

## Review Article

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## Photodynamic Therapy (PDT) Mathematical and Physical Principles Underlying Photodynamic Therapy A Precision Approach to Skin Treatment

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### ABSTRACT

Photodynamic Therapy (PDT) is a highly targeted and minimally invasive treatment that leverages the principles of mathematics and physics to treat various skin conditions. Its mechanism involves light absorption, energy transfer, and the generation of reactive oxygen species (ROS) to selectively destroy diseased cells while sparing healthy tissues. The process begins with the absorption of light, governed by the Beer-Lambert Law, which determines how light penetrates the skin and interacts with the photosensitizer. Energy transfer occurs as photons excite the photosensitizer, producing ROS through quantum efficiency and energy conversion processes. Tissue optics and scattering dynamics, modeled by radiative transport equations, further elucidate how light diffuses through skin layers. Additionally, Fick's Laws of Diffusion describe ROS distribution and their interaction with cellular targets. Mathematical models incorporating light intensity, photosensitizer concentration, and oxygen availability allow precise calculation of PDT dosimetry. This integration of physics and mathematics provides a foundation for optimizing PDT efficacy and expanding its clinical applications.

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In Photodynamic Therapy (PDT), ROS are generated when a photosensitizer, activated by light, transfers energy to oxygen molecules. These ROS induce oxidative stress, damaging cellular components such as DNA, proteins, and membranes, ultimately leading to cell death.

### Introduction

As part of this introduction, this author exposes you to the reference which is a published paper of this author in respect to the foundation of "Photodynamic Therapy (PDT) and its Mechanisms, Applications, Benefits, and Limitations," and here in this article we are discussing the principles of mathematics and physics of the subject [1].

In general, Photodynamic Therapy (PDT) has emerged as a precise and minimally invasive treatment modality for a variety of medical conditions, particularly in dermatology and oncology [1]. At its core, PDT relies on the interaction of light, a photosensitizing agent, and molecular oxygen to produce Reactive Oxygen Species (ROS), which selectively destroy abnormal cells as illustrated in Figure 1, which shows generation of ROS procedure in general, which Figure 2 is illustration of ROS interaction with skin.

This intricate process is governed by the principles of physics and mathematics, which provide the foundation for understanding how light behaves within biological tissues, how energy is transferred, and how chemical reactions occur at the cellular level.

In nutshell, Reactive Oxygen Species (ROS) are highly reactive molecules derived from oxygen, including species like singlet oxygen ( $^1O_2$ ), superoxide ( $\cdot O_2$ ), and hydroxyl radicals ( $\cdot OH$ ).

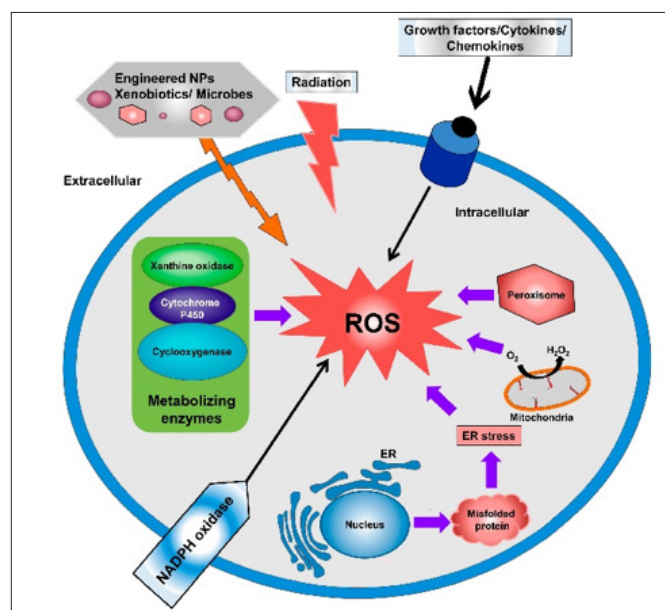
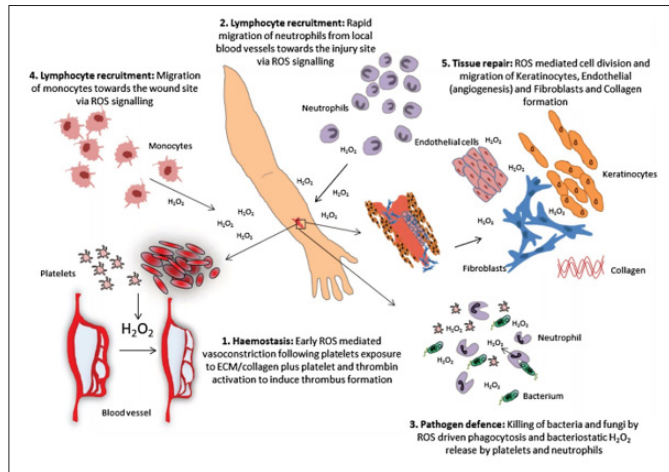


Figure 1: Reactive Oxygen Species (ROS) Generation



**Figure 2:** A Treatment Tailored to ROS Skin Interaction

The interaction of PDT with skin begins with the absorption of light, which is influenced by factors such as wavelength, tissue composition, and the concentration of the photosensitizer. This light energy excites the photosensitizer molecules, initiating a cascade of energy transfer processes that lead to ROS generation. The dynamics of light scattering, absorption, and diffusion through the skin are described by mathematical models, such as the Beer-Lambert Law and radiative transport equations. These models are essential for optimizing treatment parameters, including light dosage and photosensitizer concentration, to ensure effective and targeted therapy.

Furthermore, the distribution and activity of ROS within the tissue are influenced by their diffusion, which can be modeled using Fick's Laws. Together, these principles allow for a quantitative understanding of the PDT process, enabling precise dosimetry and enhancing the predictability of therapeutic outcomes. This introduction explores the critical interplay between mathematics and physics in PDT, emphasizing how these disciplines drive its efficacy and safety in clinical applications.

The interaction of Photodynamic Therapy (PDT) with skin involves principles of mathematics and physics, specifically in light absorption, energy transfer, and chemical reactions. Here is a concise breakdown of the underlying science, in following sections.

### Light Absorption and Beer-Lambert Law

The physics principles of PDT begins with the absorption of light by the photosensitizer in the skin. The amount of light absorbed is governed by the Beer-Lambert Law equation:

$$I(x) = I_0 e^{-\mu_a x}$$

Where:

- $I(x)$  : Intensity of light at depth .
- $I_0$  : Incident light intensity.
- $\mu_a$  : Absorption coefficient of the tissue.
- $x$  : Depth in the skin from surface of it.

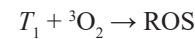
This equation explains how light intensity diminishes as it penetrates the skin. PDT is limited to superficial layers because light absorption and scattering reduces the energy reaching deeper tissues

### Energy Transfer and Quantum Yield

When light of a specific wavelength interacts with the photosensitizer, photons excite the molecule from the ground state ( $S_0$ ) to an excited singlet state ( $S_1$ ):



The molecule may transition to a more stable triplet state ( $T_1$ ) through intersystem crossing, and energy from  $T_1$  interacts with molecular oxygen ( $^3O_2$ ) to produce Reactive Oxygen Species (ROS):



The quantum yield ( $\Phi$ ) measures the efficiency of ROS production, and is mathematically expressed as:

$$\Phi = \frac{\text{Number of ROS molecules generated}}{\text{Number of photons absorbed}}$$

### Tissue Optics and Scattering

Light behavior in tissue follows radiative transport theory, which accounts for absorption ( $\mu_a$ ) and scattering ( $\mu_s$ ) coefficients. The reduced scattering coefficient ( $\mu'_s$ ) combines scattering and anisotropy ( $g$ ):

$$\mu'_s = \mu_s (1 - g)$$

Here,  $g$  represents the average cosine of the scattering angle, and determines how light diffuses through skin layers.

### Diffusion of Reactive Oxygen Species (ROS)

Once ROS are generated, their diffusion and interaction with skin tissues can be modeled using Fick's Laws of Diffusion:

$$J = -D \nabla C$$

Where:

- $J$  : Flux of ROS.
- $D$  : Diffusion coefficient of ROS in tissue.
- $\nabla C$  : Concentration gradient of ROS.

The effectiveness of PDT depends on the balance between ROS production and their diffusion to reach target cells before deactivation.

### Heat and Energy Deposition

The absorbed light energy contributes to localized heating, though PDT is non-thermal. The rate of heat generation can be approximated as:

$$Q = \mu_a \cdot I_0$$

Where  $Q$  is the heat deposited per unit volume. Excessive heat is avoided by carefully controlling light dose and exposure time.

### Mathematical Modeling of PDT Dose

The effectiveness of PDT is often quantified using a dose metric, combining light intensity, photosensitizer concentration, and oxygen availability:

$$PDT \text{ Dose} = \int_{t=0}^{t_{exp}} \mu_a I(t) C_{ps} C_{O_2} dt$$

- $I(t)$ : Time-dependent light intensity.
- $C^{\text{ps}}$ : Photosensitizer concentration.
- $C_{\text{o}_2}$ : Oxygen concentration
- $t_{\text{exp}}$ : Exposure time

This integral helps predict the therapeutic outcome of PDFT.

**Conclusion**

PDT combines physics (light-tissue interactions, energy transfer) and mathematics (diffusion models, dose calculations) to create a

precise, targeted therapy. The interplay of these principles ensures that the light energy activates the photosensitizer, producing ROS that selectively destroy diseased skin cells. Advances in mathematical modeling and tissue optics continue to enhance PDT’s efficacy and predictability.

**References**

1. Bahman Zohuri (2024) Photodynamic Therapy (PDT): Mechanisms, Applications, Benefits, and Limitations. Medical & Clinical Research 9: 1-15.

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