A New Wave in Electrosurgery – Therapeutic Applications of Microwave/RF Energy and Novel Antenna Structures *Invited Paper*

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Abstract— **This paper considers new advanced electrosurgical systems that combine the advantages associated with low frequency RF energy and high frequency microwave energy to enhance the overall clinical effect. It is discussed how the depth of penetration of the EM field and the design of the antenna structure can be optimised to ensure the desired tissue effects are achieved. It is also considered how latest developments in high frequency semiconductor power technology developed for the communications sector are enabling new microwave and millimetre wave energy based electrosurgical systems to be developed and commercialised at an affordable cost.**

Index Terms— **Electrosurgery, Therapeutic, Microwave**

I. Introduction and general review

It is known that thermal RF and microwave energy can be used to create a number of beneficial clinical effects, e.g. tissue resection, desiccation, coagulation, and ablation. Conventional electrosurgery uses energy at frequencies of between: 100KHz and 10MHz, which is high enough to prevent nerve stimulation and low enough to limit the thermal damage caused when cutting tissue. Energy at these frequencies is particularly useful for cutting and desiccating, but does not provide an efficient means of coagulating or ablating tissue structures. Thermal microwave and millimetre wave energy at frequencies of 400MHz upwards can be used in combination with suitably designed antennae to enable efficient and focused energy delivery into tissue to produce controllable heating, which provides an efficient means of coagulating vessels to stop bleeding or to controllably ablate a range of tissue structures that may or may not be cancerous. One important aspect of the antenna design is the ability to match the complex impedance of the particular tissue structure at the frequency of operation to impedance of the radiating antenna; this also helps ensure that the energy is delivered into target tissue and not surrounding structures. Conventional therapeutic microwave systems have used energy at frequencies from 434MHz [1] to 2.45GHz. Over the last decade, low frequency microwave electrosurgical systems have been developed that can be used to address conditions such as: sleep apnoea, cardiac arrhythmias, benign prostatic hypertrophy, and liver tumour ablation [2-7]. More recently, high frequency microwave and millimetre wave based electrosurgical systems have emerged; one of the key drivers behind this is new technological developments in the communication sector making it possible to generate high enough levels of high frequency microwave power to cause tissue coagulation/ablation at an affordable cost. The development of gallium arsenide (*GaAs*) and gallium nitride (*GaN*) power devices for base station amplifiers operating at 5.8GHz and 14.5GHz has made it possible to produce power stages that can deliver up to and in excess of 100W of CW power in a small enough footprint to allow a complete microwave line-up to be included within a standard desk mountable electrosurgical unit at a price that doesn't make the overall unit unaffordable to clinicians or healthcare workers.

II. System design considerations and examples of new therapeutic microwave systems

The particular clinical effect produced by an electrosurgical system is determined by the geometry and design of the antenna structure, the depth of penetration of the electromagnetic energy into biological tissue (which is a function of the frequency of the EM field) and the energy delivery profile produced by the electrosurgical generator.

II.I Geometry and design

The final antenna structure is informed by the particular clinical need, and development is an iterative process that normally involves the use EM field modelling tools such as CST Microwave Studio. If it is necessary for the structure to conform to the shape of the tissue structure being treated, e.g. the inner wall of the oesophagus, then the radiating elements may be fabricated onto a flexible substrate. If it is necessary to deliver the microwave and/or RF energy inside a natural orifice, through the instrument channel of an endoscope, through an introducer for key-hole surgery, or directly into the body, then a flexible or rigid co-axial cable may be used with a suitable radiating antenna attached to the distal end. At high microwave or millimetre wave frequencies the centre conductor within the co-axial structure and the radiating antenna may be made hollow due to the skin effect and this channel may be used to remove tissue from the body (fat cells or biopsy samples) or locally introduce substances into the body, i.e. brachytherapy or internal radiotherapy. If the energy is to be delivered to the surface of an internal or external organ, where a radiating aperture can be placed on the surface, then an unloaded or loaded waveguide structure may be used.

II.II Depth of penetration of the EM field (∂t)

The depth of penetration of the E field into biological tissue determines the power delivered and the subsequent heating profile produced. This is the distance into the tissue when the

E field has reduced to 1/e (37%) of the value at the interface or the power has reduced to $1/e^2$ (13.5%) of the value at the interface. At $5\partial t$ the E field is reduced to 1% and the attenuation into tissue is 40dB down. Skin depth decreases with increasing frequency and increasing conductivity. The expression for calculating the skin depth in biological tissue is given in Eq. 1.

$$\partial t = (1/(2\pi f))\ \{(\mu\ \varepsilon / 2)\ [\ (1+ (\sigma/ (2\pi f \varepsilon))^2]^{1/2} - 1\}^{-1/2} \qquad \text{Eq.1}$$

Where: ε is the absolute permittivity (F/m), μ is the absolute permeability (H/m), f is the frequency of operation (cycles/second), and σ is the conductivity (S/m). ∂t at 2.45GHz and 14.5GHz in the colon is 19.3mm and 1.83mm respectively, 22.57mm and 2.14mm in dry skin, 19.09mm and 1.69mm into the oesophagus, 16.12mm and 1.68mm into blood, and 117.02mm and 12.30mm into fat. It can be seen from this that if it is necessary to achieve fast heating of a small volume of tissue, e.g. to coagulate a vessel, then the higher microwave frequency should be chosen, but if it is necessary to gently raise the temperature, e.g. to turn fatty tissue to liquid, then the lower frequency is preferable.

Examples of some of the new high frequency microwave energy based systems include a 14.5GHz tumour ablation and measurement system that used dynamic impedance matching, a near field RADAR measurement system, and a bespoke 2.2mm diameter rigid co-axial antenna, with a ceramic radiator that included a matching transformer, to locate and controllably ablate breast and liver tumours [8-13]. It was demonstrated during the development of this system that the high frequency microwave energy and the dynamic impedance matching capability enabled spherical ablations of up to 38.8mm diameter to be achieved using 50W of CW power for 180 seconds [9]. It was also demonstrated that the high frequency microwave energy overcame perfusion issues encountered when using lower microwave or RF frequency energy. A power density profile for the final antenna design is shown in Fig. 1.

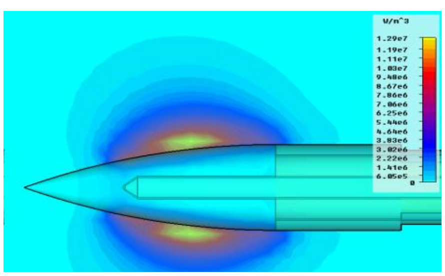

Fig. 1. Power density profile into a tumour model for a 2.2mm diameter co-axial structure with ceramic radiator and integrated impedance transformer

A derivative of the 2.2mm rigid co-axial structure was a structure that had a hollow centre conductor to allow either biopsy samples to be taken, followed by ablation of the needle channel to prevent seeding of cancerous cells, or for fat cells to be removed to perform controlled liposuction, where the depth of penetration of the electric field allows fat to be gently heated and blood vessels to be instantly coagulated [14-16].

If silver is used as the conductor of choice for the centre conductor, then the thickness required for 99% of the E field to propagate at 14.5GHz is 2.64µm, therefore the centre conductor can be made hollow and used to transport material into and/or out of the body. A further example is a travelling wave antenna structure fabricated onto a low loss flexible microwave substrate for tightening the lower oesophageal sphincter to treat gastro oesophageal reflux disease [17 – 18]. In this application, the travelling wave antenna structure is mounted onto the outer surface of an oesophageal balloon, which is expanded once located, Fig. 2. Histopathology results showed controlled ablation limited to the mucosa layer using 20W delivered into the antenna for 5 seconds at 14.5GHz. This could be used to slightly close the sphincter to prevent acid getting into the oesophagus.

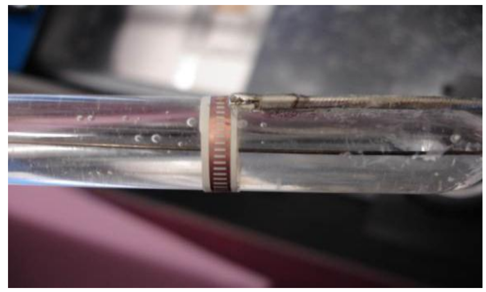

Fig. 2 Travelling wave antenna attached to the outer wall of an oesophageal balloon catheter

An example of an antenna structure for use in treating skin lesions is a waveguide structure with a quarter wave impedance matching section. The field simulation for a structure that operates at 14.5GHz and has been used to perform two positive pre-clinical studies is shown in Fig. 3. Histology result indicated that the ablated sites repair well with regenerated dermis, papillary dermis and epidermis [19-20].

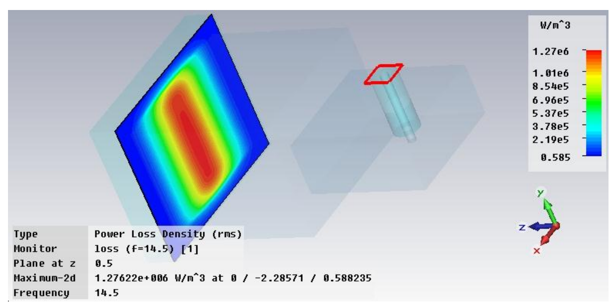

Fig.3. Power density plot for a waveguide based applicator developed for skin treatment

III. NEW WAVE INTEGRATED ELECTROSURGICAL SYSTEMS

The ultimate electrosurgical system is one that combines the advantages of low frequency RF energy for cutting or desiccating tissue structures and high frequency microwave energy for coagulating or ablating tissue [21]. Such a system could be used to perform a myriad of endoscopic, laparoscopic and open procedures. Clinical indications considered to date are open and endoscopic resection/dissection. New novel antenna structures have been developed to perform bloodless liver resections and endoscopic sub-mucosal dissection (ESD) [22-26]. A new device is currently being developed for ESD [24-26] that consists of an antenna structure that can deliver RF energy for cutting and microwave energy for controllably coagulating small blood vessels, a deployable needle to introduce a viscous fluid in the region between the mucosal and sub-mucosal layer of the colon to raise a sessile lesion from the surface to allow it to be dissected, and a ‘speedboat’ shaped hull underneath the antenna to prevent the structure being pushed through the bowel wall; Fig 4. Histology results from recent pre-clinical trials are very encouraging and indicate that it is possible to go down to the sub-mucosal layer without causing damage to the wall of the colon.

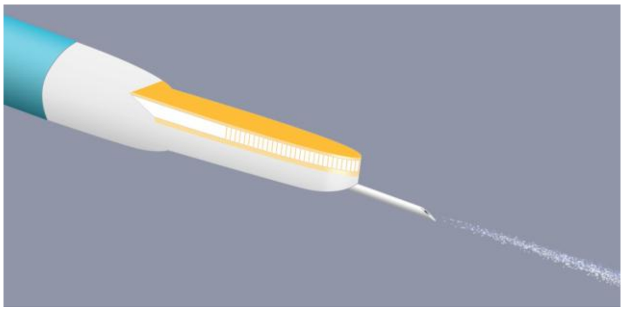

Fig.4. An illustration of the new ESD device that can deliver microwave/RF energy and fluid into biological tissue

IV. DISCUSSION AND CONCLUSION

This paper has considered therapeutic RF and microwave energy systems. Technological advances and cost reduction associated with high frequency microwave and millimetre wave semiconductor power devices, together with growing clinical needs, could lead to a new wave in electrosurgery. New combined microwave and RF energy electrosurgical systems will offer enhanced clinical effects and allow the surgeon to perform a range of clinical procedures that would otherwise have not been possible. In the near future, a single electrosurgical generator and a range of antennae may enable clinicians to carry out a range of clinical procedures in an outpatient environment or within the patient’s home.

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