Photodynamic therapy in dermatology: past, present, and future

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1 Introduction

In the past decades, photodynamic therapy (PDT) has gained wide popularity in medicine and in dermatology in particular. Since its introduction, the procedure has evolved in terms of increasing safety and efficacy. Today PDT is used worldwide not only in the field of dermatology but also for adjuvant treatment in lung, brain, esophageal, biliary and urinary tract cancer. In dermatology, this method is mainly used as a primary treatment for malignant and premalignant skin lesions, while many other nononcological applications have emerged due to the efforts of different study groups.

1.1 Principle of PDT

PDT is based on the photodynamic reaction: use of a light-sensitive substance (a photosensitizer), combined with light of a visible wavelength, to destroy target cells. This toxic biochemical reaction is oxygen-mediated. The photosensitizer absorbs a photon of visible light and then transfers most of the absorbed energy to a molecule of oxygen (Fig. 1). This converts it into a photon of visible light and then transfers most of the absorbed energy to a molecule of oxygen. As a consequence, the tissues that have accumulated the sensitizer, light-induced singlet oxygen exerts a cytotoxic effect by causing lethal oxidative damage to biologically important structures.

The selection of a proper photosensitizer has posed the greatest challenge in the years of PDT development. A substance that is naturally occurring offers a sufficient balance between selective tissue accumulation and relatively short clearance of the body, namely the protoporphyrin IX (PpIX). PpIX is a natural photosensitizer that can be made by the human body and is an intermediate product in the biosynthesis of heme (Fig. 2). It accumulates in rapidly proliferating cells of premalignant and malignant lesions, as well as in other structures, such as blood vessels, melanin, and sebaceous glands. In addition, malignant cells exert reduced ferrochelatase activity, resulting in excessive accumulation of intracellular PpIX.2

In PDT, aminolevulinic acid (ALA) or its methylated derivative—methyl-aminolevulinate (MAL)—is applied to the skin for varying periods of time, thus bypassing the rate-limiting step in the biosynthesis of heme. This leads to the conversion of ALA/MAL to PpIX. The activation of the sensitizer is accomplished by light with a specific wavelength that corresponds to the maximum absorption spectra of the sensitizer. In an ideal situation, the consecutive tissue damage is selective and only the rapidly proliferating tissue with accumulated PpIX will be destroyed with any surrounding tissue damage.

2 Historical Perspective

It was 1900 when Raab first reported the destruction of the Paramecium caudatum cells by exposure to combined acridine orange and light.1 In contrast, neither the dye nor the light separately induced the cellular death. In the next decade, the extensive work of von Tappeiner contributed to the development of the concept of PDT. He first studied the photodynamic effect in protozoa by applying aniline dyes and fluorescent light.4 One year later he described the first cases of PDT in humans by using eosin as a photosensitizer to treat a number of conditions such as condylomata lata, lupus vulgaris, and nonmelanoma skin cancer (NMSC).5 In the later years, different photosensitizers have been introduced, and hematoporphyrin is probably the most widely studied. However, the clearance of the substance from the tissue was very slow and the phototoxic reaction persisted for a long period of time.
In the late 1970s, a new substance was introduced and recently has become a gold standard in the PDT, namely hematoporphyrin purified derivative. The photoactivation was performed by visible red light, but again the accumulation in the skin lasted for up to several months. It was Kennedy in 1990 who first used ALA for topical PDT on the skin. Due to the low molecular size, ALA easily penetrated the stratum corneum. In addition, it was cleared far more rapidly than the formerly used sensitizers and phototoxicity was observed only several days after the ALA application.

### 3 Indications for PDT in Dermatology

Since its introduction, the list of PDT applications has consistently grown. Indisputably, actinic keratoses and NMSC have been the most widely used, so they will be the focus of this paper. A list of the current PDT applications is provided in Table 1.

Beyond therapeutic indications, the selective accumulation of the photosensitizer is used in the so-called fluorescent diagnostics. In this setting, the skin area of interest is illuminated by ultraviolet light (most often by using a Wood lamp) which allows the visualization of the accumulated sensitizer in the skin. The method is used in preoperative planning for the exact delineation of the tumor borders as well for control of anti-cancer therapies.

<table>
<thead>
<tr>
<th>Malignant and premalignant conditions</th>
<th>Nononcologic skin diseases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aktnic keratoses (and associated photodamage)</td>
<td>Acne</td>
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<tr>
<td>Actinic chelitis</td>
<td>Psoriasis vulgaris</td>
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<tr>
<td>Superficial basal cell carcinoma</td>
<td>Molluscum contagiosum</td>
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<td>Superficial squamous cell carcinoma</td>
<td>Human papillomavirus infection</td>
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<td>Field cancerization of the skin</td>
<td>Herpes virus infection</td>
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<tr>
<td>Bowen’s disease</td>
<td>Erythrasma</td>
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<td>Mammary and extra-mammary Paget’s disease</td>
<td>Alopecia areata</td>
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<td>Erythroplasia of Queyrat</td>
<td>Hirsutism</td>
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<td>Cutaneous T-cell lymphoma</td>
<td>Sebaceous gland hyperplasia</td>
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<td>Kaposi’s sarcoma</td>
<td>Naevus sebaceus</td>
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<tr>
<td>Malignant melanoma</td>
<td>Hidradenitis suppurativa</td>
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<tr>
<td>Keratoacanthoma</td>
<td>Keloids and hypertrophic scars</td>
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<tr>
<td>Gorlin syndrome (multiple nevoid basal cell carcinoma)</td>
<td>Pigmented purpuric dermatosis</td>
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<tr>
<td>Penile and vulvar intraepithelial neoplasia</td>
<td>Disseminated actinic porokeratosis</td>
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<tr>
<td>Langerhans cell histiocytosis</td>
<td>Erosive pustular dermatosis of the scalp</td>
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<tr>
<td>Skin metastases</td>
<td>Acquired perforating dermatosis</td>
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<td></td>
<td>Cutaneous sarcoidosis</td>
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<td></td>
<td>Cutaneous leishmaniasis</td>
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<td></td>
<td>Lichen planus</td>
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<td></td>
<td>Morphea</td>
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<td></td>
<td>Darier’s disease (dyskeratosis follicularis)</td>
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<td></td>
<td>Lichen sclerosus et atrophicus</td>
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<td></td>
<td>Lymphocytic infiltration of the skin</td>
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<td></td>
<td>Pseudopitheliomatous hyperplasia</td>
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<td>Skin and nail mycoses</td>
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<td></td>
<td>Acinetobacter baumannii skin infections</td>
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<td></td>
<td>Wound healing</td>
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<td></td>
<td>Photorejuvenation</td>
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<td>Permanent depilation</td>
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</table>
4 Factors in PDT

4.1 Sensitizer

Although the substances (ALA and MAL) used for local PDT in dermatology are generally referred to as photosensitizers, they are prodrugs. Once delivered to the viable epidermis, ALA/MAL is converted to PpIX, which is the endogenous photactivating agent. Within the next 24 to 48 h, PpIX is transformed to the photodynamically inactive heme.10

δ-5-ALA is a low molecular weight, hydrophilic molecule that can penetrate the stratum corneum and then can be included in the biosynthesis pathway of heme [Fig. 3(a)]. In the United States, ALA is marketed as 20% topical solution of hydrochloride salt. A variety of custom-made preparations as emulsions and gels are available in practice.

In addition, further substances can enhance the accumulation of PpIX, such as desferrioxamine, and the adding of DMSO and EDTA to ALA can enhance the penetration of the precursor.11 Esters of ALA are more commonly used in Europe. They are lipophilic derivates of ALA, which allows enhanced penetration through the lipid bilayers of the horny layer.12 It has been shown that MAL [Fig. 3(b)] possesses better tumor selectivity and less patient discomfort compared to ALA.13 Sixteen percent MAL cream is registered in both the United States and Europe. During photodynamic diagnosis, MAL provided higher tumor contrast than ALA in basal cell carcinoma visualization.14 The authors concluded that MAL should be preferred for use in fluorescence diagnostics.

In recent years, new systems to carry sensitizers to the cells have been developed, such as nanostructural materials, polymeric and liposomal formulations of the sensitizers, and lipid nano-carrier-mediated nuclear targeting carriers.15

The list of substances applied in PDT is increasing and includes chlorins, bacteriochlorins, auxins, phophorphibides, purpurins, phthalocyanines, and naphthalocyanines.16,17

4.2 Light Source

Different light sources of coherent (lasers) or incoherent origin are applied in PDT. Coherence is lost within the first millimeters of penetration into the skin;18 therefore, the use of such light sources is not an obligatory prerequisite. Furthermore the use of lasers is more expensive and can be related to some difficulties during the exploitation.19 Incoherent light sources remain the golden standard for PDT, including a variety of broadband lamps, light-emitting diodes, and intense pulsed light systems. Table 2 summarizes the reports in the literature data about the light intensity and dosing in PDT with incoherent light sources. Beyond blue and red light, green and white light sources have also been occasionally reported in PDT.19

Porphyrins exhibit peak absorption at approximately 405 nm (Soret band; blue light spectrum) as well as several Q bands with absorption peaks in the red light spectrum. Red light exhibits deeper penetration profiles in the skin, therefore it is the only light approved for PDT of skin tumors.16

A recently developed protocol proposed the so-called daylight-mediated PDT for actinic keratoses.20 In this setting, MAL is applied on the entire affected skin field and the patients are exposed to daylight with no further illumination with artificial light sources. A randomized multicenter study showed that this method is efficient even after a single treatment session.20 A natural daylight exposure of an hour and a half was sufficient to gain efficacy. Thin lesions responded better than the moderate and thick actinic keratoses.

5 Adverse Events in PDT

PDT is generally well tolerated. The most common adverse events include pain and a burning sensation limited to the term of the irradiation and several hours afterwards. Larger irradiation areas and sites with rich innervation, e.g., the head, hands, and perineum, are associated with greater pain sensation.11 A correlation between pain and the dose/intensity of the used light was also evidenced.13,21 Pain is greater in a second session compared with the first as shown by a single study.22 This could potentially cause a decrease in the patient’s compliance. Different strategies for decreasing the pain in PDT have been proposed. Table 3 summarizes the pain management strategies.

Further local adverse events include erythema, edema, erosions, aseptic pustulosis, necrosis of the tumor, scarring, hyperand hypopigmentation, and loss of hair. Several cases of contact allergic dermatitis to ALA23 and MAL24 have been described. Two reports describe possible coincidental association of PDT with carcinogenicity.25 Experimental studies in mice showed

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**Fig. 3** Chemical formula of aminolevulinic acid (a) and methylamino levulinate (b).

**Table 2** Light dose and intensity for incoherent light sources for PDT.

<table>
<thead>
<tr>
<th>Light source</th>
<th>Indications</th>
<th>Dose</th>
<th>Intensity</th>
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</thead>
<tbody>
<tr>
<td>Broad spectrum red light</td>
<td>Oncologic diseases</td>
<td>100–150 J/cm²</td>
<td>100–200 mW/cm²</td>
</tr>
<tr>
<td>Broad spectrum red light</td>
<td>Inflammatory dermatoses</td>
<td>10–40 J/cm²</td>
<td>50–70 mW/cm²</td>
</tr>
<tr>
<td>Light emitting diodes</td>
<td>Oncologic diseases</td>
<td>37–50 J/cm²</td>
<td>Up to 200 mW/cm²</td>
</tr>
</tbody>
</table>
that repetitive treatments with ALA-PDT even delay photo-
induced carcinogenesis.26

6 Future of PDT

In the past century, PDT has been established as a safe, effica-
cious, and generally well-tolerated therapeutic method in derma-
tology. Today, devices for performing PDT in ambulatory
settings are available. In our view, the five-year perspectives
for PDT can be summarized into the following fields:

- Novel sensitizer development and new carrier systems to
  the skin, e.g., nanotechnologies: We are witnessing the
  constant development of new molecules and delivery sys-
  tems. The challenge in this field would be a faster and
  more selective tissue accumulation of the sensitizer, as
  well as the shortened clearance period.

- New light sources: A step forward in this direction is the
  implementation of light-emitting-diode technologies in
  PDT. Decreasing the intensity of the light, and thus the
  subjective discomfort, in parallel to keeping the therapeu-
tic efficacy, poses a challenge to researchers.

- Reduction of pain during and after treatment sessions:
  New physical and/or chemical (medicamentous) methods
  should be investigated as the major adverse event during
  PDT is the pain sensation. These should not interfere with
  the PDT procedure and pharmacokinetics of the sensiti-
zers in the skin.

- Standardization of PDT procedures worldwide: Efforts
  in this area have been made and certain international con-
sensus and guidelines for PDT already exist.27 One of the
  major roles of such a consensus document exerts pro-
tective effects over medical practitioners as a part of the
  evidence-based medicine.

- New indications for PDT: This is an area which is con-
  stantly enriched by the multiple reports for the successive
  application to a variety of skin diseases. PDT has already
  been successfully applied in the treatment of skin infec-
tions with multi-drug-resistant microorganisms such as
  MRSA.28

The constant and dynamic development of novelties in the
field is a certain guarantee for the future of PDT in derma-
tology.

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