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A Lamp for Cancer Phototherapy

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Abstract

The lamp described comprises a 1000 W incandescent filament source, long- and short-wave pass filters, and a non-imaging reflector system. The output of 24 W in the 620–720 nm band is delivered through a 53 mm diameter aperture with a maximum divergence half-angle of 60°. Refracting components may be fitted to modify the output angular or intensity distribution. This lamp has been used to irradiate several different types of malignant tumour in human patients, following intravenous injection of the photoactive drug haematoporphyrin derivative, causing selective necrosis of the malignant tissue. The clinical results are regarded as encouraging.

1. Introduction

It has been known for many years that certain porphyrin compounds, when injected into the bloodstream, are absorbed and selectively retained in malignant tissue. Dougherty *et al.* (1975) reported the complete eradication of tumours in mice by the injection of a haematoporphyrin derivative (Hpd) followed by exposure of the tumours to red light. This technique has since been applied to the treatment of tumours in human patients. Encouraging results have been obtained in the treatment of skin, breast, lung, brain and gynaecological tumours (Forbes *et al.* 1980; Hayata *et al.* 1982; Ward *et al.* 1982; McCulloch 1983). The technique offers the possibility of treating certain tumours which are not presently treated satisfactorily.

It is evident that, when activated by light, Hpd takes part in reactions which are lethal to the tumour tissue. The reactions are thought to involve excitation of the Hpd molecule followed by energy transfer to molecular oxygen, producing a highly reactive singlet-excited oxygen molecule which causes cell damage (Weishaupt *et al.* 1976).

The molecule Hpd has an absorption peak at about 630 nm and several stronger peaks at shorter wavelengths. However, because Hpd is retained to some extent in normal skin and because light is strongly absorbed by most human tissue at wavelengths less than about 620 nm, these wavelengths are generally contra-indicated. Absorption by Hpd falls to zero at about 720 nm, while most tissue transmission rises steadily from about 620 nm to well beyond 720 nm. The range of efficacy then appears to be about 620–720 nm with a peak at about 630 nm; the longer wavelengths within this band are potentially important for their greater penetration depths.

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For treatment of cutaneous and sub-cutaneous tumours, appropriate light doses appear to be in the range 100–200 J cm^{-2} at 630 nm or several times this if the 620–720 nm band is used (I. J. Forbes, personal communication).

Treatments have been carried out both with lasers and with non-coherent sources. Lasers provide the great advantage that the light can be introduced via optical fibres into the tumour and indeed into internal organs including the lung. There are limitations, however, including the difficulty of delivering an adequate light dose without causing blood coagulation and excessive local heating around the fibre ends. This problem has been overcome to some extent by a metal-vapour laser and optical-beam divider [supplied by Quentron Optics Pty Ltd (Adelaide)] which can feed up to nine fibres. Non-coherent broad-band sources with suitable filters have the advantage of lower cost and simplicity and, with greater output power, allow a shorter treatment time, which in most applications is advantageous.

This paper describes a lamp which incorporates an incandescent-filament source, reflecting optics and filters; laboratory and clinical trials have demonstrated its potential usefulness.

2. Description of Lamp

A non-imaging reflector system is used to collect light from an incandescent filament, pass it through filters with a specified maximum angle of incidence and concentrate it through a smaller aperture. Additional refracting components may be added to further concentrate the output through a smaller aperture with consequent increase in the divergence or to modify the power distribution across the aperture.

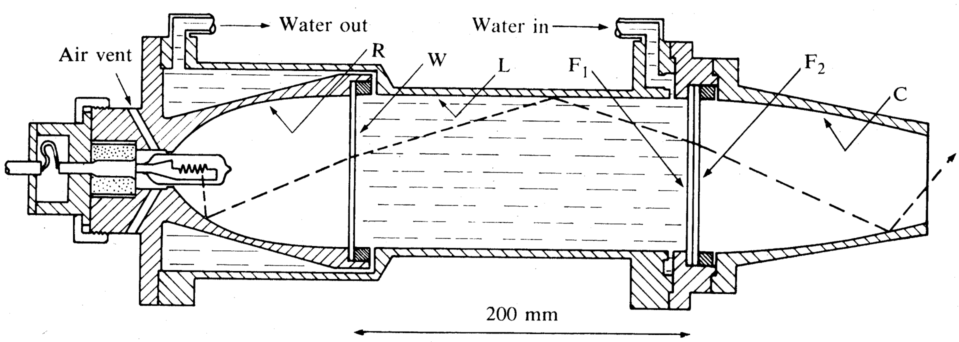
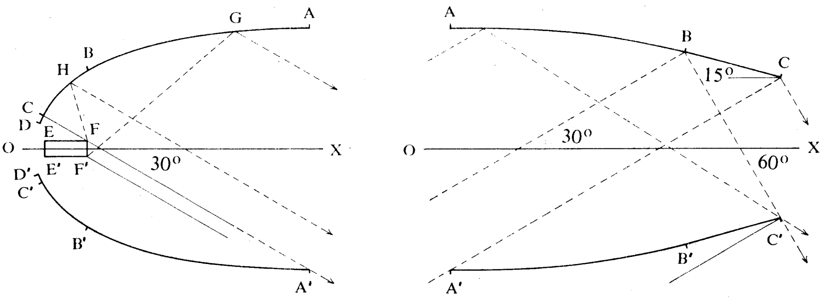


Fig. 1. Lamp head and a typical ray path from the filament, reflected once in the collector R, the water filled cylindrical section L, and the concentrator C, emerging through the 53 mm diameter output aperture with a divergence angle from the axis close to the maximum value of 60°. A fused silica window is indicated by W, a coloured glass long-wave pass filter by F_1 and an all dielectric short-wave pass filter by F_2.

The optical features of the present lamp head are illustrated in Fig. 1. The light source is a single-axial coil tungsten–halogen lamp [Sylvania FEL] with an output of 1000 W operating at 3200 K with a nominal life of 300 h. Less than 20% of its output is incident on the base. Of the remainder, all rays not absorbed by the gold-plated reflecting collector R are incident at the silica window W with a maximum angle of incidence or divergence from the axis of 30°. This divergence is reduced to 22° in the water in the cylindrical section L, the interior surface of which is gold plated. Rays emerge through the filters F_1 and F_2 with a maximum divergence of 30°. This is increased to 60° at the output of the gold-plated reflecting concentrator C. A typical ray path, involving one reflection in each section of the lamp, is illustrated in Fig. 1.



(*a*) (*b*)

Fig. 2. Details of (*a*) the collector and (*b*) the concentrator, illustrating some typical ray paths (see text).

The design principles embodied in the reflecting optics are elaborated by Welford and Winston (1978). Fig. 2*a* illustrates details of the collector (R of Fig. 1), which is a surface of revolution about the axis OX. The rectangle EFF′E′ represents the filament. The curve AB is parabolic with focus F′ and with axis parallel to FA′, which makes an angle θ of 30° to the lamp axis. Curve AB is parallel to OX at point A. The curve BC is parabolic with the focus F and axis CFA′. The point B is collinear with FF′. The arc CD is circular, centred at F. The diameter DD′ is chosen to admit the lamp envelope. Some characteristic rays are illustrated in Fig. 2*a*. If G is any point on AB, then the ray F′G is reflected to make an angle of 30° to OX. All other rays from the filament reflected at G emerge at an angle less than 30° to OX. Similarly rays reflected from any point H on BC emerge at an angle not greater than 30° to OX. The ray from F to C is reflected back through F at 30° to OX. Rays from any point on the filament to any point on CD are reflected to emerge at angles not greater than 30° to OX.

Fig. 2*b* illustrates the concentrator (C of Fig. 1), also a surface of revolution about OX. The curve AB is parallel to OX at A and is parabolic with focus C′ and with axis parallel to A′C, which makes an angle θ of 30° with OX. The portion BC is straight, tangential to AB, and makes an angle α of 15° with OX giving a maximum output beam divergence of 60° from the axis. Some characteristic rays are illustrated in Fig. 2*b*. Rays incident on AB at an angle of 30° to OX are reflected through the focus C′, the ray at B emerging at the maximum angle of 60° to OX. All other rays reflected by AB emerge at angles less than 60° to OX. Rays reflected by BC emerge at angles not greater than 60° to OX.

A small fraction of the rays emitted from the filament near E (Fig. 2*a*) are reflected more than once by the collector AD; they still emerge at angles less than 30° to OX. Some of these rays are reflected more than once by the concentrator (AC of Fig. 2*b*); all emerge at angles less than 60° to OX. The above description accounts only approximately for skew rays. Because of the small diameter of the filament, the approximation is good in the present application and only a very small fraction of the output power emerges from the concentrator at angles greater than 60° to the axis. In fact the output from the concentrator is peaked in the forward direction and falls off rapidly at angles greater than about 30° from the axis. In the plane of the output aperture of the concentrator the intensity is strongly peaked, forming a central bright spot.

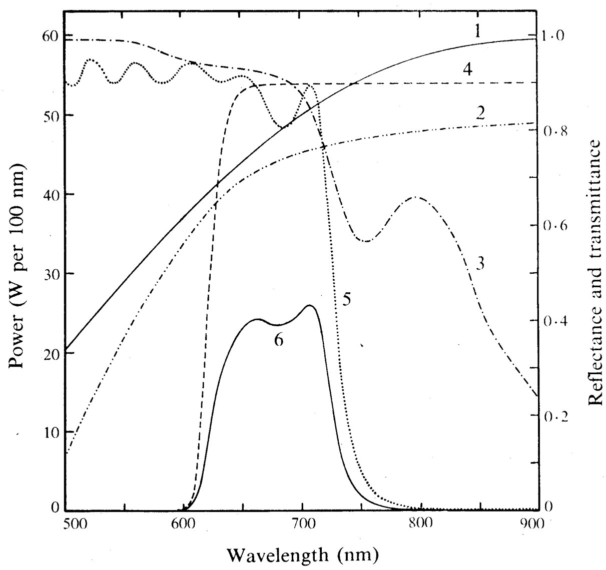


Fig. 3. Spectral characteristics of the lamp components.
1. Power output from the filament, corrected for loss by absorption in the base;
2. R^3 where R is reflectance of gold;
3. transmittance of 200 mm column of water;
4. transmittance of long-wave pass filter F_1;
5. transmittance of short-wave pass filter F_2;
6. lamp output.

The desired wavelength range is selected by separate long- and short-wave pass filters which may readily be changed to vary the lower and upper cut-off wavelengths independently for possible different laboratory or clinical applications. Referring to Fig. 1, F_1 is a coloured-glass long-wave pass filter [Hoya Type R62] with 50% of peak transmission at 620 nm; F_2 is an all-dielectric short-wave pass 'edge' filter [A. G. Thompson & Co. (S.A.) Pty Ltd, Adelaide, Type SW 730] with 50% of peak transmission at 730 nm at normal incidence. The cut-off is shifted slightly to lower wavelengths and the slope of the edge somewhat reduced in the diverging beam. This filter shows a further transmission region, beyond 950 nm, which is suppressed by absorption in the 200 mm water column shown in Fig. 1. The water serves also to cool the collector R. The spectral characteristics of the source, reflectors (assuming an average of three reflections), filters, and the calculated output are illustrated in Fig. 3. The calculated output power with the filters described is 24 W. The measured and calculated output power and spectrum are in good agreement.

The output from the lamp may be further modified by the addition of a refracting component. One such 'lens', the design principles of which are basically similar to those for the reflecting concentrator C of Fig. 1, makes use of total internal reflection to concentrate the output through a smaller aperture while increasing the beam divergence to 60° in human tissue when the output face is in contact with the skin. When the output face is in air there is some internal back reflection and the remaining output has a divergence of 90°. This has been used in several cases for irradiating the brain cavity after a tumour has been excised (McCulloch 1983). Other 'lenses' have been made to improve the uniformity of output power across the aperture; in general these cause some reduction of total power and increase in beam divergence. One such 'lens', in the form of a cylindrical rod of diameter 10 mm and length 50 mm, selects the central bright spot, scrambles it through several internal reflections and delivers 2·5 W uniformly distributed over the 10 mm aperture. This is used for treatment of induced tumours in laboratory animals for trials of various preparations of photoactive drugs etc.

A 'lens' may be fitted instead of the reflector concentrator for use as a concentrator or to modify the power-output distribution across the aperture for use in the treatment of large fields containing several tumours, for example in the treatment of secondaries following mastectomy.

3. Lamp Construction

The lamp head was machined from aluminium and a thin-walled stainless steel liner was pressed into the central cylindrical section. The internal surface of this liner was gold plated. The reflective surfaces of the collector and concentrator (R and C of Fig. 1) were electroless nickel plated, polished, then gold plated. All other surfaces were anodized. The glass window W and filters F_1 and F_2 were clamped against O-ring seals by gold-plated stainless-steel bezel rings with Teflon spacer washers.

The cooling water was pumped via a filter to a 30 L reservoir which permits continuous operation for at least 15 min without excessive temperature rise. For larger periods of operation a cooling coil immersed in the reservoir was connected from the water mains to waste. A corrosion inhibitor and a non-ionic detergent (to ensure uniform wetting of the glass and gold surfaces in the lamp) was added to the circulating cooling water.

The lamp was mounted on a mobile trolley so as to achieve a wide range of position and orientation.

4. Comments

The lamp described is being used in a continuing program of trials at the Queen Elizabeth Hospital, Adelaide, by Dr G. A. J. McCulloch, for the treatment of brain tumours and by Dr I. J. Forbes and his colleagues for the treatment of melanomas and cutaneous metastases of breast carcinoma, and transplanted sub-cutaneous carcinomas in laboratory mice. For such applications the lamp design and operation is assessed by McCulloch and Forbes (personal communication) as very satisfactory and the clinical results encouraging.

Very little information is available on the optical properties of human tissue and the effective depth of light penetration, which is determined by absorption and multiple scattering. (Research in this field is under way.) However, it is not expected that such a lamp as that described here will be generally useful for treatment of malignant tissue at depths greater than about 5 mm. Penetration through fat and brain tissue may be important exceptions. For greater depth, a laser feeding multiple fibres inserted into the tumour is undoubtedly more appropriate. Nevertheless, there is a wide range of conditions in which the present lamp has potential clinical applications either directly or after excision of the bulk of the tumour.

Because of the high power output available, care must be taken to avoid 'burning'. Pain can be alleviated by frequent dousing or spraying with water and/or by switching the lamp on and off periodically; an electronic timer is provided for this purpose. Alternatively, the optical bandwidth, and hence the power output, may be reduced. There is, in addition, a risk of damage arising from over-exposure of the skin which retains Hpd to some extent. There is some indication that this risk is reduced by intermittent exposure. Exposures of 5 min distributed through a total interval of 10 min have been used in some applications.

Some workers, viewing only scattered light from objects illuminated by the lamp, suffered a temporary hemianopic visual-field defect and headache; the use of suitable goggles is recommended.

Acknowledgments

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