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Determination of parameter β for dual-wavelength pulsed photothermal profiling of human skin

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In pulsed photothermal profiling of human skin, subsurface blood vessels may be difficult to resolve due to nonselective absorption in the overlying epidermis. The dual-wavelength excitation (DWE) technique solves this problem by exploiting spectral differences between the epidermal melanin and blood hemoglobin. An improved approach to determination of DWE-specific parameter β for depth profiling of port wine stain birthmarks *in vivo* using the 585 and 600 nm wavelengths is discussed.

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I. INTRODUCTION

Port wine stain birthmarks (PWS) are hypervascular lesions in human dermis with the aim to improve the efficacy of laser therapy, pulsed photothermal radiometry (PPTR) was recently applied to depth profiling and three-dimensional imaging of PWS.¹⁻³ However, due to melanin absorption in the epidermis (50–150 μm thick superficial layer of skin) and inherent limitations of PPTR,^{2,4,5} PWS blood vessels may not be resolved from epidermal heating when they lie in close proximity to the epidermal–dermal (ED) junction.

The dual-wavelength excitation (DWE) approach solves this problem by exploiting spectral differences between the melanin and blood hemoglobin.⁶ We describe an improved approach to determination of DWE-specific parameter β , which controls the removal of epidermal contribution to PPTR signals in depth profiling of PWS. The same approach was recently applied to three-dimensional PPTR imaging of *in vivo* PWS.⁷

II. MATERIALS AND METHODS

A PWS lesion on the forearm of a volunteer patient was irradiated with 1.5 ms pulses from a flashlamp-pumped dye laser (ScleroPLUS, Candela, Wayland, MA), at wavelengths of 585 and 600 nm and a subtherapeutic radiant exposure (5–6 J/cm²). Infrared (IR) radiant emission from the central 1.9×1.9 mm² area was recorded by an InSb focal-plane-array camera (Galileo, Raytheon, Dallas, TX) at a rate of 700 frames per second. A narrow detection band (4.5–5 μm) was used to reduce the spectral variation of the IR absorption coefficient.⁸ PPTR signals were prepared by calibrating the system response with a computer-controlled blackbody, averaging the used subset of array elements (64×64), and subtracting the background signal level.

Within the customary assumptions and approximations,^{2,4,8} PPTR signal $[S(t)]$ is related to the initial temperature profile $[\Delta T(z, t=0)]$ as

$$S(t) = \int_{z=0}^{\infty} K(z, t) \Delta T(z, 0) dz. \quad (1)$$

In the present study, we apply the kernel function $K(z, t)$ derived by Milner *et al.*² and the same tissue parameters as used in Ref. 8. From signals $S(t)$, represented by 400 measured values, temperature profiles $\Delta T(z, 0)$ in the most superficial millimeter of skin are reconstructed at 64 equidistant points using a non-negatively constrained conjugate-gradient algorithm, regularized by early termination.²

Figure 1 presents $\Delta T(z, 0)$ *in vivo* PWS, reconstructed from a PPTR signal $S_{585}(t)$, acquired after 585 nm exposure (Fig. 2). The solid line is a near-optimal solution according to L-curve analysis² (iteration number $n=5$), dashed and dotted lines are under- ($n=2$) and overiterated solutions ($n=10$), respectively. The latter is featuring characteristic oscillations.² The PWS temperature profile cannot be resolved from the heated epidermis, as the two layers lie in close proximity to each other.

III. DUAL-WAVELENGTH EXCITATION

Due to linearity of Eq. (1), $S_{585}(t) = x(t) + y(t)$, where $x(t)$ and $y(t)$ mark the contributions from PWS vessels and the epidermis, respectively. At 600 nm, hemoglobin absorption is several times weaker than at 585 nm,⁹ while the absorption and scattering properties of the epidermis and dermis are equivalent at either wavelength.¹⁰ As a result, the PPTR signal after the 600 nm excitation has a smaller PWS contribution, while the epidermal signal component is very similar. As a first-order approximation, we can write

$$S_{600}(t) = \alpha x(t) + \beta y(t). \quad (2)$$

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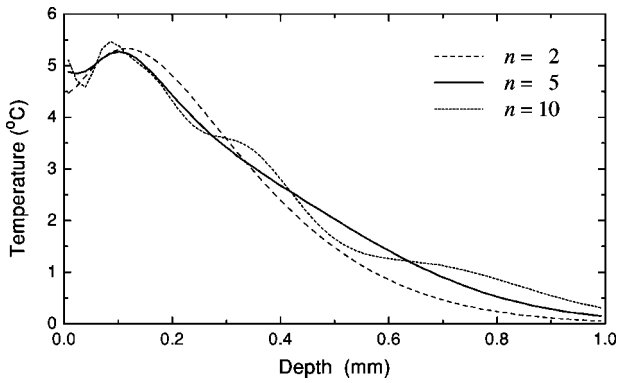


FIG. 1. Depth profile of the temperature increase $[\Delta T S_{585}(t)(z,t=0)]$ in PWS *in vivo*, as reconstructed from PPTR signal. Solid line marks the optimal solution (iteration number $n=5$), dashed and dotted lines are under- ($n=2$) and overiterated solutions ($n=10$), respectively.

From in Eq. (2), the PWS and epidermal contributions to $S_{585}(t)$ are

$$x(t) = \frac{S_{585}(t) - \beta^{-1} S_{600}(t)}{1 - \alpha \beta^{-1}}, \quad (3)$$

$$y(t) = \frac{S_{600}(t) - \alpha S_{585}(t)}{\beta - \alpha}. \quad (4)$$

The corresponding temperature profiles can be reconstructed separately after the parameters α and β are determined.

The value of α is determined based on prior anatomical knowledge that no melanin is present below the ED junction. The temperature profiles reconstructed from $y(t)$ with increasing values of α differ very little in the epidermal region, while the temperature rise deeper in skin decreases monotonically.⁶ The lowest α that yields a zero temperature rise below the ED junction is selected as optimal. At larger values of α , the epidermal temperature profile degrades and the norm of the residue increases. The described approach is theoretically sound and very reliable. In the present example, $\alpha=0.45$.

Similarly, β can be determined by utilizing the fact that no blood vessels are found in the epidermis. Since PPTR senses the tissue temperature only within a few penetration depths of the detected radiation, the PWS contribution im-

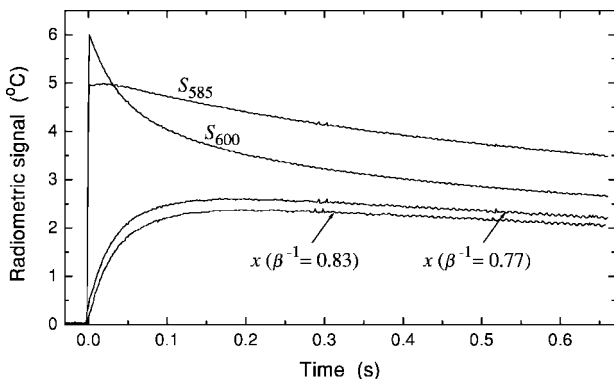


FIG. 2. PPTR signals acquired from the same PWS lesion using excitation wavelengths of 585 and 600 nm (top curves). The bottom curves are signal components $x(t)$ β assessed using the earlier proposed formula ($\beta^{-1}=0.83$), and as described in this work ($\beta^{-1}=0.77$).

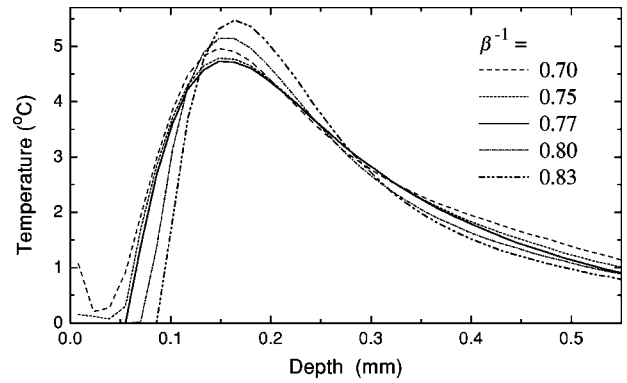


FIG. 3. $\Delta T(z,0)$ as obtained from $x(t)$ with increasing values of β^{-1} . The lowest value yielding a zero temperature increase in the epidermis is selected as optimal ($\beta^{-1}=0.77$; solid line). At higher values of β^{-1} , the PWS profile is “pushed” deeper into the skin (all curves: $n=20$)

mediately after laser exposure was assumed to be zero in our original report on DWE profiling of human skin.⁷ Such logic results in a simple formula, $\beta^{-1}=S_{585}(t=0)/S_{600}(t=0)$, which yields $\beta^{-1}=0.83$ in the present example. The corresponding signal $x(t)$ is plotted in Fig. 2.

IV. IMPROVED DETERMINATION OF PARAMETER β

Since the IR penetration depth in our system is $\sim 40 \mu\text{m}$,⁸ and blood vessels may be found 50–100 μm below the skin surface, the hemoglobin contribution to the PPTR signal may jump instantly to a nonzero value upon laser exposure. The above assumption [i.e., $x(t=0)=0$] is therefore not generally valid, and a more careful approach to determination of β is warranted.

In Eq. (3), the epidermal contribution to $S_{585}(t)$ is removed by subtracting a suitably sized signal $S_{600}(t)$. Similar to the above-described determination of α , we reconstruct the temperature profiles from $x(t)$ with increasing values of β^{-1} (Fig. 3). The lowest value yielding a zero temperature rise in the superficial 50 μm (epidermis) is selected as optimal ($\beta^{-1}=0.77$; solid line). The corresponding $x(t)$ differs significantly from that obtained using the earlier approach (Fig. 2).

At lower than optimal values of β^{-1} , some epidermal contribution is noted in the resulting temperature profiles, but the PWS component is essentially unaffected (Fig. 3). At higher values, in contrast, the top boundary of the PWS is “pushed” deeper into the skin. At $\beta^{-1}=0.83$, as obtained using the original formula, the PWS depth is overestimated by $\sim 30 \mu\text{m}$ (Fig. 3, dash-dot-dot). This is reasonable in view of the underlying assumption that no IR radiation from the PWS transpires directly to the skin surface.

Figure 4 presents the quadratic norm of the residue (i.e., difference between the measured signal and that predicted from the solution) as a function of iteration number, for the reconstructions leading to Fig. 3. With $\beta^{-1} \leq 0.77$ (solid and short-dashed lines), the residual norm reaches the same value as for the signal $S_{585}(t)$ alone (dotted line). This suggests that the quality of the reconstructed PWS temperature profiles is not affected by the remaining epidermal contribution. With higher than optimal β^{-1} values, however, the ultimate

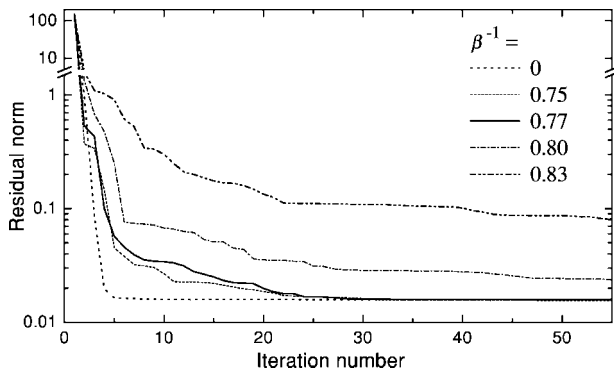


FIG. 4. Residual norm as a function of the iteration number (n), illustrating the convergence and quality of reconstructions with different values β^{-1} . With $\beta^{-1}=0.77$ (solid line) and lower, the norm reaches the same value as for the signal S_{585} alone ($\beta^{-1}=0$, dotted line). At higher β^{-1} values, the residual norm is increasingly higher.

residual norm increase by 39% at $\beta^{-1}=0.80$, and by a factor of 4.4 at $\beta^{-1}=0.83$. This happens because an overestimated β^{-1} defines a PPTR signal corresponding to a negative temperature change in the epidermal region, which cannot be accounted for by the positively constrained reconstruction algorithm.

In Figs. 5(a) and 5(b), respectively, we compare temperature profiles reconstructed from $x(t)$ with $\beta^{-1}=0.83$ (according to the original formula), and $\beta^{-1}=0.77$. With the latter, convergence of the reconstruction is significantly improved, allowing a much more reliable assessment of PWS depth and peak temperature. While the PWS depth, as determined at half-height of the temperature profiles in Fig. 5(a), is relatively stable (100 and 110 μm at $n=10$ and 20, respectively), these values differ considerably from 82 μm in the improved results [Fig. 5(b)].

To complement the final result, Fig. 5(b) includes a profile reconstructed from $y(t)$ (dash-dotted line; $\alpha=0.45$, $n=10$). Note that the two solutions (solid and dash-dotted lines, respectively) represent correctly the temperature rise in PWS and epidermis at depths up to ~ 0.2 mm, where the deeper part of the latter solution starts. (A detailed discussion of this artifact can be found in Refs. 6 and 8.)

V. DISCUSSION

In comparison with the earlier approach, the improved determination of parameter β results in: (a) more accurate determination of the PWS depth (Fig. 3); (b) improved quality of the result (Fig. 4); and (c) improved convergence of the iteration, allowing a more reliable assessment of the optimal solution (Fig. 5). These effects can be used as additional indicators in determination of optimal β . The largest improvement will result in shallow PWS, where the assumption of the earlier approach is most likely violated.

As seen in Fig. 3, variations in β only marginally influence the PWS profile, as long as the optimal value of β^{-1} is not exceeded—analogue to determination of α in our earlier report.⁶ The values of α and β affect the PWS and epidermal temperature profiles also through the nominators in Eqs. (3) and (4). Since the area under the PPTR-determined temperature profiles correlates accurately with deposited laser

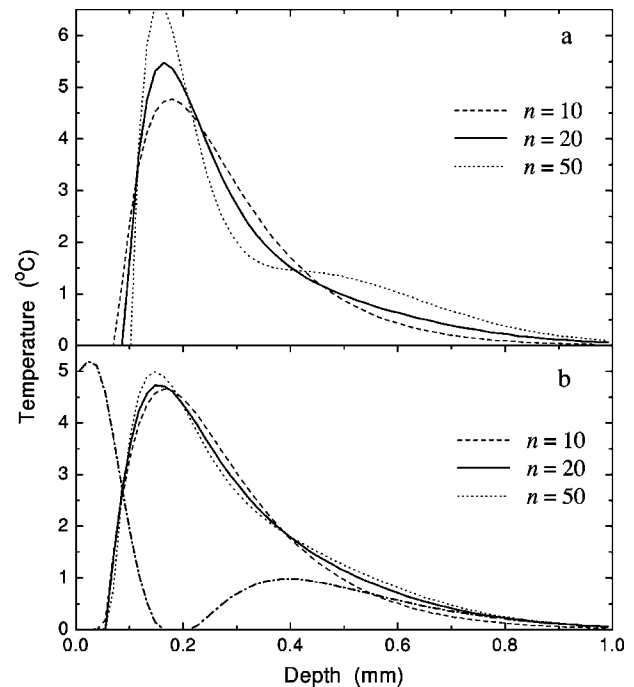


FIG. 5. $\Delta T(z,0)$ obtained using: (a) $\beta^{-1}=0.83$, and (b) the optimal value $\beta^{-1}=0.77$. Convergence of the iterative reconstruction is significantly improved in the latter example. The dash-dotted line in (b) is the profile reconstructed from $y(t)$. (See the text for details.)

energy,^{4,5} this provides an additional check on the selected values. The sum of areas under the final profiles in Fig. 5(b) is within 1.5% of that obtained from $S_{585}(t)$ alone (Fig. 1).

The overlap of the epidermal and PWS temperature profiles in Fig. 5(b) is consistent with uneven shape of the ED junction in human skin. However, it may in part result from broadening of the two profiles due to inherent limitations of PPTR profiling.^{2,4,5}

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