation electrode was dependent not only on tissue type, but also on the amount of energy delivered to the tissue, and the distance of the critical ablation margin from the applicator [15]. Most notably thermal dose required for coagulation was not constant, but correlated with current in a negative exponential fashion in both *ex vivo* and *in-vivo* models. That study, using single RF electrode, raised two important questions: *a)* Are *non-constant thermal doses* only found for radiofrequency ablation (suggesting electromagnetic influence) or is it more global phenomenon?; and *b)* Given the effects of distance and current how important is the *rate of heat transfer* within the tissue for which other formulas such as the Arrhenius damage integral may be most useful to best express thermal dosimetry parameters?

Regardless of the answer to these questions, a better understanding of this process may allow us to achieve further gains in the volume of coagulation and is necessary to achieve predictability of thermal ablation. Hence, the purpose of this study was to answer these two questions. This was done by comparing thermal dosimetry of ablation at fixed diameters, and with a fixed experimental set-up for three thermal energy sources: *twoelectromagnetic* (a radiofrequency cluster electrode and microwave) and one *non-electromagnetic* (laser). Thermal dosimetry metrics, were analyzed three ways, namely by calculating and comparing of Cumulative Equivalent Minutes at 43°C (CEM₄₃) and Areas Under the Curve (AUC), with the addition of calculation of the Arrhenius damage integral to enable determination of influence of rate of heat transfer on thermal ablation outcome.

Materials and Methods

Overview of Study Design

The study was performed in *ex-vivo* bovine liver model by creating ablation zones of specified diameters of coagulation (DOC) to determine the threshold thermal dosimetry necessary to achieve thermal ablation for three different energy sources: high and low electromagnetic (microwave and radiofrequency) and non-electromagnetic (laser). Thus, to enable direct comparison to prior results, with the exception of the newly added energy sources and corresponding applicators, our experimental set-up was identical to previously published study for a single RF internally-cooled electrode. For *radiofrequency* (RF) energy was applied for 2.5 to 40 min to create 114 ablations (DOC of 20, 30 and 40 ± 2mm) using a 2.5 cm internally cooled cluster electrode (600–1600mA in 200mA intervals). For *microwave* (MW) energy was applied for 4 to 76 min to create 45 ablations (DOC of 20, 30 and 40 ± 2mm) using a 3cm antenna (10–50 Watts in 10 Watt intervals). For *laser* energy was applied for 7 to 44 min to create 45 ablations (DOC of 20, 25, and 30 ± 2mm) using a 3cm diffusing fiber (20–30 Watts in 5 Watt intervals). Prior to all experiments, bovine livers were brought to room temperature over a period of 24hrs to achieve baseline tissue temperature of 19–21°C. For all experiments and all energy sources studied, the block of tissue containing the ablation was cut out and sectioned *immediately* (within approximately 1 minute after the application of energy was stopped) and diameter of coagulation for particular trial was determined. The endpoints, formulas and comparisons were identical as in the previous study for single RF electrode.

RF energy deposition—The RF source used for the experiments was a 500-kHz monopolar RF generator (model CC-1; Radionics, Burlington, MA) capable of delivering 2,000 mA. The tissue specimens were placed in a normal saline bath (0.9% NaCl solution in distilled water) at room-temperature (19–21°C). The RF electrode and thermocouples were placed vertically to a depth of 4 to 5cm within the tissue. The electrical circuit was completed by the way of a standardized 12.5 by 8.0-cm metal grounding pad (for 112 cm² of grounding return surface area), which was placed horizontally in the bath approximately 20 cm from the electrode (Figure 1a). Continuous (i.e. without pulsing) RF energy was applied at the selected currents

for the variable time durations via cluster 17-gauge internally cooled RF electrodes (model CC-1020; Valleylab, Boulder, CO) with a tip exposure of 2.5 cm. During RF energy application, electrode tip temperature was maintained at below 10°C by means of continuous perfusion of the internal lumina of the electrode with ~4°C water. High-current RF energy was applied according to a previously designed algorithm that has been shown to maximize energy deposition and tissue coagulation for a single applicator [16].

Microwave energy deposition—The microwave energy source used in our study was a VivaWave Microwave Generator (Vivant Medical, Mountainview, CA) and a 3cm microwave antenna in a continuous mode (10–50 W in 10 Watt intervals).

Laser energy deposition—The laser energy source used in our study was an SLT Nd-Yag laser (Photomedex, Montgomeryville, PA) with a 3cm externally cooled diffusing fiber in a continuous mode (5–30W in 5W intervals).

For both *MW and laser* experiments the tissue samples (baseline temperature 19–21°C) were placed on a plastic tray and the energy applicator (MW antenna or diffusing fiber), was inserted vertically to a depth of 4 to 5cm within the tissue.

Tissue thermometry—Temperatures were monitored continuously throughout the RF, microwave and laser energy application by means of four thermocouples (Radionics, Burlington, MA) placed at distances of 5, 10, 15 and 20mm away from the active RF electrode, MW antenna, or diffusing fiber at the level of midpoint of the active applicator tip and were recorded at 30 second intervals. Correct positioning of thermocouples was confirmed during sectioning of specimens. The thermocouples had a sensitivity of 0.1°C and were connected to an electronic thermal monitor (Radionics TC 4, Burlington, MA) integrated into the RF generator.

Data Analyses—Primary endpoints for all experiments included coagulation diameter, duration of energy application, and the isoeffective dose at the margin of the ablation zone. Recorded temperatures were used to calculate temperature at the ablation margin by interpolation of actual neighboring temperatures, as well as metrics of thermal dosimetry including: Area Under the Curve (AUC; calculated as the integral of temperature minus baseline temperature over time (using the same approach as in our previous study for a single RF electrode [12]), Cumulative Equivalent Minutes at 43°C (CEM₄₃), and Arrhenius damage integral (Ω).

Arrhenius damage integral (Ω) was calculated using the formula:

$$\Omega(t) = -\ln\left(\frac{c(t)}{c(0)}\right) = A \int_0^t e^{\left(\frac{-\Delta E}{RT}\right)} dt$$

Where: Ω is the damage sustained by the tissue, $c(t)$ = amount of the component of interest remaining, $c(0)$ = amount of the component of interest at time zero, A = frequency factor (7.39×10^{39} 1/s) and ΔE = the activation energy (2.577×10^5 J/mol for liver tissue) [17].

Cumulative Equivalent Minutes at 43°C (CEM₄₃) was calculated using the formula:

$$\text{CEM}_{43} = t \cdot R^{(43-T)}$$

Where: t = time interval, T = average temperature during time interval t , R = number of minutes needed to compensate for a 1° temperature decrease either above or below the break point (43°C), R is 0.5 for T above 43°C and 0.25 for T below 43°C [18,19]. Current (for RF) or power (for MW and laser) and distance were analyzed versus duration of ablation, minimal threshold temperature at the ablation margin, AUC, CEM_{43} and Ω . Given multiple groups, calculated values were correlated to the ablation size to determine best-fit equations using linear and higher order regression analysis. Goodness of fit was determined by the conventional sum of squared errors using proc-NLIN in SAS version 9.1. Then comparison was performed within each experimental group and between groups using multivariate analysis of variance (MANOVA) with SAS software (SAS, Cary, NC) corrected for multiple tests; $p < 0.05$ was considered statistically significant.

Results

Radiofrequency ablation (cluster electrode)

As previously reported for single **internally-cooled** RF electrodes [12], the thermal dose represented as CEM_{43} was not constant, but correlated with distance and RF current, and showed a wide range of values to the order of 10^{10} (Table I, Figure 2a). The end temperatures (at the end of energy application) at the ablation margin varied with distance (represented by the specified Diameters Of Coagulation, DOC) and current, and correlated with applied RF current as negative linear functions ($R^2=0.45\text{--}0.92$) (Figure 2b). The thermal dose calculated as AUC, was also not constant, but varied with distance and correlated with applied RF current as a set of negative exponential functions ($R^2=0.90\text{--}0.97$) (Figure 2c). The relationship between AUC and ablation duration was best described by a set of positive logarithmic functions ($R^2=0.95\text{--}0.98$) for each defined DOC (Figure 2d). The relationships between Arrhenius damage integral versus current, was best described by positive linear functions ($R^2=0.87\text{--}0.97$) (Figure 2e) and the best fit for Arrhenius damage integral versus duration of energy application was with sigmoid functions ($R^2=0.92\text{--}0.99$) (Table IV, Figure 2f), with both types of relationships being distance dependent.

Microwave

Similar to the findings for RF electrodes, CEM_{43} varied with distance and applied power over a 10^{12} range of values (Table II, Figure 3a). However, the end temperatures at the ablation margin correlated with power as a set of distance dependent positive linear functions ($R^2=0.72\text{--}0.82$) (Figure 3b). Thermal dose expressed as AUC varied with distance, and correlated with applied energy as a set of negative power functions with $R^2=0.82\text{--}0.87$ versus $R^2=0.63\text{--}0.73$ when analyzed as exponential functions (Figure 3c). The relationship of AUC versus ablation duration for each DOC was best described by a family of positive exponential functions ($R^2=0.82\text{--}0.94$) (Table I, Figure 3d). The relationships between Arrhenius damage integral versus current, was best described by positive linear function ($R^2=0.86\text{--}0.94$) (Figure 3e) and the best fit for Arrhenius damage integral versus duration of energy application was with sigmoid functions ($R^2=0.94\text{--}0.99$), with both types of relationships being distance dependent (Table IV, Figure 3f).

Laser

The thermal dose as CEM_{43} varied with power over a wide range of values (10^{10}) for analyzed DOC's (Table III, Figure 4a). The end temperatures at the ablation margin correlated with applied power as a set of positive linear functions ($R^2=0.94\text{--}0.95$) for each of analyzed DOC (Figure 4b). Thermal dose as AUC varied with distance, and correlated with applied energy as a set of negative exponential functions ($R^2=0.97\text{--}0.98$) (Figure 4c). The relationship of AUC and ablation duration for each DOC was best described by a family of logarithmic functions ($R^2=0.92\text{--}0.98$) (Figure 4d). The relationships between Arrhenius damage integral versus

current, was best described by positive linear function ($R^2=0.87-0.94$) and the best fit for Arrhenius damage integral versus duration of energy application was with sigmoid functions ($R^2=0.96-0.99$), with both types of relationships being distance dependent (Table IV, Figure 4f).

Comparison between energy sources

Overall, regardless of energy source, the patterns and mathematical relationships observed were similar, and both distance and energy dependent. The best-fit curves describing the amount of heat needed to achieve ablation (AUC), varied with energy applied and coagulation diameter as a negative exponential (for RF electrodes and laser) or negative power (for microwave) functions ($R^2=0.82-0.98$). Yet, for a given ablation diameter (DOC), there were significant differences ($p<0.001$) in required thermal dose among the energy sources, so that laser required about $10^1 - 10^2$ times more energy (range from 1,019,550°C-sec to 3,802,458°C-sec) than MW (range from 19,392°C-sec to 157,419°C-sec); MW had at least an order of magnitude greater requirement than the RF cluster electrode (range from 3,996°C-sec to 78,548°C-sec). The range of end temperatures recorded at the margin of coagulation, also differed among the energy sources and was lowest for the RF cluster electrode (33–58°C), higher for laser (52–72°C), and the widest range of coverage for microwave (42–95°C). These end temperatures correlated with applied energy, as sets of linear functions (negative for RF cluster electrode and positive for MW and laser) for all three comparisons ($R^2=0.74-0.96$). For all three modalities, the Arrhenius damage integral (Ω) varied with positive linear correlation to energy applied and with sigmoid correlation to duration of ablation for all analyzed diameters of coagulation ($R^2=85-0.97$). Similarly, the CEM43 values varied exponentially with energy and distance ($R^2=0.52-0.76$), over a wide range of values ($10^{10}-10^{12}$) for all three modalities studied.

Discussion

Thermal ablation using a wide range of energy sources has established itself as a viable treatment option for solid tumors in multiple organs and sites [20]. During these procedures, very intense thermal doses are usually applied upon the tissue, with the observed temperature profiles being markedly higher than those seen in traditional hyperthermia applications, often reaching (and in some cases exceeding) the boiling point of the tissue. This enables the energy to be applied for much shorter periods of time than for hyperthermia (usually less than 15–30 minutes). Furthermore, while in hyperthermia applications once a thermal steady state is achieved (typically within 10–15 min) temperatures do not change appreciably throughout the volume of the tissue for the rest of the several hours of treatment [21]; during thermal ablation the temperature profile is *constantly* changing rapidly across the volume of tissue surrounding a point source of energy (i.e. RF electrode, microwave antenna or laser diffusing fiber) [22].

We have shown in our previously published studies a wide range of thermal sensitivity among tissues subject to RF ablation [11], and that the classic equations used for hyperthermia applications, like CEM₄₃ may not be as useful for much higher temperature ranges observed during thermal ablations [12]. Particularly, in that recent study performed with a single cooled tip RF electrode, the thermal dosimetry (as measured by [AUC]) was not constant, but both current-dependent and distance-dependent. This result led to the question if this observation was a phenomenon specific only for a limited range of electromagnetic spectrum (i.e. specific to radiofrequency ablation at 500kHz), or widely reproducible for wide electromagnetic spectrum and non-electromagnetic energy sources as well. Therefore, in our present study we performed experiments to determine and compare thermal dosimetry metrics for the three energy sources most commonly used for the purpose of thermal ablation, namely a confirmatory second RF device (an internally-cooled cluster electrode), as well as microwave,

and laser. For all energy sources in this study, we varied the applied energy in a systematic fashion and measured the time-temperature data at defined radial distances from the energy applicator. In this way, we were able to establish thermal history and calculate thermal doses at specified distances (i.e. diameters of coagulation). By eliminating the variability of DOC, our approach enabled us to study the effects of thermal dose as affected by energy and distance.

Similar to our previous experiment with a single internally cooled RF electrode, thermal dosimetry metrics, including CEM_{43} and AUC, were not constant, but distance and energy dependent, which held true for all three energy sources studied. Specifically, CEM_{43} , again showed very wide range of values in a range of 10^{10} to 10^{12} . For AUC the range of values was not as wide; however, we saw significant differences among the energy sources, with highest requirement for laser, and lower for microwave and the cluster RF electrode. We postulate, that the highest requirement for laser may be related to the fact that more energy may be needed for tissue penetration of light compared to electromagnetic radiation. This is in keeping with known observations of high levels of light scattering interfering with optical techniques applied for measuring protein denaturation in vitro. [23]. As for our observations for a single RF electrode, the relationship of AUC vs. applied energy was best described by exponential relationships for the RF cluster electrode and laser, yet again variability in the required thermal dose to achieve a specified diameter of coagulation was seen. The greatest heat at applicator source, as well as the highest temperature gradient observed for microwave could be responsible for the fact that it's relationship of AUC vs. applied power was best described by an even steeper power function. This difference in potential curve form and the wide range of end temperatures at the ablation margin at the end of energy application, suggests that the rate of heat transmission may play a role in inducing ablation and further underscores how unreliable the end temperature alone is as a single parameter for predicting ablation outcome. Additionally, we again saw both negative and positive linear correlations for relationship between the temperature at the ablation margin and energy applied for cluster RF electrodes (albeit in a narrower range and at greater distances than for a single RF electrode) and for laser and MW energy sources, respectively.

The second question raised by apparent effects of distance and current on thermal metrics in our prior study with a single RF electrode was the importance of the rate of heat transfer within the tissue. To answer that question we calculated Arrhenius damage integrals $[\Omega]$ and looked at its relationships to applied energy and ablation duration. Again, rather than anticipated constant values of Ω , we found distance specific positive linear correlations of Ω vs. energy applied and positive sigmoid correlations for Ω vs. duration of ablation. This may suggest that for radiating heating gradients about a point source, as occurs in all ablation methodology to be able to more accurately predict the outcome one has to take into account both the absolute temperature and the rate of heat transfer.

The differences in the amount of energy that was required to achieve thermal ablation may be related as well to the complexity of chemical changes that cause our defined endpoint "ablation" (i.e. observable coagulation, which in itself is not homogeneous in appearance). Indeed the variability seen in previously studied tissues, and in essence a primary factor in variable thermal sensitivity of different cell types [24], may be due to coagulation of different proteins proceeding with varying rate and at varying temperatures. These effects may be seen more easily with hyperthermia, where they occur much more gradually than in tissues exposed to rapidly changing high temperature gradients typical for thermal ablation. Nevertheless, while the specific mechanism of cell killing by hyperthermia is unknown, the high activation energy of cell killing and other responses to hyperthermia [25] suggest that protein denaturation is the rate-limiting step, with approximately 5% protein denaturation necessary for detectable killing by the aggregation of both denatured and native protein inducing multiple effects on cellular function [26]. With much higher temperature gradients during thermal ablation all these

processes can occur much more rapidly which makes them much less distinct and thus one of limitations in determining the accurate thermal dosimetry for models studied so far is the complexity of simultaneous processes undergoing in ablated tissue. Hence, to further address this issue we are designing experiments studying thermal dosimetry using a single protein models which is a subject of ongoing study. In conclusion, we demonstrate that the dosimetry of thermal ablation can not be determined based solely on end temperature at the margin of the zone of coagulation and duration of energy application for multiple electromagnetic and laser sources. Thermal dosimetry is not constant, but distance dependent, and determining more precise thermal dosimetry for ablation likely requires taking into account the rate of heat transfer within the tissue as well.

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Figure1.

(a). Overview of the experimental design . An internally cooled 2.5cm cluster RF electrode (white arrow) has been inserted into a sample of bovine liver placed in a 0.9% saline bath. The RF generator (lower black arrow) and a temperature measurement device (upper black arrow) can be seen in the background. (b). RF cluster electrode, (c) Microwave 3cm antenna and (d). Laser 3cm externally cooled diffusing fiber, are noted by arrows. For all energy applicators thermocouple probes (arrowheads) were placed at defined distances (5,10, 15, and 20mm diameter) from the device, which enabled precise measurement of temperature over time over the course of the ablation.

Figure 2.

Relationships of analyzed parameters for RF cluster electrode (a) CEM₄₃ versus current (b) End temperature versus current (c) AUC versus current, (d) AUC versus duration, (e) Arrhenius damage integral (Ω) versus current and (f) Ω versus duration. For this and all subsequent figures each trial of the experiments run in triplicate are represented as a data point.

Figure 3.

Relationships of analyzed parameters for MW antenna (a) CEM_{43} versus power (b) End temperature versus power (c) AUC versus power, (d) AUC versus duration, (e) Arrhenius damage integral (Ω) versus current and (f) Ω versus duration.

Figure 4.

Relationships of analyzed parameters for laser (a) CEM_{43} versus power (b) End temperature versus power (c) AUC versus power, (d) AUC versus duration, (e) Arrhenius damage integral (Ω) versus current and (f) Ω versus duration.

Table I

Summary of the relationships between thermal parameters, distance and current for RF cluster electrode.

	y	Distance	Function	r^2
AUC vs. RF current	AUC (°C-sec)	20mm	$y = 267044e^{-0.0041x}$	0.97
		30mm	$y = 563027e^{-0.0032x}$	0.96
		40mm	$y = 331504e^{-0.0021x}$	0.90
AUC vs. duration	AUC (°C-sec)	20mm	$y = 10094\ln(x) - 4695.4$	0.98
		30mm	$y = 30260\ln(x) - 40568$	0.95
		40mm	$y = 32585\ln(x) - 50276$	0.96
End Temperature vs. RF current	End temperature (°C)	20mm	$y = -0.0072x + 40.6$	0.45
		30mm	$y = -0.0033x + 44.947$	0.07
		40mm	$y = -0.0172x + 71.443$	0.91
CEM vs. RF current	CEM ₄₃	20mm	$y = 2E-05e^{0.0202x}$	0.52
		30mm	$y = 6E-07e^{0.0304x}$	0.77
		40mm	$y = 4E-23e^{0.0844x}$	0.83
Arrhenius integral vs. RF current	Arrhenius integral	20mm	$y = 3E-06x + 0.0032$	0.92
		30mm	$y = 2E-05x + 0.0215$	0.96
		40mm	$y = 5E-05x + 0.0404$	0.99

Table II

Summary of the relationships between thermal parameters, distance and power for MW antenna.

	y	Distance	Function	r²
AUC vs. power	AUC (°C-sec)	20mm	$y = 1E+06x - 1.093$	0.87
		30mm	$y = 808149x - 0.909$	0.80
		40mm	$y = 956256x - 0.8704$	0.86
AUC vs. duration	AUC (°C-sec)	20mm	$y = 46895 \ln(x) - 58565$	0.89
		30mm	$y = 54695 \ln(x) - 93161$	0.90
		40mm	$y = 61797 \ln(x) - 119574$	0.94
End Temperature vs. power	End temperature (°C)	20mm	$y = 0.9166x + 55.064$	0.82
		30mm	$y = 0.3427x + 56.163$	0.75
		40mm	$y = 1.1567x + 42.446$	0.72
CEM vs. power	CEM ₄₃	20mm	$y = 2E-05e^{0.0202x}$	0.52
		30mm	$y = 6E-07e^{0.0304x}$	0.77
		40mm	$y = 4E-23e^{0.0844x}$	0.83
Arrhenius integral vs. power	Arrhenius integral	20mm	$y = 3E-05x + 0.0036$	0.99
		30mm	$y = 0.0004x + 0.0403$	0.96
		40mm	$y = 0.0007x + 0.0574$	0.98

Table III

Summary of the relationships between thermal parameters, distance and power for laser diffusing fiber.

	v	Distance	Function	r²
AUC vs. power	AUC (°C-sec)	20mm	$y = 4E+06e-0.0468x$	0.97
		25mm	$y = 4E+06e-0.0476x$	0.98
		30mm	$y = 7E+06e-0.0523x$	0.98
AUC vs. duration	AUC (°C-sec)	20mm	$y = 1E+06Ln(x) - 1E+06$	0.92
		25mm	$y = 1E+06Ln(x) - 2E+06$	0.92
		30mm	$y = 2E+06Ln(x) - 3E+06$	0.98
End Temperature vs. power	End temperature (°C)	20mm	$y = 0.7749x + 42.898$	0.95
		25mm	$y = 0.8493x + 41.5$	0.94
		30mm	$y = 1.0493x + 40.44$	0.95
CEM vs. power	CEM ₄₃	20mm	$y = 2E-05e^{0.0202x}$	0.52
		25mm	$y = 6E-07e^{0.0304x}$	0.77
		30mm	$y = 4E-23e^{0.0844x}$	0.83
Arrhenius integral vs. power	Arrhenius integral	20mm	$y = 0.0336x + 23.705$	0.93
		25mm	$y = 0.0438x + 19.165$	0.90
		30mm	$y = 0.0206x + 39.522$	0.87

Summary of the relationships between Arrhenius integral vs. duration and energy applied. Parameters presented are best-fits for the formula:

$$Y = \frac{A_1 - A_2}{1 + e^{(X - X_0) / dx}} + A_2$$

Table IV

	energy	r ²	A1	A2	X0	dx
Arrhenius integral vs. duration RF cluster electrode	600mA	0.92	-1730.7	47.9	-3790.8	923.9
	800mA	0.96	-779.4	53.3	-2989.0	955.1
	1000mA	0.96	-331.8	65.3	-1508.4	748.0
	1200mA	0.98	-1122.0	67.2	-1432.3	442.9
	1400mA	0.99	-723.1	114.2	-1425.9	691.4
	1500mA	0.99	-575.9	628.3	54.5	1893.6
Arrhenius integral vs. duration MW antenna	1600mA	0.99	-13.13002	65.02	43.785	122.87
	10W	0.94	10.43263	43.21	203.8	257
	20W	0.98	-10.8419	57.22	33.616	195.32
	30W	0.99	7.8057	50.28	85.897	100.88
	40W	0.99	-301.01397	62.66	-618	306.07
	50W	0.99	-135.98162	99.28	-161.1	236.11
Arrhenius integral vs. duration laser fiber	10W	0.96	-15.41863	86.32	507.54	873.89
	15W	0.98	-3.06785	54.28	272.23	440.45
	20W	0.99	-26.50642	70.08	79.662	570.18
	25W	0.998	93909	75.4	504.62	277.67
	30W	0.997	1.1334	65.42	351.04	248.68