RADIATION APPLICATOR

This invention relates to radiation applicators and, in particular, to microwave ablation devices.

A known radiation applicator, used for microwave ablation of tissue, comprises a microwave generator operatively coupled to an elongate waveguide for conveying the microwaves to the ablation site. The waveguide is sufficiently thin to be inserted into the body and contains a core of dielectric material which enables efficient transmission of microwaves through the waveguide. At the emission end of the waveguide, the dielectric core protrudes and provides a radiating tip for coupling microwaves into surrounding tissue. An object of the inventor is to provide an improved radiation applicator.

According to one aspect, the invention consists in an elongate device for insertion into a living body, the device having an antenna at its tip for coupling radiation into biological matter and a dielectric body surrounding the antenna so as to encompass substantially the whole of the near-field of the radiation emitted by the antenna.

The invention is based on an appreciation of the fact that the antenna generates a near-field, and that the near-field contains large field amplitudes which exist quasi-statically in the local region of the antenna and do not radiate energy. In a normal communications antenna, this local region is air-filled and these near-field amplitudes have no effect except to contribute reactance to the antenna impedance. However, in a medical application, if the near-field region contains biological matter, which is highly lossy, the near-field amplitudes will generate heat. Because of the high amplitudes and small volume of the near-field region, much heat can be generated in the near-field region, which reduces the energy in the far-field. Field penetration is therefore reduced, and local charring in the near-field region becomes a limiting factor in the power that can be input to the antenna.

The dielectric body according to the invention serves to provide a low loss environment to encompass the near-field region so that more power is transmitted to the biological matter in the far-field region.

The extent of the near-field is determined by the wavelength λ of the radiation in the dielectric and the major dimension L of the antenna according to the relationship $2L^2/\lambda$. Furthermore, in an antenna, L is proportional to λ. The extent of the near-field therefore is proportional to λ, and it is possible to reduce the extent of the near-field region by increasing, the dielectric constant of the body to reduce the wavelength of the radiation within it. The overall external dimension of the device can therefore be reduced for insertion into a living body. A higher dielectric constant will also accommodate the use of lower frequency radiation, which would otherwise increase the wavelength and the extent of the near-field; the lower frequency radiation being beneficial in increasing radiation penetration into the far-field.

In one embodiment of the invention, the dielectric body comprises a cylindrical shape with the antenna extending axially along its centre a distance L, with the radius of the cylinder being substantially equal to $2L^2/\lambda$. A device of this kind can be designed with a minimum radius for insertion into biological matter such as a liver, and will create an annular radiation field around it. A pointed tip may be provided at the free end of the dielectric body to assist penetration of biological matter.

The length L of the antenna may be substantially equal to half a wavelength, in which case the radius of the cylindrical dielectric body is substantially equal to half a wavelength. The antenna is then tuned to act as a resonator, which increases the power it radiates.

However, as the dielectric constant is increased, it may exceed that of the biological matter, which can lead to total internal reflection of radiation within the dielectric and a consequent reduction in transmitted radiation. In order to overcome this problem, the dielectric body is formed so that the dielectric constant at its core is higher than that at its outer periphery, the latter having a value intermediate that of the core and the biological matter. Thus, the dielectric constant at the core may be higher than that of the surrounding biological matter so as to help reduce the overall diameter of the device. The different dielectric constants may correspond to different layers of dielectric, each with a different dielectric constant, or may correspond to different levels in a dielectric in which the dielectric constant varies throughout its depth.

According to another aspect, the invention consists in an elongate device for insertion into a living body, the device having an antenna at its tip for coupling radiation into biological matter and a dielectric body surrounding the antenna so as to enhance transmission of radiation in the forward direction of insertion.

Preferably, the dielectric body completely envelops the antenna and has a tip portion that extends beyond the end of the antenna to support internal reflection of the radiation in the forward direction. Advantageously, the dielectric body is tuned to act as a resonator to further enhance radiation from the tip of the elongate device in the insertion direction. In particular, the diameter of the dielectric body is substantially equal to the wavelength of the radiation, and the tip portion is substantially hemispherical and has a radius substantially equal to half a wavelength of the radiation.

The elongate device may further comprise a coaxial conductor (preferably packed with a dielectric) which supplies radiation to the antenna from a radiation generator. Preferably, the antenna then comprises an exposed length of the central conductor of the coaxial conductor at its distal end. Preferably, the exposed length of the central conductor providing the antenna, is substantially half a wavelength long. The coaxial conductor may be rigid or a flexible cable.

Preferably, the dielectric body has a dielectric constant, or relative permitivity, such that the length of the antenna is reduced. Advantageously, there can be a transformer between the coaxial conductor and the dielectric body to reduce reflection of radiation back into the coaxial conductor from the boundary between it and the dielectric body. Such a transformer can advantageously contain a space into which the dielectric packing of the coaxial conductor can expand.

According to yet another aspect, the invention consists in methods of coupling radiation into biological material using the devices according to the invention.

Further advantages and features of the invention will become apparent to readers skilled in the art upon consideration of the following description of embodiments of the invention, the embodiments being described by way of example only, and with reference to the accompanying figures, in which:

Figure 1 shows a first embodiment of the radiation applicator;

Figure 2 shows the tip section of the radiation applicator of Figure 1 in more detail;

Figure 3 shows a second embodiment of the tip section of the radiation applicator incorporating a transformer;

Figure 4 shows a third embodiment of the radiation applicator;

Figure 5 shows the tip of the radiation applicator of Figure 4; and

Figure 6 shows a side-elevation of a variation in design of the radiation applicator of Figure 4.

Figure 1 shows the general arrangement of the radiation applicator system 100. A radiation generator 110, for example, a microwave generator, produces radiation which is coupled into coaxial cable 120 which transmits the radiation to a distal tip region 130 at which there is an antenna for emitting the radiation into the material surrounding the tip 130. In use, the coaxial cable 120 is introduced into a living body and the tip 130 is positioned adjacent a region which it is desired to irradiate. For example, the device could be inserted into an artery to irradiate plaques on the walls thereof or the device could be introduced into a uterus to irradiate the endometrium. The supply of radiation is controlled by a control device 140, often a foot pedal, which is used to signal the microwave generator to begin, adjust or stop the supply of radiation to the tip 130.

Figure 2 shows the tip region 130 of the radiation applicator of figure 1 in more detail. The tip region, generally indicated 200, shows the distal end of the coaxial cable which comprises an outer conductor 210 spaced from a core conductor 220. The space between the conductors 210 and 220 is filled with a dielectric material 230. The antenna for emitting radiation conducted by the cable comprises a length 240 of the core conductor of the coaxial cable extending beyond the outer conductor 210 at the distal end of the coaxial cable. To enhance the radiating qualities of the antenna 240, it is preferred that the length of core conductor providing the antenna is about one half of a wavelength of the radiation in the dielectric. The antenna 240 is enveloped by dielectric body 250 in which the wavelength of the employed radiation is reduced below its free-space value hence enabling

the exposed length 240 of the core conductor providing the antenna to be shorter than might otherwise be possible. In order to enhance radiation from the antenna in the forward direction, the dielectric body 250, in addition to comprising a cylindrical portion 260 which envelops the exposed length of core conductor 240, comprises a hemispherical section 270 which supports partial internal reflection of the radiation from the antenna in the forward direction as indicated by arrows 280 and 290. Preferably, the hemispherical section 270 is dimensioned so as to provide a resonator which further enhances radiation from the dielectric body in 250 in the forward direction. Resonance of radiation partially reflected within the dielectric body 250 can be encouraged by, for example, dimensioning the hemispherical section 270 to have a radius approximately equal to one half of a wavelength of the radiation employed. It will be appreciated that the dielectric body can have other dimensions and shapes provided that they encourage forward propagation of the radiation by means of internal reflection and/or resonance.

When this equipment is to be used for endometrial ablation it is desirable to use radiation having a frequency around 9.2GHz. In free-space, the wavelength of such radiation is about 32mm. Forming the dielectric body from, for example, a material having a dielectric constant ε_R=25 reduces the wavelength to about 6mm. Correspondingly, the diameter and overall length of the dielectric body are then also about 6mm.

Figure 3 shows an alternative embodiment of the tip section of the radiation applicator device, generally indicated 300. Here, in order to reduce reflection of radiation from the coaxial cable at the boundary between it and the dielectric body, a transformer 310 is incorporated between the coaxial cable and the dielectric body. The transformer 310 comprises several sections (for example, three: 320, 330, 340) of cylindrical shape and of successively increasing radius towards the dielectric body. Advantageously, at least the section 320 of the transformer adjacent the coaxial cable does not contain a solid filler material. This provides the benefit that, when the device is heated, for example in manufacture or in use, the dielectric material filling the space between the core and outer conductors of the coaxial cable can expand into the transformer thus relieving otherwise deleterious pressures.

The near-field radiation generated by the applicator of Figures 2 and 3 extends from the antenna 240 a distance determined by the formula $2L^2/\lambda$, where L is the exposed length of the antenna, and λ is the wavelength of the radiation in the dielectric body 250. However, the preferred value of L is $\lambda/2$, and therefore the near-field radiation is contained within a region of radius $\lambda/2$ about the antenna. Therefore, the near-field radiation does not extend into the more lossy biological material that surrounds the applicators in use, and the resulting detrimental affects of local charring and reduction of radiation penetration are reduced or avoided. Instead, the microwave power is emitted into the far-field to increase penetration and power transfer.

Figure 4 shows yet another embodiment of the invention in which a generator 310 supplies microwave energy via a rigid coaxial conductor 320 to a tip region at the distal end of the conductor. Dielectric packing 330 is provided between the inner and outer conductors of the coaxial conductor 320. As shown in more detail in Figure 5, a length of the inner conductor 340 at the tip is exposed by removal of the outer conductor so as to form an antenna to emit radiation. The antenna 340 is embedded axially in a cylindrical body of dielectric 350 which has substantially the same outer diameter as the coaxial conductor 320. A pointed metal tip 370 is fixed to the end of the dielectric body 350 and serves to assist penetration into biological matter, such as a liver to perform ablation on a tumour. The antenna 340 preferably has a length substantially equal to half a wavelength of the radiation in the dielectric, and the radius of the dielectric body 350 is also preferably substantially equal to half a wavelength of the radiation in the dielectric. The near-field radiation emitted by the antenna will then lie within a region $2L^2/\lambda$, which is equal to a radius of half of the wavelength of the radiation in the dielectric so that the near-field lies substantially totally within the dielectric. The dielectric constant of the dielectric body is selected to be high so as reduce losses within the dielectric. The microwave energy is therefore emitted into the far-field region in an annular pattern around the tip so as to increase field penetration and power transfer. Typically, a radiation applicator used with a generator operating at 10 GHz and having a dielectric body with dielectric constant ε_R=25, will have a dielectric body radius of 3 mm.

In order to reduce the diameter of the tip of the applicator, the dielectric body is made of a material with as high a dielectric constant as possible, except that this is limited by the dielectric constant of surrounding biological matter in which the applicator is used. When the dielectric constant of the dielectric body exceeds that of the biological matter, total internal reflection can occur at the outer surface of the dielectric body, and field penetration becomes evanescent and localised. In order to overcome this limitation, the dielectric body 350 may be formed with an inner core 360 composed of a material with a high dielectric constant, and an outer layer 380 composed of a dielectric with a lower dielectric constant intermediate that of the core and the surrounding biological material so as to match the wave impedance of the radiation between the core and the biological material. In order to achieve this, the refractive index of the outer layer 380 should be equal to the geometric mean of the retractive index of the core 360 and that of biological material, and the outer layer thickness should be equal to a quarter of the wavelength of the radiation in the outer layer. Thus, the core radius would also be equal to a quarter of the wavelength of the radiation in the core in order to produce an overall nominal radius of half a wavelength at the tip.

In alternative embodiments of the invention, multiple outer layers may be used to increase the band-width of the applicator (i.e. the range of frequencies over which the applicator can be used) by making the layers each with a suitable refractive index and thickness. However, this will lead to an increase in the overall diameter of the tip. In the limit, the dielectric body could be made with a continuously varying refractive index which decreases towards its outer surface.

An alternative technique to reduce the dielectric constant of the outer layer 380 comprises forming indentations such as grooves 390, shown in Figure 6, in the outer surface so that the average dielectric constant of the dielectric and the material in the grooves is reduced. The grooves may run longitudinally or circumferentially around the body 350.

It will be appreciated that the embodiment of Figures 2 and 3 can also be modified to incorporate an outer layer or layers of different dielectric constant, such as shown in Figures 5 and 6, the outer layer following the curve of the hemispherical tip.

Dielectric materials with a high dielectric constant that are suitable include those such as TiO_2 with a permittivity of 100 and $CaTiO_2$ with a permittivity of 155. These dielectrics would be suitable for use in the core 360 so as to reduce its diameter. The outer layer(s) 370 could be made of a composite of TiO_2 and AlO_2 having a permittivity between that of the core and the biological material. Materials with even higher permittivities may be used such as ferroelectric materials, an example being Ba_{1-x} Sr_x TiO_3 (BST) which has a permittivity of around 600.

Therefore, by suitable choice of dielectric(s) it is possible to produce radiation applicators with a tip diameter as low as 3 to 6 mm to allow their use in laparoscopic medical procedures, or even below 3 mm to allow percutaneous medical procedures.

Radiation applicators according to the invention can also be used to measure the dielectric constant of biological material by measuring the microwave radiation reflected back from the tip through the coaxial conductor.

Claims

1. An elongate device for insertion into a living body, the device having an antenna (240,340) at its tip for coupling radiation into biological matter and a dielectric body (250,350) surrounding the antenna so as to encompass substantially the whole of the near-field of the radiation emitted by the antenna.

2. A device as claimed in claim 1 in which the dielectric body (250,350) extends from the antenna (240,340) a distance determined in accordance with the wavelength of said radiation in the dielectric.

3. A device as claimed in claim 1 or 2 in which the dielectric body (250,350) extends from the antenna a distance determined in accordance with the major dimension (L) of the antenna (240,340) in the dielectric.

4. A device as claimed in any one of the preceding claims in which the dielectric body (250,350) extends from the antenna (240,340) a distance at least substantially equal to $2L^2/\lambda$, where L is the major dimension of the antenna and λ is the wavelength of the radiation in the dielectric.

5. A device as claimed in any one of the preceding claims in which the dielectric body (250,350) comprises a substantially cylindrical portion with the antenna (240,340) extending axially at its centre a distance L.

6. A device as claimed in any of claims 2 to 5 in which the dielectric body (250,350) extends from the antenna (240,340) a distance substantially equal to half the wavelength of said radiation in the dielectric.

7. A device as claimed in any one of the preceding claims in which the dielectric body (350) is such that it has a dielectric constant at its core (360) which is higher than the dielectric constant at its outer periphery (380), the latter being more closely matched to that of said living tissue.

8. A device as claimed in claim 7 in which the dielectric body (350) comprises an inner core (360) and an outer layer (380), each of a different dielectric constant.

9. A device as claimed in claim 8 in which the inner core 360) and outer layer (380) have those dimensions that extend from the antenna (340) determined in accordance with the dielectric constant of each so that the overall dimension is a predetermined fraction of the nominal wavelength of the radiation in the dielectric.

10. A device as claimed in claim 9 in which the inner core (360) and outer layer (380) each have a dimension substantially equal to a quarter of the wavelength of radiation therein.

11. A device as claimed in any of claims 8 to 10 in which the outer layer (380) is formed with indentations in its outer surface which serve to reduce the dielectric constant in this region when the indentations are filled with other matter.

12. A device as claimed in claim 7 in which the dielectric constant of the dielectric body (350) varies continuously over at least a part of the distance from the antenna (340).

13. A device as claimed in any one of the preceding claims which has a tip portion (270,370) that extends beyond the end of the antenna.

14. A device as claimed in claim 13 in which the tip portion (370) is pointed to assist penetration of biological matter.

15. A device as claimed in claim 14 in which the tip portion (370) is composed of a different material to the dielectric body (340).

16. A device as claimed in claim 13 in which the tip portion (270) is an extension of the dielectric body (250) and is rounded so as to support forward transmission of radiation.

17. A device as claimed in claim 16 in which the tip portion (270) is substantially hemispherical.

18. A device as claimed in claim 17 in which the tip portion (270) has a radius substantially equal to half the wavelength of the radiation in the dielectric (250).

19. A device as claimed in any one of the preceding claims in which the elongate device comprises a coaxial conductor (120,320) with a central conductor (220,240) that projects beyond outer screening of the coaxial conductor at the distal end to form the antenna (240,340).

20. A device as claimed in claim 19 in which the antenna (240,340) has a length substantially equal to half the wavelength of the radiation in the dielectric.

21. A device as claimed in claims 19 or 20 including a transformer (310) between the coaxial conductor (120,320) and the dielectric body (250,350) to reduce reflection of radiation back into the coaxial conductor at the boundary with the dielectric body.

22. A device as claimed in claim 21 in which the transformer (310) includes a space within the coaxial conductor into which packing of the coaxial conductor can expand.

23. An elongate device for insertion into a living body, the device having antenna (240) at its tip for coupling radiation into biological matter and a dielectric body (340) surrounding the antenna (240) so as to enhance transmission of radiation in the forward direction.

24. A device as claimed in claim 23 in which the dielectric body (250) has a rounded tip portion (270) that extends beyond the end of the antenna (240) to support forward transmission of radiation reflected internally from the outer surface of the dielectric body.

25. A device as claimed in claim 24 in which the tip portion (270) is substantially hemispherical.

26. A device as claimed in claim 25 in which the tip portion (270) has a radius substantially equal to half the wavelength of the radiation in the dielectric.

27. A device as claimed in any one of claims 23 to 26 in which the antenna (240) extends a distance substantially equal to half the wavelength of said radiation in the dielectric.

28. A device as claimed in any one of claims 23 to 27 in which the dielectric body (250) comprises a substantially cylindrical portion with the antenna means (240) extending axially at its centre.

29. A device as claimed in any one of claims 23 to 28 in which the dielectric body (250) extends from the antenna (240) a distance substantially equal to half a wavelength of the radiation in the dielectric body.

30. A method of coupling radiation into biological material, the radiation being generated by an applicator comprising an antenna (240,340) surrounded by a dielectric body (250,350), comprising the steps of selecting the dielectric constant of the body (250,350) in accordance with the wavelength of the radiation in the dielectric so that substantially the whole of the near-field of the radiation is encompassed by the dielectric body (250,350).

31. A method as claimed in claim 30 in which the dielectric constant of the body (250,350) is further selected in accordance with the major dimension of the antenna (240,340).

32. A method as claimed in claim 30 or claim 31 in which the dielectric body (250,350) extends from the antenna a distance at least substantially equal to $2L^2/\lambda$, where L is the major dimension of the antenna and λ is the wavelength of the radiation in the dielectric.

33. A method as claimed in any one of claims 30 to 32 in which the major dimension of the antenna (240,340) is its length, which is substantially equal to half a wavelength of the radiation in the dielectric.

34. A method as claimed in any one of claims 30 to 33 in which the dielectric body (250,350) is located in relation to the biological material so that the far-field radiation lies within the biological material.

35. A method as claimed in any one of claims 30 to 34 in which the dielectric constant of the body (250,350) is high, but is lower than that of the biological material.

36. A method as claimed in any one of claims 30 to 34 in which the dielectric constant of the dielectric body (350) varies, and is higher at its core (360) than its outer periphery 380), and the dielectric constant at its outer periphery is lower than that of the surrounding biological matter.

37. A method as claimed in claim 35 in which the dielectric constant at the core (360) is greater than the dielectric constant of the biological matter.

38. A method of coupling radiation into biological material, the radiation being generated by an elongate applicator comprising an antenna (240) surrounded by a dielectric body (250), the dielectric body being configured so as to enhance transmission of the radiation in the forward direction along the elongate axis of the applicator.

39. A method as claimed in claim 38 in which radiation is partially reflected internally of the dielectric body (250) so as to be transmitted in the forward direction.

40. A method as claimed in claim 39 in which the dielectric constant of the body (250) is high but is lower than that of the biological material.

41. A method as claimed in any one of claims 38 to 40 in which the dielectric body (250) has a substantially hemispherical tip portion (270) with a radius substantially equal to half the wavelength of the radiation in the dielectric.

42. A method as claimed in any one of claims 38 to 41 in which the antenna (240) has a length substantially equal to half the wavelength of the radiation in the dielectric.

43. A method as claimed in any one of claims 38 to 42 in which the dielectric body (250) extends from the antenna (240) a distance substantially equal to half the wavelength of the radiation in the dielectric.