Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL27542

Organic Light-Emitting Diodes Applications in Biomedical Therapy Mechanisms Clinical Studies and Challenges

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Abstract. This paper mainly discusses the use of Organic Light-Emitting Diodes (OLEDs) in photodynamic therapy (PDT) and photobiomodulation (PBM) for curing typical basal cell carcinoma, Bowen disease, actinic keratosis. The innovative PDT method has several advantages than the traditional ones—OLEDs plays an essential role in reducing the pain for patients according to case studies and patients can barely experience uncomfortable feelings during the therapeutic process than before. It is also much more light-weighted and can be more closely attached to skin. Therefore, this device can also be applied to the elderly and infants at any location and at any time without going to the hospital. However, there are still some remaining issues such as the chronic pain, which is hard to be eliminated due to the conflict situation since reactive oxygen species (ROS) will cause major pain, however, if completely removing ROS will decrease the effect of PDT. Therefore, more researches need to be done in this field.

Keywords: OLEDs, PDT, skin diseases

1. Introduction

The initial purpose of OLEDs is to utilize as display screens, and with recent innovations, OLEDs can now be use in many other aspects including the biomedical field, which includes the therapeutic treatment. Wearable OLEDs can be used as a light source for ensuring the outpatient care especially for people who are currently not available to go to hospital frequently. There are two main applications of OLEDs: PDT (photodynamic therapy) and PBM (photobiomodulation). PDT is one way to kill bacteria and cure cancer and has now been used in many aspects, e.g., in oncology, dermatology, ophthalmology, and dentistry [1]. It needs light at certain wavelength to send energy to a photosensitizer. Photosensitizer is kind of compound that can absorb energy within certain wavelengths in the ultraviolet region (25-420nm) or visible light region (400-800nm). After the excitation of photosensitizer, there will be interactions between oxygen molecules in the tissue, raising oxygen from the triplet ground state to the singlet state. In this case, the new created singlet oxygen molecules will be able to send radical attacks to kill the nearby bacteria [2]. The key principle of this transition is OLED, which help to develop new photosensitizers based on phosphorescent and TADF emitters. To have a better penetration through skin, red light is an optimal choice since there is high reliance on high power light sources to deliver the light to certain areas to achieve the target. One of the ramifications of OLED is NIR, which plays an essential role in the

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biological applications, due to the NIR has little overlap of the cell's own autofluorescence (AFL). OLEDs are thin, light-weighted, and flexible solid-state devices that can be fabricated on large-area, conformable materials. This intrinsic flexibility allows them to conform to the curvilinear surfaces of human skin or organs, ensuring unparalleled uniformity of light emission across the entire treatment area.

2. The advantages of OLED's application in medical treatment

OLEDs convert electrical energy into light energy through electroluminescence. OLEDs are flexible, lightweight and can be easily conformed to skin. These basic features make it outstanding to be an optimal choice for minimally invasive surgery. OELDs can be fabricated on flexible substrates (e.g., plastic films), which makes it possible to be integrated onto adhesive clothing or patches [3]. The whole working process is also explicit and efficient. The electrons are injected from the anode indium tin oxide and the cathode low work function metal respectively. After that, they recombine in the emissive layer to form excitons. The stack-like structure of anode, hole transport layer, emissive layer, electron transport layer, and cathode works on an energy-balanced carrier. Organic photodiodes (OPDs) are based on the reverse process. The photoactive layer absorbs photons to generate excitons. Although OLED's function and OPD's function work in an opposite way, they share the same exciton behavior control mechanism - OLEDs need to achieve an efficient radiative recombination of excitons, while OPDs need to maximize exciton dissociation efficiency. The integration of these technologies promotes the development of integrated display and sensing systems and photoelectric coupling systems. Compared with other conventional treatments, PDT combining OLEDs and OPDs has numerous advantages, such as fewer side-effects and enhanced cosmetic and clinical outcomes. It is typically used for treatments of basal cell carcinoma, Bowen disease, actinic keratosis.

3. An application of OLED in a clinical study

In a clinical study, Attili et al. used a wearable red OLED delivering 0.05 mW cm $^{-2}$ at a peak wavelength of 620 nm to treat nonmelanoma skin cancer. In his study, patients contended lesser pain when the OLED was used, compared to a control group that was treated with an inorganic LED delivering a similar dose but at a higher fluence of 0.75 mW cm $^{-2}$ [4]. Therefore, OLED is the key solution to alter the PDT treatment into a much more comfortable and convenient way for patients.

Due to the new technology is targeted to the elderly and the infants, therefore it is extremely important to minimize the pain, which is a key obstacle in PDT treatment. Combining The traditional PDT (photodynamic therapy) has one of its major flaws—the pain is sometimes significant to patients. That is mainly the consequence of its use in dermatology. Patients who take the conventional PDT described it as an extreme burning sense and is almost intolerant. Therefore, pain has been proved to be positively associated with the fluence rate and also been adduced by PpIx. And with innovations to reduce fluence rate is helpful to eliminate the painful feelings. When the fluence rate is < 60 mW cm $^{-2}$, the pain score is consistently and significantly lower than with rates > 60 mW cm $^{-2}$. Besides, pain intensity displays a direct proportion growth with fluence rates < 60 mW cm $^{-2}$. Relatively, no significant correlation is observed when the fluence rate is > 60 mW cm $^{-2}$. Figure1 represents a positive-related curve between PDT efficacy and fluence rate at fixed irradiation duration, and accurately depicts when the influence rate is larger than 60 mWcm $^{-2}$, the curve is gradually switching into a horizontal line which has no significant change [5].

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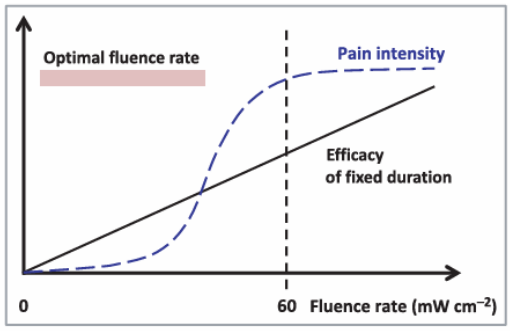

Figure 1. The relationship between optimal fluence rate and pain intensity [5]

The newly-developed equipment consists of a low-irradiance, skin-fitting and light weight OLEDs, and emits light source for approximately 2 cm. Twelve patients with Bowen's disease were recruited into this treatment utilizing the PDT method combining the OLEDs. Two treatments (45–60 J cm^{-2} red light, 550–750 nm, peak 620 nm, irradiance 5 mW^{-2}) were administered 1 month apart following application of aminolaevulinic acid for 4 h. Results At the 12-month follow-up, seven of the 12 patients remained clear, with four of the non-responders exhibit margin failure. Patients were asked to rate their pain instantly after the treatment using the numerical rating scale (NRS)from 1-10. All 12 patients who take the treatment scored pain as < 2 using the NRS (median score 1).

4. Challenges

While OLEDs-based PDT has shown significant advantages in improving patient comfort and therapeutic efficacy for conditions like nonmelanoma skin cancer, its clinical application still faces notable challenges, with pain management remaining a core issue that requires in-depth analysis of contributing factors.

External factors that can cause pain, for example, battery is an external factor which can cause additional pain. According to studies, products consist of PpIX, ROS might trigger pain in PDT [6]. However, a plight is encountered when this situation is being balanced. It is not an ideal solution to remove the ROS although it release cytotoxicity and trigger pain. Since eliminating ROS would decrease the therapeutic effect of PDT, more researches need to be done in this field [7].

Internal factor that can cause pain, the characteristic features of skin lesions are significant contributors to pain variation during PDT. These factors primarily include the lesion's location, size, and type. PDT performed on the face and scalp generates greater pain than at other anatomical sites, a correlation likely explained by the highest sensory nerve innervation density in these areas. Furthermore, larger lesions are associated with increased pain. Among different conditions, psoriatic lesions tend to be the most painful, surpassing AK, BD, SCC, and acne. This is presumably due to their elevated metabolic rate and heightened local production of reactive oxygen species (ROS), which intensifies nerve stimulation [8].

5. Conclusion

PDT is an efficient method to treat specific kinds of skin diseases and due to nowadays technology, it takes much shorter time to treat patients and time to recover. During this process, OLEDs play an important role in the overall PDT process and present an innovative movement. By moving away from conventional rigid and bulky light sources towards a future of personalized, wearable

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medicine. Their fundamental mechanism of action—converting electrical energy into specific wavelengths of light with high efficiency—enables the precise activation of photosensitizers in PDT and the delivery of therapeutic photons for wound healing and neural stimulation. Since OLEDs take credits in significantly reducing the pain, the whole treatment is currently more comfortable. Future research on OLEDs in biomedical therapy will focus on addressing current limitations to enhance practicality and therapeutic efficacy. Efforts will prioritize optimizing wearable OLED device design —such as developing high-efficiency, low-power architectures to extend battery life and scaling device size while ensuring uniform light distribution—to better treat larger skin lesions. For the ROS-related pain dilemma, precision modulation strategies will be explored to balance cytotoxicity and pain reduction. Integrating real-time biosensors with OLEDs to enable dynamic adjustment of light parameters for personalized pain management is another key direction. These include overcoming material stability issues related to moisture and oxygen degradation, enhancing light output efficiency and penetration depth, especially for treating deeper tissues Additionally, expanding applications beyond nonmelanoma skin cancer using NIR OLEDs and unraveling anesthesia resistance mechanisms in PDT will further enhance OLEDs' potential in transforming PDT into a more comfortable, accessible therapeutic option.

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