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Exposure Assessment of Electromagnetic Fields Near Electrosurgical Units

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Electrosurgical units (ESU) are widely used in medical health services. By applying sinusoidal or pulsed voltage in the frequency range of 0.3–5 MHz to the electrode tip, the desired mixture of coagulation and cutting are achieved. Due to the high voltage and current in the cable, strong electromagnetic fields appear near the ESU. The surgeon and others inside the operating room such as nurses, anesthesiologists, etc., will be highly exposed to these fields. The stray fields surrounding the ESU have previously been measured, but now a deeper analysis has been made of the curve shape of the field and the implication of this when assessing exposure from a commonly used ESU in accordance with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. The result showed that for some of the modes, especially those using high-pulsed voltage with only a few sinusoidal periods, the E-field close to the cable could reach linear spatially averaged values of 20 kV/m compared to the 2.1 kV/m stated in ICNIRP guidelines. Assessing the E- and B-field from ESU is not straightforward since in this frequency range, both induced current density and specific absorption rate are restricted by the ICNIRP guidelines. Nevertheless, work needs to be done to reduce the stray fields from ESU. Bioelectromagnetics 31:513–518, 2010. © 2010 Wiley-Liss, Inc.

Key words: surgical diathermia; magnetic field; electric field; ICNIRP

INTRODUCTION

Electrosurgery is widely used in medical health services during surgical procedures. Most electrosurgical units (ESU) used today have special modes for cutting and coagulating. For cutting purposes the main principle is to achieve high (>100 °C) and fast heating of the cell to get cell explosions. A sinusoidal voltage of at least 200 V is applied to the electrode tip. In the coagulation mode a much slower heating process is desired to get the cell plasma to coagulate, and for this purpose pulse-modulated voltage is applied. The rated frequency for ESU is normally between 0.3 and 5 MHz.

Most modern ESU have many different mixtures of coagulation and cutting, where both the pulse length and applied voltage are varied. This means that the process on how to assess the exposure is not straightforward, and knowledge about the shape of each signal used is required.

The electromagnetic fields near ESU have previously been measured [Paz et al., 1987; Mantiply et al., 1997; Liljestrand et al., 2003; De Marco and Maggi, 2006], but in this work a deeper analysis has been made with respect to the different settings in cutting and coagulation modes. Only monopolar modes have been assessed since these give rise to the highest stray fields. In this study, the EMF exposure from the ESU has been measured, and different aspects of how to evaluate the exposure in accordance with the International Commission on Non-Ionizing Radiation Protection guidelines [1998] are discussed.

Exposure to electromagnetic fields (EMF) in the intermediate frequency (IF) range (100 kHz to 10 MHz) is complicated since both heating effects and nerve stimulations are possible and, therefore, the ICNIRP guidelines restrict both the specific absorption rate (SAR) and the induced current density in the exposed body. It is not perfectly clear how to assess pulse-modulated IF exposure in accordance with the ICNIRP guidelines, especially for pulses containing only one or a couple of sinusoidal periods; this will be further discussed in the article. The need of discussing these issues has increased now that the European Union (EU) directive on occupational exposure to EMF [EU, 2004] is under way (Directive 2004/40/EC).

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TABLE 1. Description of the Evaluated VIO 300D Modes

	Wave form	Max. HF peak voltage (V_p)	Max. output power (W)	No. of periods in the pulse
AUTOCUT	cw	740	300	—
HIGHCUT	cw	950	300	—
DRYCUT	pm	1450	200	7
SOFTCOAG	cw	190	200	—
SWIFTCOAG	pm	2500	200	3
FORCEDCOAG	pm	1800	120	2
SPRAYCOAG	pm	4300	120	1

Wave form: cw, continuous wave; pm, pulse-modulated.

MATERIALS AND METHODS

In this work a VIO 300D system (ERBE Elektromedizin, Tübingen, Germany) has been used as an exposure source, but most brands used today in medical health services employ the same principle for cutting and coagulation, but with different settings. From a methodological point of view the approach is thus the same for other brands as well.

For cutting and/or coagulating tissue, the system provides different modes for various purposes. The rated frequency is 350 kHz and unmodulated sinusoidal voltage or different pulse-modulated voltage is applied to obtain the desired function. Seven different modes have been evaluated, and in Table 1 a brief description of these modes is given.

The current in the cable connecting the ESU with the monopolar electrode was measured with a current probe (P6021, Tektronix, Beaverton, OR) connected to an oscilloscope (TDS 1012, Tektronix). The electric and magnetic field strength were measured using a Narda EMR-300 (L^3 communication, Narda Safety Test Solutions, Hauppauge, NY) with E- and B-field probes (models 2244/90.22 X0005 and 2244/90.28, respectively). The frequency response of the E-field probe was 3 MHz to 18 GHz, and for the B-field probe, 300 kHz to 30 MHz. The diameter of the E- and B-field probes was 6.6 and 12 cm, respectively. The field probes are peak value sensitive and, therefore, were calibrated in a Crawford cell to each of the various signals used by the ESU (Table 1) in order to measure the root mean square (rms) value in the pulse. The frequency response of the probes at 350 kHz has also been verified by use of the Crawford cell. Both the various pulse repetition frequencies and the nominal frequency of 350 kHz have been taken into consideration in the calibration protocol. Also, the current probe was calibrated to the signals used by the ESU (Table 1) by use of a true rms-sensitive ampere meter (Fluke 199, Everett, WA) and a function generator (HP 3312A, Agilent Technologies, Santa Clara, CA). The measurement error is estimated to ±2 dB including probe accuracy and positioning of the probe.

Using a piece of meat, the field strengths were measured in free field during cutting and coagulation, with the operator standing away from the cable (Fig. 1). The probe was positioned with the probe tip directly in contact with the cable, and measurements were taken at different positions (heights above ground) simulating a surgeon standing with the cable hanging over the shoulder. This position was chosen as a worst-case scenario, and is also rather common in real practice [Liljestrand et al., 2003]. The probe was positioned with a tripod and measurements were done close to the return cable. Linear and quadratic spatially averaged values of the field parameters were also calculated to be compared with the ICNIRP guidelines. Also, average values for the head and trunk were calculated separately. The linearly average values are based on rms in the pulse, and the quadratically average values on the rms during a one-pulse repetition period.

The ESU has an automatic power control used to protect against unintentional thermal damage to the patient. That means that the output power will change automatically throughout the surgical procedure. Thus, the measured values are not completely representative

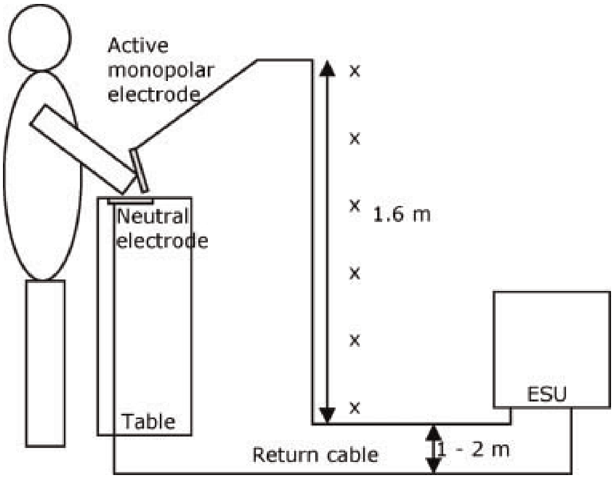

Fig. 1. Simplified schematic of the measurement situation. The measurement points are marked with an "x."

of all uses at the different times and modes. Also, different modes can be used in various high-frequency (HF) power steps and with a predefined maximum output power. The measurements were carried out with a typical setting of these parameters and with maximal output power. In the following text, the setting of the modes used are presented, for example, as "AUTOCUT(8/300)," where the first figure represents the effect level, the other the maximum output power. The output power will then vary automatically up to this maximum intensity. The user can chose between a number of preset settings for each mode.

The ESU has integrated software that measures the HF current, voltage, and power during operation; this was used to evaluate the HF current and voltage in the measurements.

RESULTS

Snapshot oscilloscope pictures of the measured current in time domain for AUTOCUT (8/300), DRYCUT (8/200), and SPRAYCOAG (2/120) are shown in Figure 2. These measurements are done in the highest effect level of each mode. In Table 1 the maximum HF voltage for each mode is presented along with the shape of the signal; the maximum output power is indicated as effect level/max effect (W) in the table. For further information about the ESU used in these measurements, see the VIO 300D user manual [VIO 300D, 2005].

The logged peak voltage during SPRAY mode operation is shown in Figure 3. The peak voltage varied between about 1 and 4 kV.

The measured linear spatially averaged E-fields over the height of a surgeon are given in Table 2. The measurements were taken at two different settings of effect level and maximum HF power (W), indicated as effect level/max effect in the table. The highest linear spatially averaged E-field was found for SPRAYCOAG (20 kV/m, head and trunk) and the lowest values were found for SOFTCOAG.

The measured B-field correlated well (within ±10%) with values calculated from the current in the cable. In Table 3, the calculated B-field values at 10 cm distance are shown. In Figure 4 the HF peak current during the first second in AUTOCUT mode is shown; worth noting is the high initial peak value of ~1 kA. In Table 3 the HF current used in the calculation is based on the stabilized mean value after the first hundred milliseconds. Using the initial peak value of 1 kA instead will give rise to a B-field about five times higher than those stated in Table 3.

The E- and B-fields close to the return cable were of the same magnitude for the lead cable (not shown).

DISCUSSION

When assessing the E- and B-field in the IF range in accordance with the ICNIRP guidelines, both the squared 6-min average value to protect from thermal

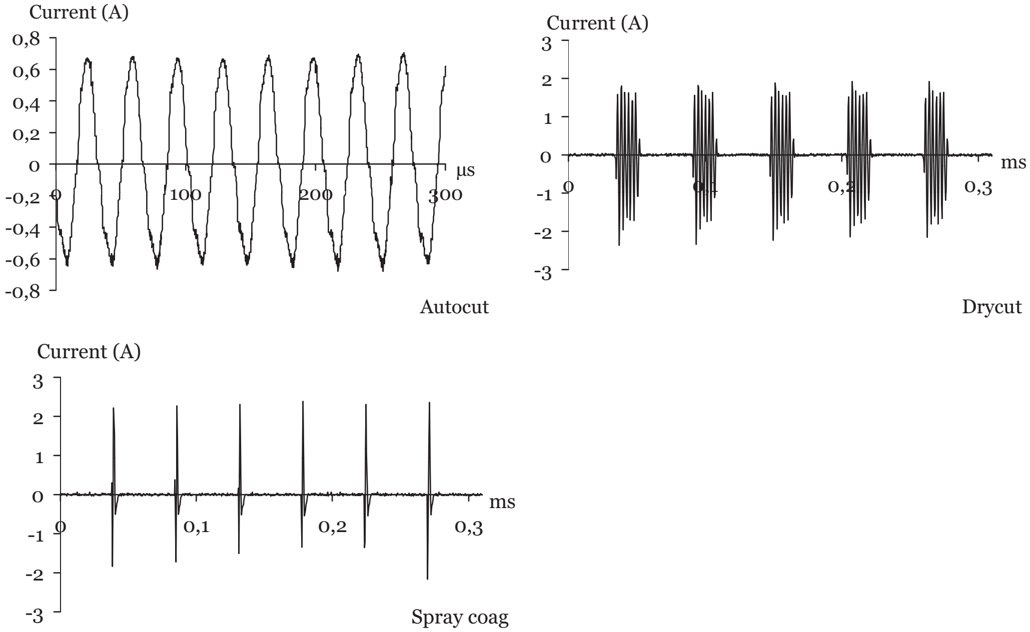

Fig. 2. Oscilloscope pictures of the measured current (A) in the active cable for AUTOCUT (8/300), DRYCUT (8/200), and SPRAYCOAG (2/120).

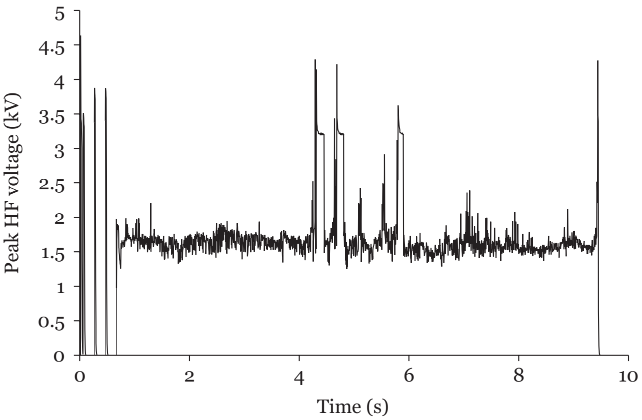

Fig. 3. Peak HF voltage (kV) as a function of time in SPRAY mode. The sample rate is 4 ms.

injuries as well as a linear averaged instant value to protect from nerve excitation, need to be taken into account. The reference values in the ICNIRP guidelines from 100 kHz to 10 GHz are to be compared with the quadratic spatially averaged values of the E- and B-field. The ICNIRP guidelines also provide peak reference values from 100 kHz, but no time averages are given. For 350 kHz, the peak reference value (occupational exposure) is calculated to 20 μT and the squared 6-min average value is set at 5.7 μT; for the E-field, the corresponding figures are 2.1 and 0.61 kV/m, respectively. E-fields are generally difficult to assess since the surroundings affect the readings. In these measurements, efforts have been made to achieve free-field conditions with the surgeon, measurement operator and electrical conductive objects as far away as possible from the measurement position.

When comparing the linearly averaged E- and B-field values it is obvious that the measured E-field exceeds the reference value of 0.61 kV/m for the modes where higher HF peak voltage are used, at least for the higher effect levels. The calculated B-field at 10 cm distance from the cable exceeds the reference values of the ICNIRP guidelines of 5.7 μT for some of the modes. But as mentioned previously, the current is much higher during the first hundred milliseconds which mean that the B-field initially is also much higher; it is not quite clear how to deal with this.

The 6-min spatially averaged values of the E- and B-field are more difficult to assess since they depend strongly on the handling of the ESU, for example, the total cutting/coagulation time during any 6-min period. From previous measurements [Liljestrand et al., 2003] it was shown that during the first hour of bypass operations, which last 3–4 h, the ESU was activated about half an hour in total. This means that the during an arbitrary 6-min period the ESU was activated at least half that time. The measured squared E-field exceeds the reference value by a factor of about 2 for AUTOCUT mode and up to 3 for HIGHCUT mode. Theoretically, the 6-min average E^2 and B^2 could be exceeded, but in normal practice this is probably not an issue since the intensity (current and voltage) is constantly changing during cutting and coagulation, and the measurements were done at the highest effect level.

All measurements were done using a piece of meat. Compared to realistic situations where "live" materials are used, the applied voltage and current will,

TABLE 2. Measured E-Field (kV/m) at Different Heights Above Ground for Various Modes and Distances From Cable

	AUTOCUT		DRYCUT		HIGHCUT		SOFTCOAG		SWIFTCOAG		FORCEDCOAG		SPRAYCOAG	
	4/180	8/300	4/180	8/200	4/180	8/300	4/180	8/200	4/180	8/200	2/80	4/120	1/60	2/120
Height (m)														
1.8	0.75	1.1	0.84	1.5	0.59	1.5	0.17	0.22	3.2	4.8	2.5	3.9	13	11
1.6	0.72	1.0	0.81	1.5	0.57	1.4	0.16	0.21	3.1	4.6	2.4	3.8	13	10
1.2	1.2	1.7	1.3	2.4	0.94	2.4	0.27	0.34	5.1	7.7	4.0	6.3	21	17
0.8	1.4	2.1	1.6	2.9	1.1	2.9	0.33	0.41	6.2	9.3	4.8	7.5	26	21
0.4	0.72	1.0	0.81	1.5	0.57	1.4	0.16	0.21	3.1	4.6	2.4	3.8	13	10
0.1	0.82	1.2	0.92	1.7	0.64	1.6	0.19	0.23	3.5	5.2	2.7	4.3	15	12
Spatially averaged values														
Linear														
Whole body	0.9	1.3	1.1	1.9	0.74	1.9	0.22	0.27	4.0	6.1	3.1	4.9	17	13
Head and trunk	1.1	1.6	1.3	2.3	0.88	2.2	0.26	0.32	4.8	7.2	3.7	5.9	20	16
Quadratic														
Whole body	1.0	1.4	0.37	0.68	0.77	2.0	0.22	0.28	0.64	1.0	0.38	0.60	1.5	1.2
Head and trunk	0.93	1.3	0.36	0.65	0.73	1.9	0.21	0.27	0.61	0.91	0.36	0.57	1.4	1.1

Measurements are taken at two different settings (effect level/maximum output power, W) for each mode and are expressed as rms values in the pulse for the linearly averaged values, and rms during a pulse repetition period for quadratically averaged values. Linear and quadratic average values for the whole body, and head and trunk are also shown in the table. The reference value for occupational exposure is 0.61 kV/m and the peak value is 2.1 kV/m [ICNIRP, 1998].

TABLE 3. Measured Peak Current (A) in the Cable Connecting the ESU With the Monopolar Electrode, and the Calculated Magnetic Field (μT) as rms in the Pulse at 10 cm Distance

	AUTOCUT		DRYCUT		HIGHCUT		SOFTCOAG		SWIFTCOAG		FORCEDCOAG		SPRAYCOAG	
	4/180	8/300	4/180	8/200	4/180	8/300	4/180	8/200	4/180	8/200	2/80	4/120	1/60	2/120
Peak current (A)	0.2	0.8	2	3	0.3	0.8	0.2	—	3	5	2	2	2	3
B-field (10 cm)	0.7	3	6	9	0.8	2	0.5	—	8	13	5	6	4	7

The reference value for occupational exposure is 5.7 μT and the peak value is 20 μT [ICNIRP, 1998].

in some situations, vary rapidly. This is mainly because of variations in resistance of different materials being cut, and also that the contact between the electrode tip and the material will change during the surgical procedure. As mentioned earlier, all measurements were done in a worst-case situation, simulating the surgeon having the cable hanging over the shoulder. This is a common and realistic situation; however, in many situations the cable is placed beside the surgeon with only parts of the body close to the cable. The E- and B-field will decrease rapidly with distance from the cable, theoretically with $1/r$ [Barger and Olsson, 1987]. Liljestrand et al. [2003] have measured the E-field at different distances from the cable, and based on this and theory yields E-field decreases of ~20% of the measured value in direct contact with the cable at a distance of 20 cm. Based on our measurements, the linear averaged E-field is still in conflict with the action values at a distance of 20 cm for the modes with highest exposure (for instance, SPRAY and SWIFT COAG).

Worth noting is that the recently published draft for consultation from ICNIRP [2009] where, in general, higher reference values are proposed in the frequency range up to 100 kHz, will not affect the exposure assessment around ESU since they operate at higher frequencies (0.3–5 MHz).

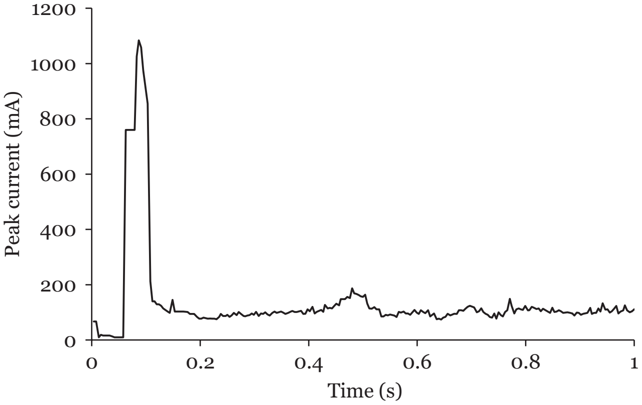

Fig. 4. HF Peak current (mA) as a function of time during the first second in AUTOCUT mode.

When doing assessment to protect from nerve excitations in general, the reference values are set as rms values, but no average time is given. Some instruments use an average time of 1 s, which can only be used when pure sinusoidal fields are evaluated. In this specific case, when the ESU is used in coagulation mode and a pulsed current is used, this becomes important to discuss since the number of whole sinusoidal periods in the pulse can be as low as one.

Reilly [1998] discusses the dependence of the number of sinusoidal cycles on the nerve excitation threshold where, in general, the current threshold decreases with increasing number of cycles of sinusoidal stimulation. This implies that we can tolerate higher induced current density if the number of sinusoidal cycles decreases. This has not been discussed in the ICNIRP guidelines, where the basic restriction is based on continuous sinusoidal exposure. When doing exposure assessment for ESU, this is probably of great importance since the highest used voltage between the electrode and the patient are applied just in coagulation mode, where single cycles are used. For the particular ESU used in this work, this is especially true for SWIFT, FORCED, and SPRAY modes, where high voltage is applied but only up to three sinusoids per pulse are used. This is also why the linearly averaged E-field values are much higher than the quadratically averaged values for the above-mentioned modes since quadratically averaged values are rms values of a whole pulse period, and linearly averaged values are rms only of the sinusoidal pulse.

For non-sinusoidal B-field exposure below 100 kHz, two different methods have been suggested: the multiple-frequency rule and the weighted peak approach [Jokela, 2000, 2007]. It is suggested that the weighted peak approach can also be used for E-field, but since there are not many sources emitting broadband E-fields below 100 kHz, there is no urgent need to develop a model for this as well. There are, to my knowledge, no methods suggested for complex exposure above 100 kHz other than the multiple-frequency rule suggested in the ICNIRP guidelines. Regarding nerve excitation, the weighed peak approach could probably be used in the frequency range of

100 kHz to 10 MHz, but with a different cut-off frequency.

Since the reference values of the ICNIRP guidelines provide a conservative approach, more information is needed on the current density in the exposed body from ESU. Numerical calculations with realistic body models, taking into account the variation in maximum applied voltage and current between different modes, is warranted. No routine methods, however, are available for this today. Since the SAR is also restricted by the guidelines, numerical calculations of this are also needed. Based on the measurement of this and other published work, where the handling of this type of equipment in realistic situations is also described [Liljestrand et al., 2003] it seems, however, not likely that the SAR values stated by the ICNIRP guidelines are exceeded.

Based on the reference values of the ICNIRP guidelines, both the instant B- and E-fields are exceeded close to the cable. Since it is common that the surgeon is standing with the cable hanging over the shoulder, this is a relevant situation. It is also possible that other personnel (theater nurses, anesthesiologists, etc.) in the operation theater may be exposed to rather high stray fields due to similar exposure near the return cable. Therefore, if the European Commission adopts the ICNIRP guidelines (1998 or 2009 draft) the action levels will be exceeded for ESU in normal operation.

Liljestrand et al. [2003] suggested that shielding the cable would reduce the E-field by a factor of 10. Due to safety reasons, shielding the cable is not straightforward since it could lead to an increased risk of high-frequency leakage current, which could cause alternate site burns. Nevertheless, work needs to be done in order to decrease the stray fields near ESU.

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REFERENCES

Barger VD, Olsson MG. 1987. Classical electricity and magnetism. A contemporary perspective. Newton, MA, USA: Allyn and Bacon.

De Marco M, Maggi S. 2006. Evaluation of stray radiofrequency radiation emitted by electrosurgical devices. Phys Med Biol 51:3347–3358.

EU. 2004. Directive 2004/40/EC of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). PE-CONS. p 18. Brussels, Belgium.

ICNIRP. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). International Commission on Non-Ionizing Radiation Protection. Health Phys 74:494–522.

ICNIRP. 2009. Draft Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). International Commission on Non-Ionizing Radiation Protection, Open consultation (Oct 2009). www.icnirp.org (Last accessed 30 October 2009).

Jokela K. 2000. Restricting exposure to pulsed and broadband magnetic fields. Health Phys 79:373–388.

Jokela K. 2007. Assessment of complex EMF exposure situations including inhomogeneous field distribution. Health Phys 92:531–540.

Liljestrand B, Sandström M, Hansson Mild K. 2003. RF exposure during use of electrosurgical units. Electromagn Biol Med 22:127–132.

Mantiply E, Pohl K, Poppell S, Murphy J. 1997. Summary of measured radiofrequency electric and magnetic fields (10 kHz to 30 GHz) in the general and work environment. Bioelectromagnetics 18:563–577.

Paz J, Milliken R, Ingram W, Frank A, Atkin A. 1987. Potential ocular damage from microwave exposure during electrosurgery: Dosimetric survey. J Occup Med 29:580–583.

Reilly JP. 1998. Applied bioelectricity: From electrical stimulation to electropathology. New York, NY, USA: Springer-Verlag. p 563.

VIO 300D. 2005. User manual, Art. No. 80104-521. Tubingen, Germany: ERBE Elektromedizin.