Relevance of the Structure of Time-Resolved Spectral Output to Light-Tissue Interaction Using Intense Pulsed Light (IPL)

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Background and Objectives: High quality IPLs can offer simple, safe and effective treatments for long-term hair removal, removal of benign vascular and pigmented skin abnormalities, skin rejuvenation and acne treatments. Significant differences in clinical outcome have been recorded among different free-discharge and constant current IPLs despite identical settings. We investigated the differences in optical output of 19 IPLs in normal clinical use in the UK to evaluate spectral output, energy density values and pulse structure and propose a correlation between light-tissue interaction and spectral output as measured by time-resolved photo-spectrometry.

Study Design/Materials and Methods: Using a fast spectrometer, generating 1,000 full spectral scans per second, time resolved spectral data of IPL outputs was captured with a resolution of 0.035 nm. IPL spectral outputs were calculated and graphically modelled using MathCAD™ software for comparison.

Results: Several IPLs, which professed matching of pulse durations to the thermal relaxation times of specific follicular or vascular targets were shown to have effective pulse durations that were vastly shorter than those claimed. Some IPLs claiming 'square pulse' characteristics failed to show constant spectral output across the duration of the pulse or sub-pulses.

Conclusions: This study provides a suitable method to determine accurately key parameters of the emitted light pulses from IPLs and confirms the direct correlation between the electrical discharge current profile and the output energy profile. The differences measured between first generation free discharge systems and modern square pulse systems may have important clinical consequences in terms of different light-tissue interactions and hence clinical efficacy and safety. IPL manufacturers should provide time-resolved spectroscopy graphs to users. Lasers Surg. Med. 40:83–92, 2008.

Key words: selective photothermolysis; spectral footprint; square pulse; time-resolved spectroscopy

INTRODUCTION

Most IPL systems have a number of parameters, which the operator can alter to match the patient's skin type and treatment selected. These parameters may include: exposure time of intense light (pulse duration or total duration of sub-pulses) in millisecond, energy density (fluence) in J/cm^2, and cut-off filters to eliminate unwanted wavelengths. Each of these parameters is important to produce the most desirable thermal profile in the melanin of the hair follicle or epidermis, or in the haemoglobins in the blood vessel, whichever is the major chromophore being targeted. Positive but not always consistent clinical outcomes are widely documented in the literature using a number of well-established IPL devices. The recent increase in the number of IPLs produced worldwide without thorough clinical data to support manufacturer's claims of the efficacy, safety, and reliability of the manufacturers' assertions raises the question of the effectiveness and dependability of these devices.

IPLs can be categorised into two main types by the method, which they use to generate and deliver the energy required for light-based treatments, they are:

(1) Free discharge.
(2) Constant current.

A free discharge system applies a large electrical charge to a capacitor or a number of capacitors in parallel then discharges the entire stored energy directly though the flashlamp, this discharge profile is characterised by a rising/falling slope. As the current through a xenon flashlamp starts with a low initial value, the light spectrum is shifted predominantly towards the infrared end of the spectrum. As the current increases exponentially, the spectrum shifts towards the blue part of the electromagnetic spectrum, then as the current falls away, the optical spectrum moves back to the red end of the spectrum (Figs. 1a and 2a). This effect of 'spectral jitter'

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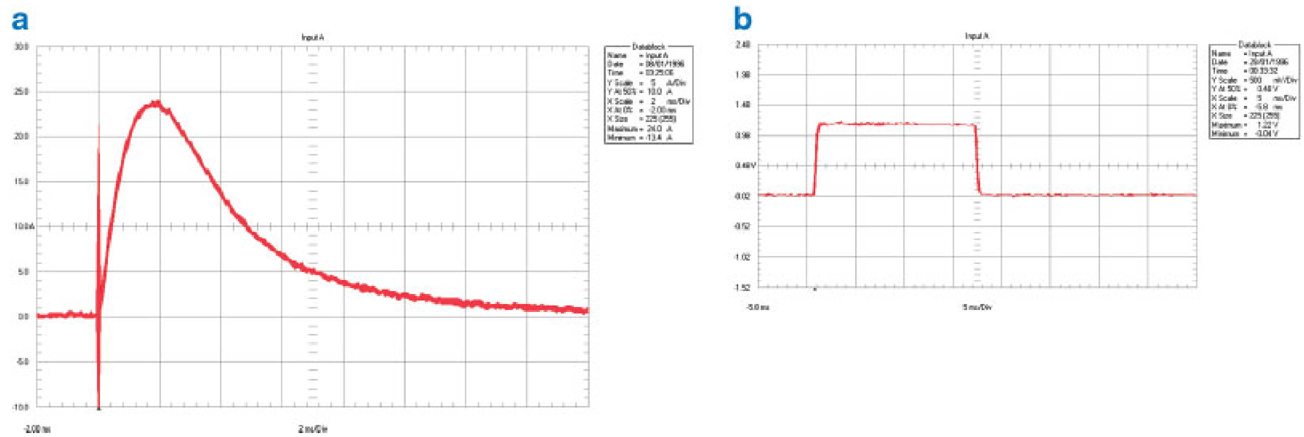

Fig. 1. **a**,**b**: Typical rising-falling slope trace of a free discharge IPL (Chromolite, Chromogenex Ltd) compared with a 'Square Pulse' pulse discharge profile of a constant current IPL (iPulse, Cyden Ltd) as measured on a digital oscilloscope and plotted on a graph against time.

during the pulse means that the optical output not only varies during the pulse but may also differ significantly from one energy setting to another [1–3].

Most free discharge systems are unable to generate true long pulse durations to match the thermal relaxation time (TRT) of the target structure (e.g. hair follicle or blood vessel). The TRT of a typical hair follicle is in the order of 25–55 milliseconds and therefore, for optimum thermal destruction of the hair, the light energy should be delivered in the same time regimen [4–6]. Most conventional free discharge IPLs therefore deliver a train of shorter, high energy sub-pulses with variable on and off times to generate an overall pulse duration and average energy density in the range of the TRT of the target chromophore. Whilst this method may initially produce a clinically measurable result, it may not be the most efficient way of achieving long-term stable hair reduction or long-term vessel clearance with the minimal number of treatments and low incidence of adverse effects.

A constant current ('square pulse') IPL system generates energy in the same way as a free discharge system by charging a large capacitor or a number of capacitors in parallel, the difference between the two systems is the way in which the energy is delivered to the flashlamp. Constant current systems create a square pulse discharge profile through the xenon flashlamp at an optimum energy level and discharges are repeated without variation. As a result, little energy is wasted and the constant current IPL system

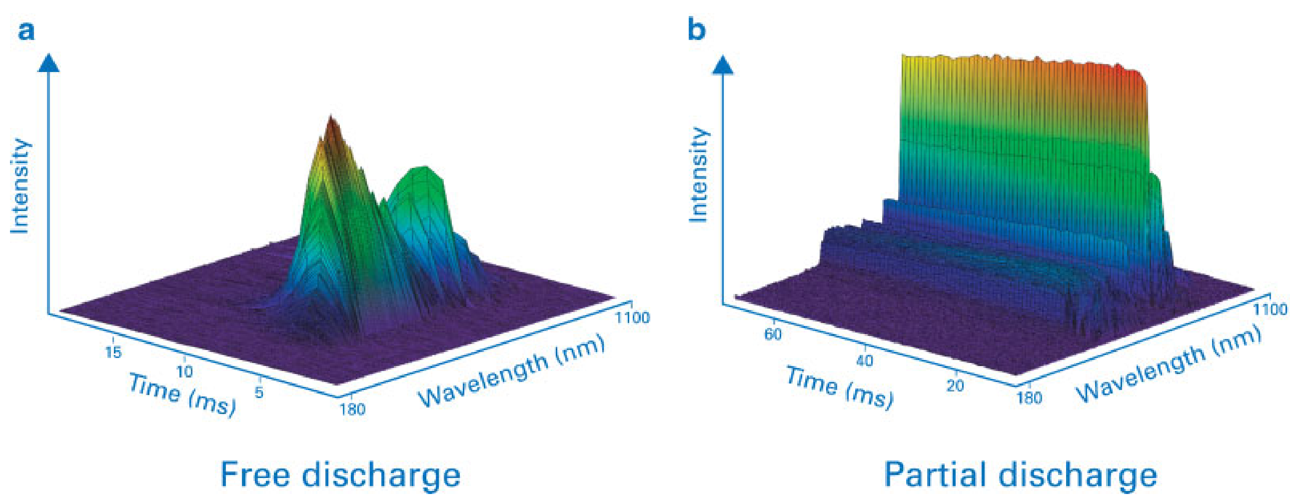

Fig. 2. **a**,**b**: Time-resolved spectral measurements of a free discharge IPL (Chromolite, Chromogenex Ltd) compared with a 'Square Pulse' pulse discharge profile of a constant current IPL (iPulse, Cyden Ltd). The two measurements show differences in spatial and temporal characteristics of the two types of IPL, confirmed by the spectral jitter seen in the short plasma phase of the free discharge IPL during which most of the light energy is released in an invariable 3–4 milliseconds compared with the constant spectral output spread evenly across the entire pulse of the partial discharge IPL with a variable range of pulse durations 10–50 milliseconds.

can operate efficiently and effectively at lower energy levels whilst still producing a constant spectral output across the entire pulse duration (Figs. 1b and 2b).

The duration of the discharged pulse or sub-pulses of intense light may be measured using a reversed biased photodiode, acting as a light dependant switch. Most manufacturers represent the spectral output of their IPL as an average spectral measurement taken across the entire pulse duration as measured above. It is useful to note the approximate distribution of energy across the different wavelengths from a xenon lamp delivering the bulk of the energy in the range 530–800 nm with several specific atomic lines between 820 and 920 nm and referenced to the absorption curves for melanin and oxyhaemoglobin (Fig. 3).

STUDY DESIGN/MATERIALS AND METHODS

Discharge Current Profile Measurement

A constant current through the xenon flashlamp may be critically important in the successful treatment of certain skin conditions. Potentially, much of the discharged energy may be wasted due to uneven wavelength distribution of the light energy across the pulse duration. The current discharge profile through the xenon flashlamp, which should produce a balanced spectrum of light to achieve the desired photo therapeutic effect, can be measured by two methods as described by Town et al. [8]:

(1) The current can be measured by inserting a 0.01 ohm resistor in series with the flashlamp inside the applicator handpiece. The current flowing through the electrodes is measured across the 0.01 ohm resistor using a digital oscilloscope and plotted against time to give a graphical representation of the current ionising the xenon gas.

(2) The current waveform can be measured by the induced current through a hand turned cable of thin enamelled copper wire wound around the electrode wire and a ferrite core. This method can be used when the applicator can be opened easily by a technician but cannot be physically altered in any way without the manufacturer's permission.

Example measurements were made of several different types of IPL to confirm the current discharge profiles.

Time-Resolved Spectrum

Whilst the role of measurement of pulse duration and pulse profile for lasers and intense pulsed light sources has been recognised recently [7,8], only a few studies to date have attempted to document methods for measuring IPL pulse durations or examine in detail the time-resolved spectral output of IPLs that is across each millisecond of the pulse duration [8–10]. Time-resolved spectroscopy graphically modelled using MathCAD™ software is intended to demonstrate simply the light energy distribution

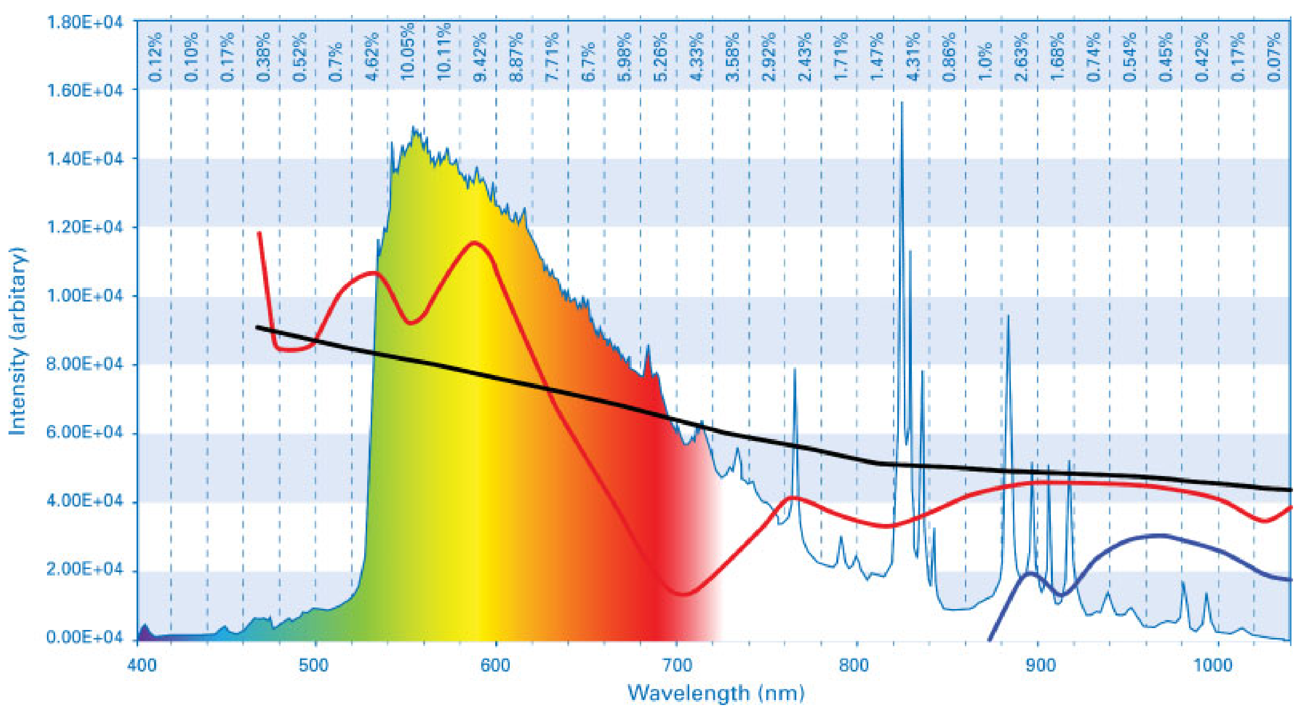

Fig. 3. Example standardised spectral distribution of a typical xenon lamp IPL (iPulse, Cyden Ltd) measured in 20 nm bandwidths as a percentage of the total energy beneath the graph curve. Absorption curves for oxyhaemoglobin (red) melanin (black) and water (blue) have been overlaid to reference optimal absorption characteristics.

(or 'spectral footprint') and spectral stability during a light pulse. Two of the authors performed measurements over a 6-month period on 3 constant current and 16 free discharge systems, which were all in active daily use in private dermatology clinics and salons in UK. These included StarLux, (Palomar Medical Technologies, Inc., Burlington, MA), iPulse, (CyDen Ltd, Swansea, UK), NovaLight (Ultramed Ltd, Geneva, Switzerland), Chromolite, (Chromogenex Ltd, Llanelli, UK), Crystal512 (Active Optical Systems Ltd, Petach-Tikva, Israel), EllipseFlex/EllipseLight (DDD A/S, Hørsholm DK, Denmark), Harmony (Alma Lasers Ltd, Caesarea, Israel), ULTRA (Energist Ltd, Swansea, Wales), BBL (Sciton Inc., Palo Alto, CA), Lumina600 (Lynton Lasers Ltd, Cheshire, UK), GPFlash1 (General Project srl, Montespertoli, Florence, Italy), Plasmalite (Medical Biocare Sweden AB, Vastra Frolunda, Sweden), Ecolite (Greenton London Ltd, London, UK), Quantum/Aculight (Lumenis, Inc., Santa Clara, CA), Freedom IPL (Freedom Beauty Ltd, Leicester, UK), Trinity (Espansione Marketing Spa, Bologna, Italy) and SkinStation (Radiancy (Israel) Ltd, Yavne, Israel).

Conventional spectrometers need relatively long sample time rather like the exposure time on a camera. This averaging effect dampens or eliminates the variations in spectral peaks. Time-resolved spectral measurements make it possible to assess variations in spectral composition during the light pulse, and hence evaluate the quality and consistency of sequential flashes of the IPL. These assessments may then form the basis for hypotheses on improvements that might be made to the pulse duration and spectral pattern of an IPL's output characteristics to produce improved clinical outcomes.

The time-resolved spectra in this study were produced using an Ocean Optics HR2000+ spectrometer and its counterpart SpectraSuite software (OceanOptics Inc, Dunedin, FL). This software has the capability of sampling a spectrum of light with a minimum integration time of 1 millisecond by generating 1,000 full spectral scans per second. Time-resolved spectral data of IPL outputs was captured and stored with an optical resolution of a monochromatic source measured as full width half maximum (FWHM) resolution of 0.035 nm. This fast spectrometer uses a Sony ILX511 2048-element linear silicon CCD-array detector to capture data into memory every millisecond interfaced to a PC via a USB 2.0 port for later analysis. The HR2000+ spectrometer has the facility of stray light correction to correct for ambient light, which could otherwise create a slight offset in the results. Every result was recorded with this facility enabled.

The spectrometer is externally triggered using a breakout box and because of the relatively quick pulse duration of an IPL system, the sampling was taken over an extended time period to ensure capture of the data. The source of the intense light from the IPL system and the spectrometer optical fibre was separated by a distance of 150–180 cm to prevent saturation of exposed light upon the CCD array within the spectrometer. During testing Shade 3 IPL protective eyewear was worn by all persons present within the enclosed room.

IPL spectral outputs were calculated and graphically modelled using MathCAD™ software. For optimal, uniform visual representation of the images, three specific visual aspects were chosen to show the results:

(a) Distribution view of spectral wavelengths (x-axis) taken at 1 millisecond intervals (y-axis), used to compare with accompanying figures.
(b) Time-resolved spectrum view, which shows energy decay with time (typically seen in foreground where bulk of energy occurs) NB. Atomic peaks in background typically contain little energy. This view also shows 'true' pulse duration.
(c) 3D 'flying view' of all the dimensions in proportion showing exactly where and when optical energy changes during the pulse duration.

To clarify, the 3-D images are shown with the time axis flowing from right to left in order to have a clear picture of the pulse structure on the left hand side as this is where the plasma energy is distributed and is the area of greatest interest. When observing the graphs with the axis in the opposite direction the pulse structure is hidden by the atomic peaks around 825 nm, which have high intensity but little energy.

RESULTS AND DISCUSSION

Discharge Current Profile Measurement

Figure 1a,b compares the typical rising-falling slope oscilloscope trace of a free discharge IPL (Chromolite, Chromogenex Ltd) with a 'Square Pulse' partial discharge profile of a constant current IPL (iPulse, Cyden Ltd). Similar traces were recorded for individual sub-pulses of both free discharge and 'Square Pulse' IPLs generating sequences of sub-pulses with inter-pulse delays.

Figure 2a,b compares the same devices and pulse structures in Figure 1a,b as three-dimensional time-resolved 'spectral footprints' measured with the HR2000+ fast spectroscope and produced with SpectraSuite/MathCAD software. The rising/falling discharge slope seen on the oscilloscope is substantially reflected in the time-resolved images but with the ability to visualise accurately where the bulk of the optical energy occurs and more accurately determine 'true' pulse duration.

Explanation of the Spectral Graph

The spectral analysis of light emitted from flashlamps contains both discrete line structure and continuum radiation. The continuum radiation is blackbody radiation, a characteristic of the temperature of the plasma in the discharge. The sharp peaks in the distribution of the wavelength spectrum are due to specific energy transitions of electrons interacting within the xenon plasma. Figure 3 shows a spectral graph of a typical IPL system (iPulse, CyDen Ltd), with 64% of the total energy found between 540 and 700 nm (the key wavelengths for hair depilation and vascular abnormalities) and illustrates the proportional distribution of the wavelengths in convenient 20 nm bandwidths. Absorption curves for oxyhaemoglobin (red) melanin (black) and water (blue) have been overlaid to reference optimal absorption characteristics.

The xenon plasma results in the emission of photons with a range of energies and the spectrum from the xenon ions is therefore continuous. This is known as a bound-free transition and was discovered in 1939 by Wildt [11]. The line spectra in the infrared region of the graph are more dominant where bound transitions between energy levels of atoms and ions dominate and these lines are known as the 'Paschen Series'. Although these peaks have a high intensity, the total energy generated by these wavelengths is small in significance to the continuous part of the spectrum (550–700 nm).

A sharp cut-off point usually around 500–600 nm can be seen on the graph. This is due to either a dichroic coated filter formed on the rear surface of the treatment transmission glass block or a separately located dichroic or coloured glass absorption filter to remove any wavelengths below the chosen cut-off. Shorter wavelengths in the blue and ultraviolet region of the spectrum are heavily absorbed in epidermal melanin, and may burn the patient's skin due to extreme heat built-up in the epidermis or cause other unwanted UV-related cellular changes and are therefore removed. In addition, most flashlamp envelopes (the glass tubes containing the xenon gas) are of cerium or titanium doped quartz and exhibit the property of filtering out the most harmful of these wavelengths in the ultraviolet region that is below 400 nm. A few IPL systems also use filters to cut-off infrared wavelengths as these are absorbed predominantly in tissue water and therefore do not contribute to specific heating of either melanin or haemoglobin. These filters may reduce the need for skin surface cooling during the treatment.

The time-resolved spectral measurements show that in some cases for free discharge systems, despite average pulse durations quoted by the manufacturer, the optical energy is often only concentrated in a narrow time domain of the pulse. This difference between specified pulse duration and biologically effective optical output may explain the relatively high number of unwanted side effects or sub-optimal clinical results observed in clinical practice. For example, in hair reduction treatments, a pulse duration that delivers most of its spectral energy in only a few milliseconds may only heat up the hair shaft and fail to coagulate the entire follicle resulting merely in an extended telogen stage and therefore providing only temporary hair loss.

Free Discharge

Figure 4a–c is the corresponding sequence of time-resolved spectral emission views for the Chromolite, (Chromogenex Ltd) IPL measured with the pulse profile shown in Figure 1a with a total measured pulse duration of 15–17 milliseconds and shows an analogous rising and falling optical output. The total pulse duration is achieved through the long 'tail' of near IR energy but most of the biologically 'useful' energy, however, is concentrated into only approximately three to four milliseconds. No pulse duration was given in the manufacturer's user manual or displayed on the Chromolite (Chromogenex Ltd) system. SkinStation (Radiancy (Israel) Ltd), Ecolite (Greenton London Ltd) and Trinity (Espansione Marketing Spa) were free discharge IPL systems measured, that claimed pulse durations in the user manual or system display much longer than the effective pulses that were actually measured in this study when observing the spectral footprint.

These systems discharge a huge amount of energy within a non-determined, short period of time. As a consequence, it is not possible for the operator to select a pulse duration of light to match the TRT of the biological target and since the effective pulse duration is vastly shorter than expected this may result in excessive energy accumulation by certain skin chromophores leading to adverse skin reactions such as severe erythema or even necrosis of the patient's skin. Also, pulse durations which are significantly shorter than the TRT of the target do not produce the expected clinical result. With too short a pulse duration, the maximal electrical energy through the flashlamp will be larger than expected by the operator and an unwanted high proportion of the total light energy will be delivered as shorter wavelengths. The optical penetration depth will therefore be shallower compared with a system, where the light flux and spectral distribution is constant throughout the entire specified pulse duration. Such systems often incorporate skin surface cooling to compensate for the overheating of the superficial skin layers.

Constant Current

Figure 5a–c is the corresponding sequence of time-resolved spectral emission views for the IPL measured with the pulse profile shown in Figure 2a with a total measured pulse duration of 15 milliseconds and the Square Pulse discharge is reflected in the constant spectral output. Figure 5b,c shows both the atomic peak at 825 nm in the background but the bulk of the energy in the foreground is spread almost evenly across the entire pulse duration (peak at 555 nm). There is preserved spectral distribution of the optical energy throughout the entire pulse duration and only slight attenuation of optical output towards the end of the pulse.

Low but relatively stable electrical energy delivered to the flashlamp across the pulse duration ensures a constant spectrum of light energy to the intended target chromophores and reduces the risk of exceeding the threshold of damage to skin structures. Significantly lower energies can be used to obtain equivalent clinical results compared with free discharge systems with variable spectral output and high fluences or grouped short peaks of light energy, and if combined with appropriate cut-off filters skin cooling is often not needed in constant current profile systems. Absence of any operator-dependant contact skin cooling also reduces the number of variability factors which determines the effective shot-to-shot energy delivered to the skin. These systems therefore have larger 'therapeutic windows' compared to free discharge IPL systems. Similar results and an even distribution of energy with a flexible

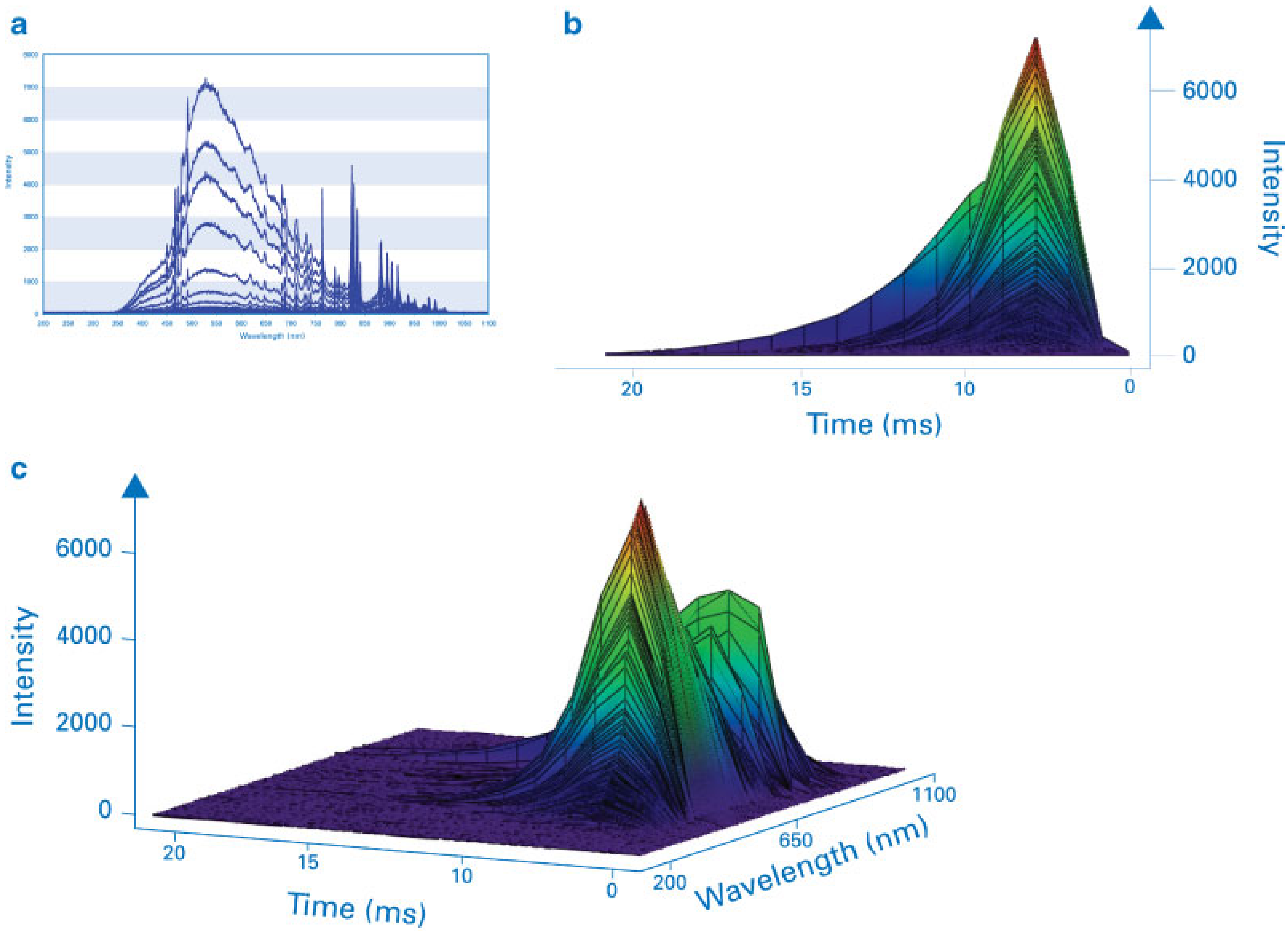

Fig. 4. **a**: Spectral distribution graph of a single pulse, free discharge IPL (Chromolite, Chromogenex Ltd), each trace taken at time intervals of 1 millisecond used to compare with accompanying (**b**,**c**). Time-resolved spectral images with a measured total pulse duration of 17 milliseconds but with the bulk of the useful spectral output concentrated into only a few milliseconds.

range of pulse durations were seen also for the other constant current systems StarLux, (Palomar Medical Technologies) and NovaLight (Ultramed Ltd).

Grouping of Pulses

Figure 6a–c illustrates multi-pulsing spectral outputs from the EllipseFlex (DDD A/S, Hørsholm DK, Denmark) using tight groups of nearly square sub-pulses to produce long almost even total pulse durations. This type of IPL has a single large bore diameter flashlamp requiring significant total electrical energy to create sufficient current density. However, owing to this large bore flashlamp, the impedance changes quickly and if there is insufficient electrical capacity, rapidly depletes the reserved energy from the capacitors as seen by the energy tailing off towards the end of each set of sub-pulses. This causes the distribution of wavelengths to be shifted preferentially to the infrared spectrum toward the end of the set of sub-pulses. Similar measurements and results were produced for EllipseLight (DDD A/S), Harmony (Alma Lasers Ltd) and Plasmalite (Medical Biocare Sweden AB) although the Plasmalite works in a unique analogue mode, it still exhibits significant decay of energy during its discharge.

Figure 7a–c demonstrates multi-pulsing spectral outputs from the Lumina600 (Lynton Lasers Ltd) using groups of short, high energy sub-pulses with long inter-pulse delays to produce long overall pulse durations with an appropriate mean fluence. However, the average optical energy is created by overcompensating with high energy peaks. Such IPLs probably discharge a number of capacitors separately for each sub-pulse, which may explain why the energy of each sub-pulse can be of differing energies and spectral distribution compared to the other sub-pulses.

It can be seen in all cases that by stacking short pulses to create a longer pulse duration does not produce stable consistent optical energy. The last sub-pulse in Figure 6a–c can be clearly seen to be approximately twenty three percent of the first sub-pulse. This exponential decay of the output energy due to capacitor depletion will probably have

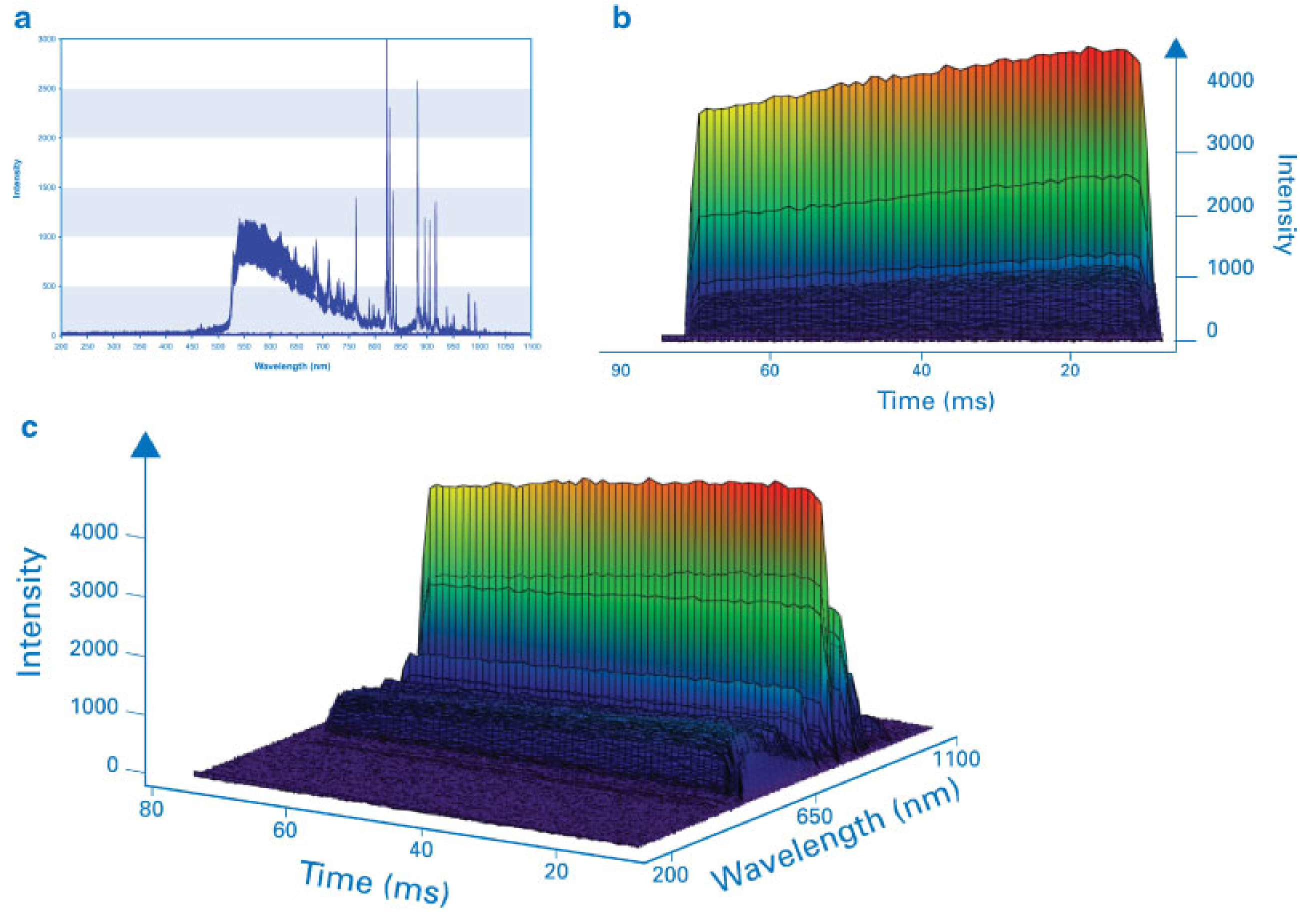

Fig. 5. **a**: Spectral distribution graph of a single pulse, constant current IPL (iPulse, Cyden Ltd) each trace taken at time intervals of 1 millisecond used to compare with accompanying (**b**,**c**). Time-resolved spectral images with a measured total pulse duration of 50 milliseconds providing an almost perfectly constant spectral discharge with the three-dimensional view of the same pulse (c) allowing better visualisation of all the wavelengths across the entire pulse duration.

an effect on clinical efficacy as the useful energy is preferentially confined to the initial part of the pulse duration. However, in IPL systems where the interval between the individual sub-pulses is short, probably the effect will be biologically identical to a single, long pulse, but if the light peaks are short and the intervals longer, a phenomenon resembling 'pulse stacking' will occur, which again may add to clinical treatment variability or side effects. Also, the very high peak power of narrow light peaks—which are required to produce a useful average energy across the entire pulse duration—may induce unexpected photo-acoustic effects in the tissue, leading to tissue disruption and purpura. Similar measurements and results were produced for Quantum/Aculight (Lumenis Inc), Freedom IPL (Freedom Beauty Ltd), ULTRA (Energist Ltd) and BBL (Sciton Inc).

CONCLUSION

The measuring and presentation of comparative 'spectral footprints' using time-resolved optical spectroscopy is still in its infancy and further debate can be expected in the interpretation of such data in terms of clinical outcomes. However, this first study of time-resolved spectral footprints of a series of IPLs presently in normal clinical use in the UK does allow the authors to draw some early conclusions:

This study provides a method to determine accurately, key parameters of the emitted light pulses from IPLs. This article demonstrates the direct correlation between the electrical discharge current profile to the flashlamp and the output optical energy profile at the point of contact with the skin.

The difference in the produced pulse durations of free discharge IPL systems and modern square pulse systems show that the latter have a flexible range of pulse durations, whereas free discharge system have a fixed pulse duration, which is that of the time for the capacitor to be depleted of energy. The differences measured between first generation free discharge systems and modern square pulse systems

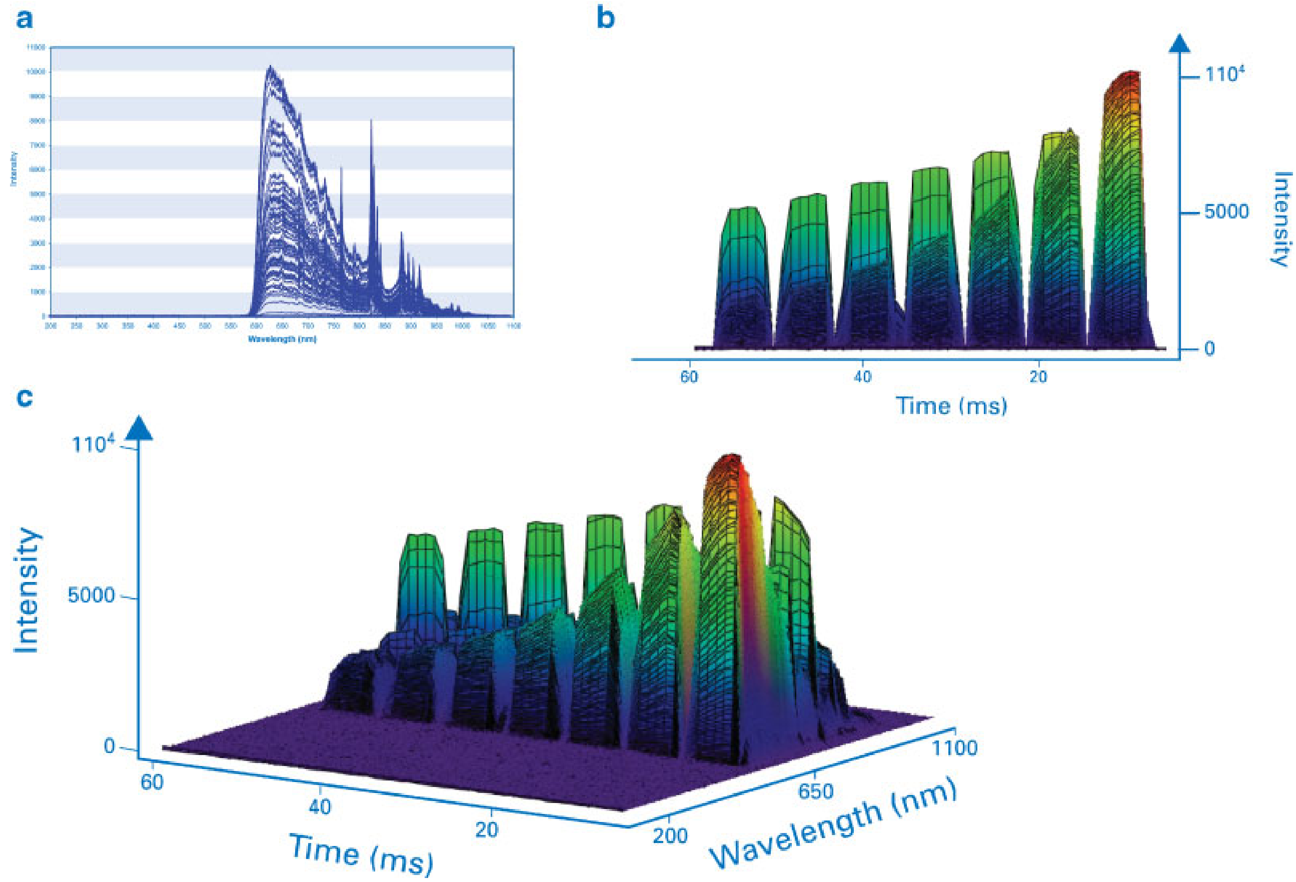

Fig. 6. **a**: Spectral distribution graph of a multi-pulsing, free discharge IPL (Ellipse, DDD, Denmark), each trace taken at time intervals of 1 millisecond used to compare with accompanying (**b**,**c**) using groups of nearly square sub-pulses to produce long almost even spectral outputs over the entire train of sub-pulses (b). Owing to the large bore diameter of such flashlamps, the impedance changes quickly and depletes the reserved energy from the capacitors resulting in the energy tailing off towards the end of each set of sub-pulses (c).

may have important clinical consequences in terms of different light-tissue interactions and hence clinical efficacy and patient safety.

Time-resolved optical spectroscopy is a valuable tool to assess the performance characteristics of commercially available IPL systems and for the construction of improved IPL systems for future clinical treatments. Optical spectral footprints provide valuable information regarding IPL systems' performance, clinical efficiency and patient safety. We suggest, that IPL manufacturers should provide time-resolved spectroscopy graphs to users.

These measurements could be helpful in determining whether there is a potential impact on efficacy of absorption of light by the primary skin chromophore targets of interest.

APPENDIX

How a Flashlamp Works

When a flashlamp is designed, the gas fill type and pressure can be varied to suit the specific application for which the flashlamp is to be used. The spectral output of a flashlamp is chiefly determined by the current density that is the amount of current flowing per unit of cross sectional area of the lamp. Current density through a flashlamp is given by the expression:

$$J = \frac{4I}{\pi d^2} \tag{A}$$

where $d =$ the bore diameter, $I =$ the current through the flashlamp. J is expressed in A cm^{-2}

Current density is therefore proportional to the inverse square of the internal bore diameter of the flashlamp. Thus, a flashlamp of 8 mm diameter requires four times as much current as a 4 mm diameter flashlamp to deliver the same energy density. Hence a system, which uses narrow flashlamps uses far less energy than its large diameter counterparts.

An expression which does not take into account the time dependence of current change is called the E_0:TA ratio. This is used to describe the loading rather than current density of a pulsed lamp and does not include a term for time

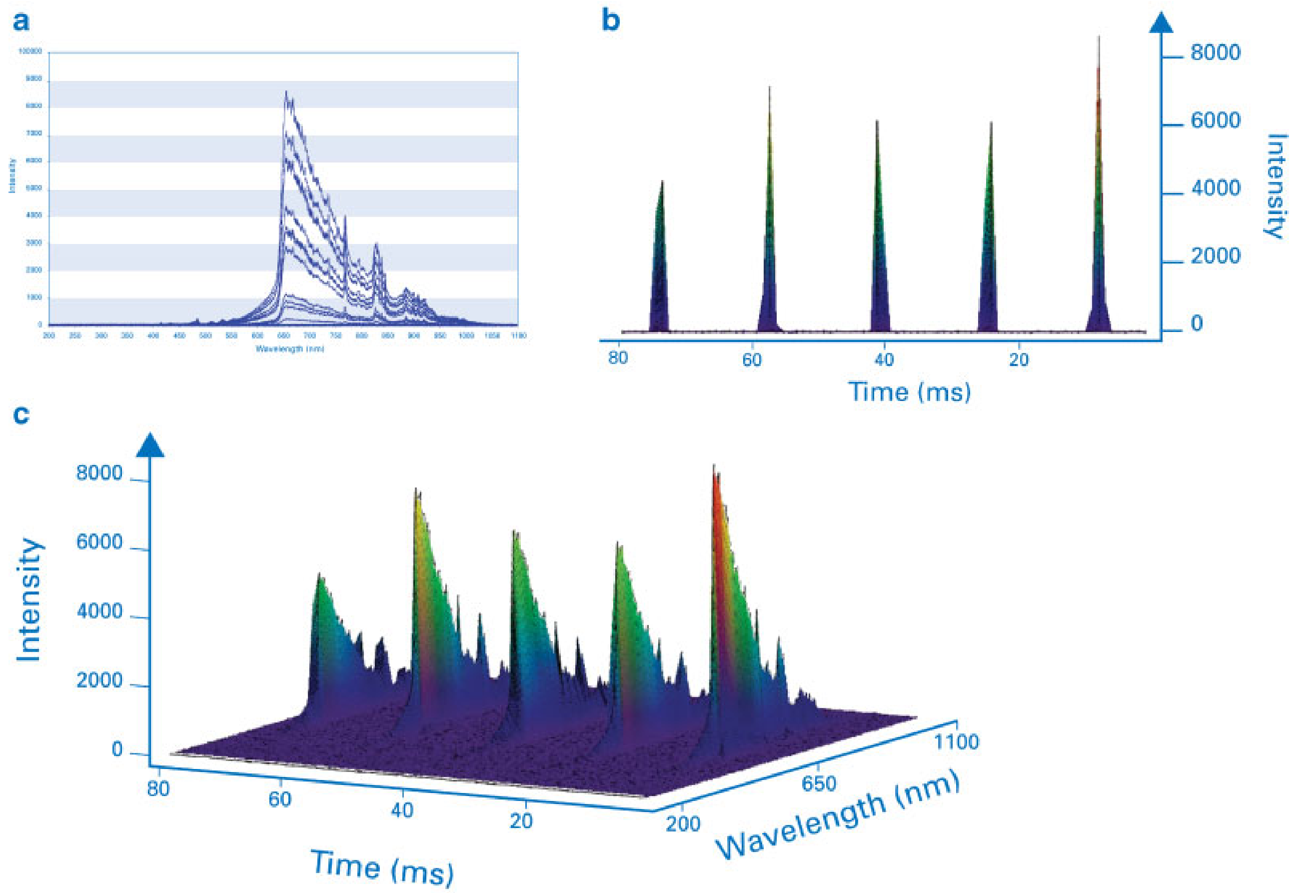

Fig. 7. **a**: Spectral distribution graph of a multi-pulsing, free discharge IPL (Lumina600, Lynton Lasers Ltd) each trace taken at time intervals of 1 millisecond used to compare with accompanying (**b**,**c**). IPL generates groups of widely spaced short sub-pulses of high energy (b). These groups of sub-pulses produce long total pulse durations but with considerable spectral output shifts within the pulse train (c).

dependence with respect to the current. The unit of measurement of this ratio is Watts per square centimetre ($\mathrm{W\,cm^{-2}}$) and so it is a measure of power density rather than current density. E_0 is the pulse energy in Joules supplied to the flashlamp and T is the pulse duration in seconds. The area (A) in this ratio refers to the internal surface area of the lamp envelope in the discharge region. The area is approximately πdL_A where L_A is the arc length of the lamp and not the cross sectional area of the lamp bore, which is the area used in measuring current density.

The conversion of energy efficiency will increase with gas fill pressure in the xenon lamp up to a saturation point, but the disadvantage is that the lamp requires a higher trigger voltage and if a simmer current is used it will be more difficult to create and sustain. Default fill pressures in pulsed flashlamps are approx. Four hundred and fifty Torr in xenon lamps and approx. 700 Torr in krypton lamps.

The internal impedance of a flashlamp changes over the duration of the plasma discharge. This is a direct result of the almost instantaneous heating of the gas plasma within the flashlamp bore. When a flashlamp has no potential difference across the tube it is non-ionised and thus has very high impedance, around 10^7 ohm or more, and thus initially, the entire power supply unit current flows into capacitor C, illustrated in Figure 8. If the voltage across the capacitor reaches a value equal to the breakdown voltage of the flashlamp, ionisation of the lamp gas starts to occur and so its impedance begins to decrease. A low impedance path quickly forms directly between the electrodes of the

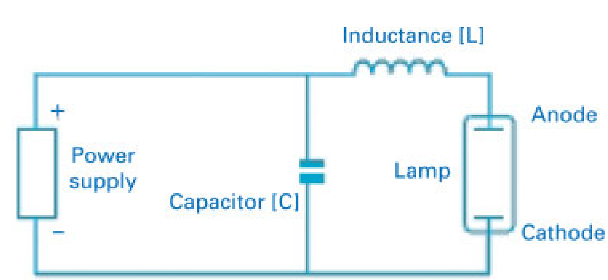

Fig. 8. Typical circuit diagram for a flashlamp power supply.

flashlamp as more gas atoms are ionised. Current now starts to flow from the capacitor into the flashlamp and the impedance of the lamp continues to fall, dropping down to about 1 ohm or less. If sufficient energy is available, the plasma of ionised gas in the lamp completely fills the internal bore. Eventually all the energy stored in the capacitor is expended and the lamp returns to a deionised state. Conduction through the lamp ceases and the power supply unit begins to recharge the capacitor and thus the process continues.

Assuming the plasma growth is instantaneous and completely fills the entire envelope in contact with the inner walls, the impedance is described by having the following relationship with time:

$$K_0(t) = |V(t)[I(t)]^{-1/2}| \quad \text{(B)}$$

(where $V(t)$ = voltage across the lamp at time t, in volts, $I(t)$ = current through the lamp at time t, in amps, $K_0(t)$ = arc impedance parameter at time t, in $\Omega A^{1/2}$ and $K_0(t)$ = is a function of the time dependant size of the arc and the nature and fill pressure of the gas in the lamp).

$$K_0(t) = \left[\frac{1.28 L_A}{d_A(t)}\right] \times \left[\frac{P}{N}\right]^{-1/5} \quad \text{(C)}$$

(where L_A = arc length, in mm, $d_A(t)$ = arc diameter at time t, in mm, P = gas fill pressure in the lamp, in Torr and N = a constant dependant on gas type [xenon = 450]).

A good approximation can be reached without dealing with the time dependant Equations (B) and (C) above, by assuming that the diameter of the arc is always equal to the diameter of the bore of the flashlamp d and by assuming $d_A(t)$ is not time dependant. In general the time taken to reach wall-confined stabilization is less then one hundredth of the pulse duration:

$$K_0 = 1.28\left[\frac{L_A}{d_A}\right] \times \left[\frac{P}{N}\right]^{-1/5} \quad \text{(D)}$$

K_0 can now be referred to as the impedance constant of the flashlamp. This is constant as it depends only upon the flashlamp's physical dimensions and the type and pressure of gas fill. K_0 is a critical parameter in describing a pulsed flashlamp. In systems using constant current power supplies, designers are primarily concerned with the K_0 of the flashlamp as this determines the flashlamp's power output and hence the power of the flashlamp itself.

The approximation for K_0 based on bore diameter, arc length, gas type and cold fill pressure Equation (C) still remains for lamps used under constant current operation. In considering a constant current in terms of both lamp current and lamp voltage, and where the discharge is fully wall-confined, reference to the timing within the pulse is no longer relevant, as it is the same at all stages during the wall stabilised pulse. This simplifies some of the theory, and the relationship between voltage, current, and K_0 previously described can now be expressed as:

$$V = K_0 I^{1/2} \quad \text{(E)}$$

$$\text{PulsePower} = K_0 I^{3/2} \quad \text{(F)}$$

$$I = \left[\frac{E_0}{K_0 T}\right]^{2/3} \quad \text{(G)}$$

(T = Pulse width in seconds).

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