Light-Emitting Diode Phototherapy in Dermatological Practice

R. Glen Calderhead

Introduction

- Phototherapy is not new! It was being used more than 4,000 years ago
- Light-emitting diodes have attracted interest as a phototherapeutic source
- LEDs are solid state and robust
- LEDs are comparatively inexpensive

History of Phototherapy

Phototherapy in its broadest sense means any kind of treatment (from the Greek *therapeia* 'curing, healing,' from *therapeuein* 'to cure, treat.') with any kind of light (from the Greek *phos, photos* 'light'). The modern accepted definition of phototherapy, however, has become accepted as: "the use of low incident levels of light energy to achieve an athermal and atraumatic, but clinically useful, effect in tissue". Under its basic original definition, phototherapy is an ancient art because the oldest light source in the world is the sun, and therapy with sunlight, or heliotherapy, has been in use for over 4,000 years with the earliest recorded use being by the Ancient Egyptians.[1] They would treat what was probably vitiligo by rubbing the affected area with a crushed herb similar to parsley, then expose the treated area to sunlight. The photosensitizing properties of the parsley caused an intense photoreaction in the skin leading to a very nasty sunburn, which in turn hopefully led to the appearance of postinflammatory secondary hyperpigmentation, or 'suntan' thereby repigmenting the depigmented area. In their turn the Ancient Greeks and Romans used the healing power of the sun, and it was still being actively used in Europe in the eighteenth, nineteenth and early twentieth century, particularly red light therapy carried out with the patient placed in a room with red-tinted windows. One famous patient was King George III of Great Britain and Northern Ireland who ruled from 1760 to 1801, popularly though erroneously known as 'Mad King George'. We now strongly suspect that he was actually suffering from the blood disease porphyria, so being shut in a room with red-draped walls and red tinted windows to treat his depression probably only served to make him even more mad, since porphyria is often associated with severe photosensitivity! Entities treated this way included the eruptive skin lesions of rubella and rubeola, and even 'melancholia', as was the case with King George III, now recognised as clinical depression. Hippocrates, the Father of Medicine, certainly concurred with the latter application some two millennia before King George: Hippocrates prescribed sunlight for depressive patients and believed that the Greeks were more naturally cheerier than their northern neighbors because of the greater exposure to the sun.

In the field of wavelength-specific phototherapy research, red light therapy was examined at a cellular level under the newly-invented microscope by Fubini and colleagues in the late eighteenth century,[2] who were able to show that visible red light, provided *via* lenses and filters from sunlight, selectively activated the respiratory component of cellular mitochondria. There is nothing new under the sun. However, the sun is a fickle medical tool, particularly in northern Europe, and modern phototherapy as we know it started around the turn of the last century with Finsen's electric arc lamp-based system, giving phototherapy at the turn of a switch, independent of the sun.[3] However, apart from the use of blue light therapy for neonatal bilirubinemia which continues to the present day, phototherapy was, in the majority of its applications, overtaken in the first part of the twentieth century by better medication or improved treatment techniques.

The development of the first laser systems, a race which was narrowly won by Theodore Maiman in 1960 with his flashlamp-pumped ruby-based laser, next gave clinicians and researchers a completely different and unique light source to play with. In the 4 years between 1960 and 1964, the ruby laser

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was followed by the argon, helium-neon (HeNe), neodymium: yttrium-aluminum-garnet (Nd:YAG) and carbon dioxide (CO_2) lasers all of which have remained as workhorses in the medical field, and the HeNe laser (632.8 nm) has in fact provided a large bulk of the phototherapy literature over the last three decades. As for light-emitting diodes (LEDs), the first light from a semiconductor was produced in 1907 by the British experimenter H. J. Round. Independently in the mid 1920s, noncoherent infrared light was produced from a semiconductor (diode) by O-V Losev in Russia. These studies were published in Russia, Germany and the UK, but their work was completely ignored in the USA.[4] It was not till 1962 that the first practical and commercially-available visible-spectrum (633 nm, red) LED was developed in the USA by Holonyak, regarded as the 'Father of the LED' while working with the General Electric Company. In the next few years, LEDs delivering other visible wavelengths were produced, with powers ten times or more that of Holonyak's original LED. For reasons which will be discussed later, these LEDs were really inappropriate as therapeutic sources, although they were extremely bright and very cheap compared with laser diodes, and it was not till the late 1990s that a new generation of extremely powerful, quasimonochromatic LEDs was developed by Whelan and colleagues as a spin-off from the National Aeronautic and Space Administration (NASA) Space Medicine Program.[5] Unlike their cheap and cheerful predecessors, the so-called 'NASA LEDs' finally offered clinicians and researchers a new and truly practical therapeutic tool.[6]

The What and Why of LEDs

What Is an LED?

Light-emitting diodes belong to the solid state device family known as semiconductors. These are devices which fall somewhere between an electrical conductor and an insulator, although when no electrical current is applied to a semiconductor, it has almost the same properties as an insulator. Simply explained, light-emitting semiconductors or diodes consist of negative (N-type) and positive (P-type) materials, which are 'doped' with specific impurities to produce the desired wavelength. The n-area contains electrons in their ground or resting state, and the p-area contains positively charged 'holes', both of which remain more or less stationary (Fig. 1a–c). When a direct current electric potential with the correct polarity is applied to an LED, the electrons in the N-area are boosted to a higher energy state, and they and the holes in the P-area start to move towards each other (Fig. 1d), meeting at the N/P junction where the negatively-charged electrons are attracted into the positively-charged holes. The electrons then return to their resting energy state and, in doing so, emit their stored energy in the form of a photon, a particle of light energy (Fig. 1e). The wavelength emitted is noncoherent, ideally very narrow-band, and depends on both the materials from which the LED is constructed, the substrates, and the p-n junction gap. Table 1 shows a list of the main substrates and associated colors. Figure 2 shows the anatomy of a typical dome-type LED. These can be mounted on circuit boards at regular and precise distances from each other to provide an LED array, part of which is shown in Fig. 3. However, the latest generation of LEDs actually form part of the board (so-called 'on-board' chips) which are much more compact than the dome-type LED and more efficient.

What Is the Difference Between LEDs and Lasers or IPLs?

The laser is a unique form of light energy, possessing the three qualities of monochromaticity, collimation and phase which make up the overall property of 'coherence'. Monochromaticity means all the photons are of exactly the same wavelength or color; collimation means the built-in parallel quality of the beam superimposed by the conditions of the laser resonator; and phase means that all of the photons march along together exactly equidistant from each other in time and in space. Laser diodes do not have inherent collimation, but because they are still true lasers, and therefore a so-called point source, the light can be gathered and optically collimated: the humble but ubiquitous laser pointer works on this principle. Intense pulsed light is, on the other hand, totally noncoherent, with a very large range of polychromatic (multicolored) light from near infrared all the way down to blue; has no possibility of collimation with extreme divergence; and has its vast variety of photons totally out of phase. The new generation of LEDs, on the other hand, has an output plus or minus a few nanometers of the rated wavelength, and so are classed as quasimonochromatic; some form of optical collimation can be imposed on the photons which are divergent but do have some directionality; but they are not in phase. Laser energy can easily produce high photon intensity per unit area, IPLs much less so, but provided LEDs are correctly arrayed, they are capable of almost laser-like incident intensities. Figure 4 schematically illustrates the differences between lasers, IPLs and LEDs. In short, LEDs for therapeutic applications must be quasimonochromatic, be capable of targeting wavelength-specific cells or materials, have stable output, and be able to deliver clinically useful photon intensities.

Why Use LEDs?

There are many excellent laser and intense pulsed light (IPL) systems available to the dermatologist. Why should LEDs be

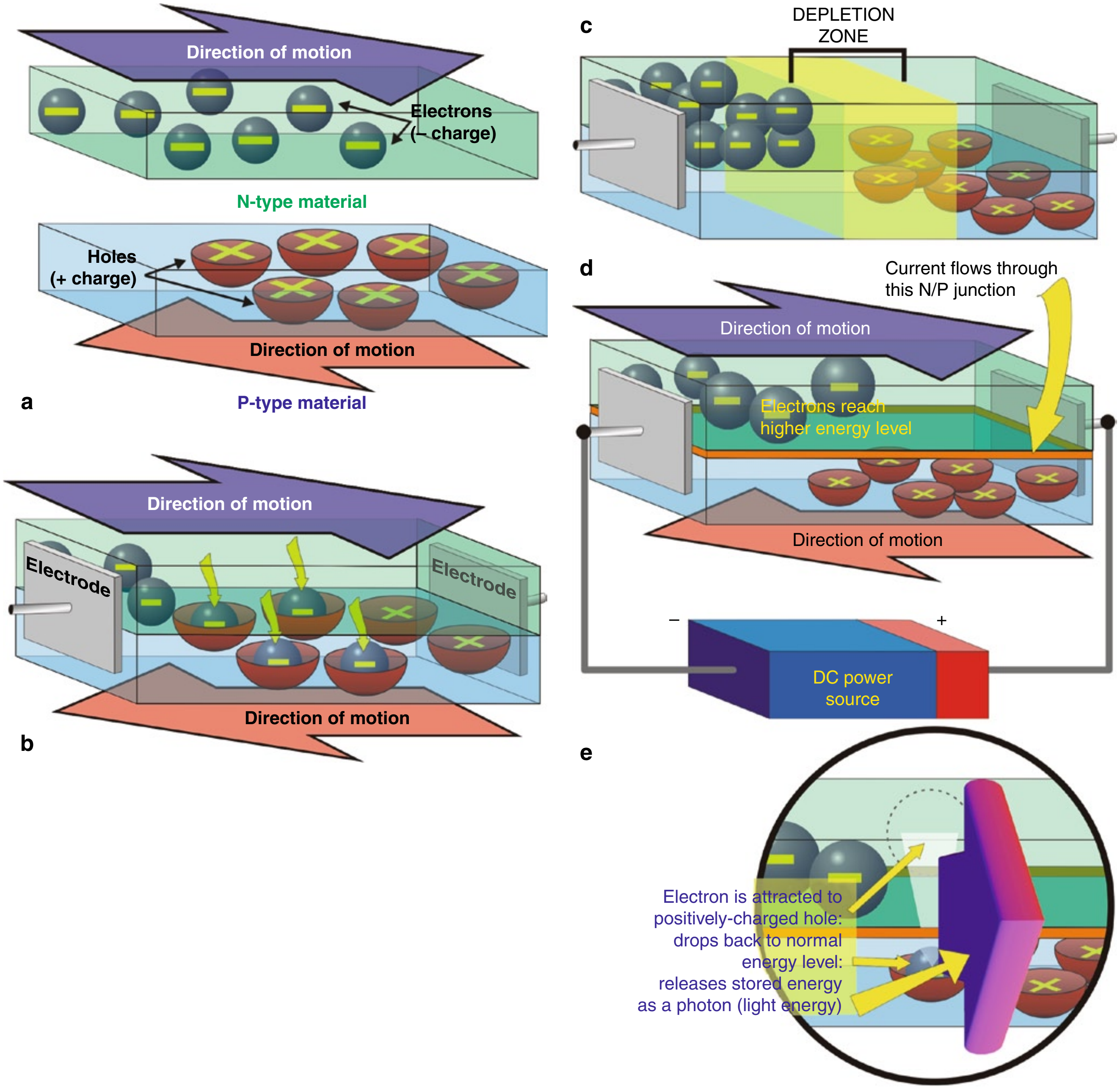

Fig. 1 What is an LED and how can it produce light? (**a**) An LED is basically composed of two materials, the N-type or negative material and the P-type or positive material. The N-material contains negatively charged electrons which move as shown, and the P-material contains positively charged holes, which move in the opposite direction. When the materials are apart and not connected to any power source, movement continues, so both materials are conductors. (**b**) When the materials are sandwiched together, however, without any power applied to the electrodes attached to opposite ends, the negatively charged electrons in the center of the chip are attracted to the holes, and form an area called the depletion layer as seen in (**c**) and all movement ceases in both the N- and P-materials: the chip is now an insulator. (**d**) Power is applied to the electrodes, with the positive electrode or anode at the origin of movement of the holes and the negative electrode or cathode at the origin of movement of the electrons. Observing the polarity when connecting a direct current (DC) power source is extremely important. Power flows through the junction between the materials, called the N/P junction, and movement of both electrons and holes starts again, but with power applied the electrons move to a higher energy level from their ground or resting state. (**e**) As in 1b above, the N-electrons are attracted to the P-holes, but in moving down through the N/P junction they must return to their ground energy level, and lose their extra stored energy in the form of a photon, the smallest packet of light energy. Unlike the situation in 1b, however, when power is applied this action continues endlessly and no depletion layer is formed. The N- and P-materials are 'doped' with other materials which determine the distance of the 'fall' between electrons and holes: the greater the distance the electrons have to fall, the higher is the energy level of the photons emitted. Photons with high energy levels have shorter wavelengths than those with lower energy levels, thus the wavelengths of the emitted light are determined by the materials and their doping. High quality N- and P-materials and pure doping substances will give photons of very nearly the same wavelength, i.e., quasimonochromatic light

Table 1 Most common substrate combinations and the colors they are capable of producing

Substrates	Formula	Colors produced
Aluminum gallium arsenide	(AlGaAs)	Red, infrared
Aluminum gallium phosphide	(AlGaP)	Green
Aluminum gallium indium phosphide	(AlGaInP)	Green, yellow, orange, orange-red(all high-intensity)
Gallium arsenide phosphide	(GaAsP)	Yellow, orange, orange-red, red
Gallium phosphide	(GaP)	Green, yellow, red
Gallium nitride	(GaN)	Blue, green, pure green (emerald green): also white (if it has an AlGaN Quantum Barrier, so-called 'white light' LED)
Indium gallium nitride	(InGaN)	Near ultraviolet, blue, bluish-green

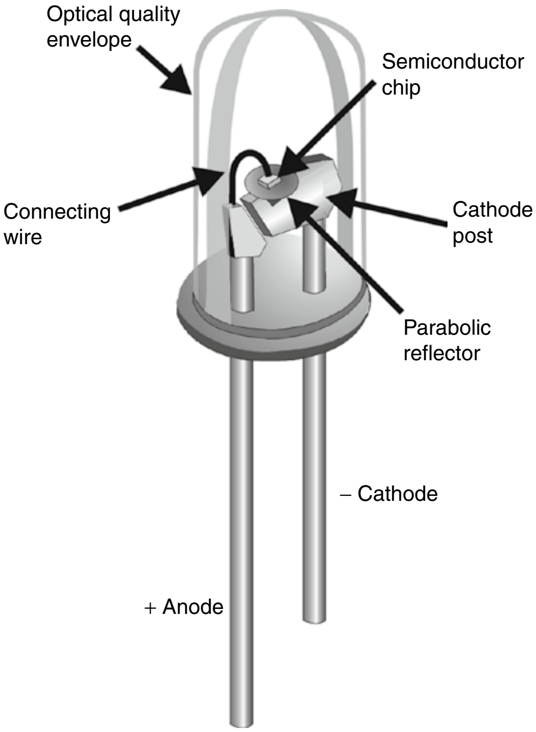

Fig. 2 Anatomy of a typical high-quality dome-type LED. The cathode is always shorter than the anode and there is a flat surface in the base of the LED by the cathode so polarity is clearly determined when connecting to a DC power source. On top of the cathode post and forming part of the negative electrode of the LED chip is a parabolic reflector in which the chip itself is mounted thus ensuring as much light as possible is directed forwards, with a consistent angle of divergence, typically 60° steradian or less depending on the specifications of the LED. A fine wire connects the positive electrode of the chip to the anode post, thus completing the circuit. The entire assembly is encapsulated in an optical quality clear plastic envelope, giving the final assembly its robust nature

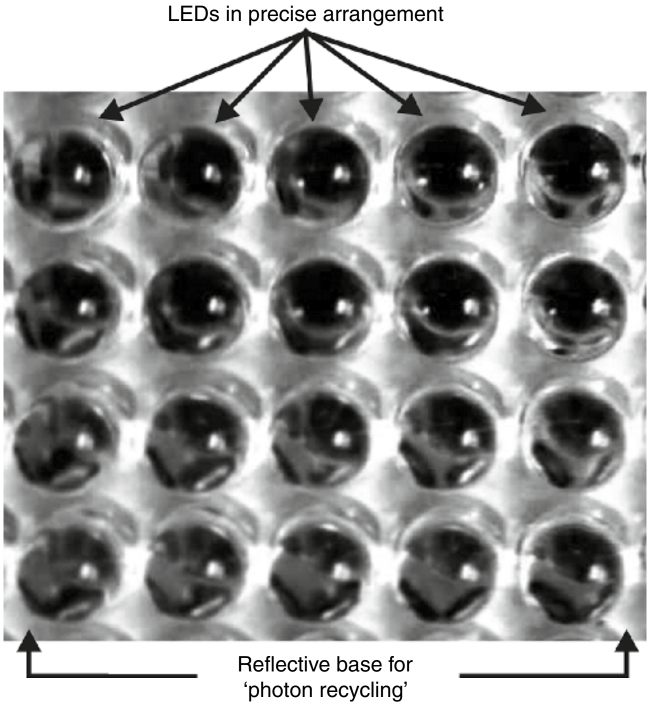

Fig. 3 Close-up view of dome-type LEDs mounted in an actual array from a therapeutic system. Note the precise x-y spacing of the LEDs, (*cf* Fig. 6 and associated text), and the reflective backing into which they are mounted. When light is incident on living skin, a certain amount will be reflected from the outer layer of skin, the stratum corneum. The longer the wavelength, the greater this reflection will be. In addition, some light is always back-scattered out of skin. The purpose of the reflective backing of the array is to capture these photons and reflect them back into the skin, known as 'photon recycling'

considered as a viable alternative phototherapy source? The main reasons are efficiency and price. The electricity-light conversion ratio of a typical laser is very low, requiring 100 or even 1,000 of watts in to give an output of a few watts. The same applies to IPL systems, where the flashlamp has to be pumped with enormous amounts of energy to provide polychromatic light, which may however be filtered (cut-on or cut-off). Even when filtered, IPL energy is delivered over a waveband rather than at a specific wavelength. In the case of LEDs, which are quasimonochromatic and require no filtering, the conversion efficiency is very high so that very few watts at a low voltage are required to produce a clinically useful output. LEDs are much less expensive than even laser diodes. Depending on quality and wavelength, anywhere from 300 new-generation LEDs can be purchased for the cost of a single laser diode. The cost of laser and IPL systems

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