Diagnostic Volume Phenomenon in Noninvasive Medical Spectrophotometry and a Simple Theoretical Definition of That

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Abstract— The article proposes a strict definition of the notation of "diagnostic volume" (DV) in a modern medical *in vivo* spectrophotometry. Theoretical description of a calculation algorithm to evaluate DV with the use of exact modified one-dimensional Kubelka-Munk approach is proposed as well. In a general case, numeric calculations show that for typical human soft tissues effective DV in the simplest one-dimensional theoretical case is lying in a range of 1–8 mm of a depth of the both scattering and absorbing medium.

1. INTRODUCTION

In recent 10–15 years, a general medical practice has been successfully enriched with some new methods of noninvasive optical diagnostics such as a Laser-Doppler Flowmetry, Laser Fluorescent Diagnostics, Tissues Reflectance Oximetry, etc., which all in totality we now call a *Noninvasive Medical Spectrophotometry* (NMS) [1]. All these methods allow a doctor to evaluate both *in vivo* and more exactly a functional condition of soft tissues, especially to study finenesses of respiratory and blood microcirculation processes in a skin or mucosa [2, 3]. NMS technique is based on a dependence of all photometric properties of biological tissues and liquids (spectral coefficients of absorption, scattering, fluorescence, etc.) on an anatomical and morphological structure of the tissue as well as on a content of various biochemical components (hemoglobin, collagen, fat, water, natural porphyrins, etc.) in it [4, 5]. Regarding a quantitative evaluation of volume concentration of different biochemical substances in tissues by NMS methods, especially while executing comparative (relative) measurements in the pathological area and in a chosen intact (normal) point on patient's body, it is necessary for the depth of penetration of radiation in the object being researched to be the same every time. At least, during each diagnostic measurement, a doctor needs to have an opportunity to evaluate the effective volume of biological tissue from which the main useful signal arrives into the registration system. Thus, it is necessary to have an opportunity to evaluate the so called "*sampling volume*" or "*diagnostic volume*" (DV) of the object being studied during the experiment. In a case of any functional or physiological changes, caused by the sickness in biological tissues, their DV will be changing as a result of changes of optical properties of blood, changes of the blood fraction in the volume of examination, changes of optical properties of the skin, etc. That is why the evaluation and determination of DV are extremely important in the practice of NMS. Various authors today have under consideration different aspects of DV in NMS [5, 6]. However, up to now the notion of DV has not been strictly determined and widely accepted yet in a modern biomedical optics. So, the goal of our study was: The looking for a convenient theoretical definition and description of the DV term in exact items of light transport and scattering theory what potentially makes it possible to have a simple and uniform theoretical calculation algorithm to evaluate DV in the most of practical cases of NMS.

2. THE MAIN DEFINITION AND A DIAGNOSTIC PROCEDURE

To reach our goal we have defined the notion of DV as [7] "*an effective volume of biological tissue (the medium of propagation of light radiation) in the area being tested, which brings in the registered optical signal at least* $P_{\min}$ *of power, where* $P_{\min}$ *is estimated at a 75–95% level of the total power of radiation being registered from the biological tissue (signal evaluation by the level of 0.75* ($P_{0.75}$)*, the level of 0.95* ($P_{0.95}$)*, etc.)*". This definition potentially allows anyone to evaluate DV which is reached in experiments in the strict terms of physic and mathematical models of the classic Radiative Transport Theory (RTT). In general, any *in vivo* conventional diagnostic procedure in NMS (Fig. 1) consists of illumination of a part of biotissue by low-level optical radiation, for example, by low-level laser light radiation, and of receiving of a part of backscattered radiation from the tested biological tissue back by the diagnostic system to analyze. As theoretically, the backscattered flux is described and calculated in frameworks and terms of the RTT, the definition resulted above adheres concept of DV to a registered stream of radiation.

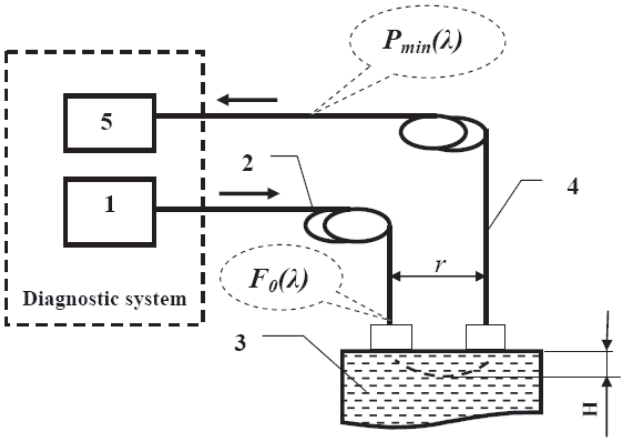

Figure 1: Diagnostic procedure and diagnostic system's setup. 1 — sources of light power; 2 — illumination fiber; 3 — biotissue; 4 — receiving fiber; 5 — photodetectors. $F_0(\lambda)$ — Initial illumination flux as a function of wavelength; $P_{\min}(\lambda)$ — Registered flux as a function of wavelength; H — indicates a depth.

For a purpose of a creation of a first simplified theoretical model, describing DV in NMS, it can be first considered a following simple theoretical problem of one-dimensional ($r = 0$) distribution of optical radiation in a macro-homogeneous turbid medium with multiple scattering. In this our study, we have tried to use the new Modified Exact Kubelka-Munk approach (MEKM) [8–10] in a capacity of the theoretical tool to calculate DV in the one-dimensional (1D) problem. If it is supposed an illumination of biological tissues and a registration of a backscattered flux from the front surface of the biological tissues (see Fig. 1), then the mathematical formulation of the 1D problem is: To determine such an effective depth H (DV in 1D case) of scattering medium with predefined transport optical properties $K = \mu_a$ and $S = \mu_s$ (absorption and scattering in terms of classic Kubelka-Munk model and RTT) from which the backscattered radiation $P_{\min}(H)$, being registered by the NMS device, constitutes a part of $\gamma = 0.9$–0.95 of the total backscattered radiation $P_{bs}(\infty)$ from the same semi-infinite medium — The medium of a geometrical depth significantly exceeding H, i.e.,

$$P_{\min}(H) = \gamma \cdot P_{bs}(\infty). \tag{1}$$

Calculating a backscattered radiation from the semi-infinite medium with similar known transport optical properties, on the basis of (1), it is easily possible to count up a stream $P_{\min}(H)$ as well as an effective H corresponding $P_{\min}(H)$.

3. SIMPLE THEORETICAL NUMERIC EXAMPLES

In the most simple and explicit case, we suppose a 1D problem ($r = 0$) and a perfect scattering medium with $\mu_a = 0$. For this case under a multiple scattering, it was obtained previously [8, 10]:

$$\mu_s = R\mu_\rho/(1 - R), \tag{2}$$

where: R — A reflection coefficient on the borders of optical heterogeneities, μ_ρ — Transport density of scattering heterogeneities in the medium.

A power of backscattered flux from a depth H of the scattering medium can be determined as [9]:

$$P_{bs}(H) = F_0\mu_s H/(1 + \mu_s H), \tag{3}$$

where: F_0 — is a power of the initial illuminating flux.

Supposing a unit stream of outer radiation ($F_0 = 1$), as it follows from (3) under $H = \infty$:

$$P_{bs}(\infty) = F_0 = 1. \tag{4}$$

So, combining (1)–(4), it is easy to obtain:

$$H = \frac{\gamma}{\mu_s(1 - \gamma)}. \tag{5}$$

As one can see, the effective H values will range 0.16–19 cm for typical $R = 0.02$–0.05; $\mu_\rho = 50 \ldots 1000\,\mathrm{cm}^{-1}$ and, accordingly, $\mu_s \approx 1 \ldots 55\,\mathrm{cm}^{-1}$ (typical biological tissues). It is necessary to

note, that for every separate wavelength λ the DV (H in the 1D case) will differ because of the dependence of μ_s on λ.

The presence of absorption in the medium ($\mu_a \neq 0$), evidently, significantly decreases the effective DV. Analogous calculations in the general case of light-scattering medium with absorption not equal to zero can be made with the use of general results of MEKM model [8]. Omitting some intermediate calculation, the final exact equation can be written as:

$$H = \frac{1}{2\alpha} \cdot \ln\left[\frac{\alpha(1+\gamma)/(1-\gamma)+\beta_1}{\alpha+\beta_1}\right], \tag{6}$$

where:

$$\alpha = \sqrt{\beta_1^2 - \beta_2^2};\ \beta_1 = \omega \cdot \frac{\mu_a - \mu_\rho \ln(1-R) + \mu_\rho \ln\left(1-\omega+\sqrt{\omega^2 - R^2 e^{-2\mu_a/\mu_\rho}}\right)}{\sqrt{\omega^2 - R^2 e^{-2\mu_a/\mu_\rho}}}$$

$$\beta_2 = R\cdot e^{-\mu_a/\mu_\rho} \cdot \frac{\mu_a - \mu_\rho \ln(1-R) + \mu_\rho \ln\left(1-\omega+\sqrt{\omega^2 - R^2 e^{-2\mu_a/\mu_\rho}}\right)}{\sqrt{\omega^2 - R^2 e^{-2\mu_a/\mu_\rho}}};\ \omega = \frac{1-(1-2R)\cdot e^{-2\mu_a/\mu_\rho}}{2}.$$

In the case, the numeric calculations for different combination of transport optical properties of tissues are more complex, but with the use of modern personal computer technique are not very difficult yet.

On the graph Fig. 2, curves show some changes in H as a function (6) for different sets of R, μ_a, μ_ρ under $\gamma = 0.95$. As it is seen, here the typical effective values of H turn out to be lying in a range of 1–8 mm for the typical absorbing soft human turbid tissues. It must be additionally noted that for any spatial tasks (2D or 3D when $r \neq 0$) H will differ for different base r of the measurements (see Fig. 1). So, together with DV the base of measurements r becomes one of the main metrological parameters of diagnostic equipment in NMS. To execute reproducible as well as steadily comparable measurements in NMS using different diagnostic equipment, it is necessary to have the same DV and r for them all time.

If transport optical properties of a tested biological tissue are not known *a priori*, the only way out while defining DV is to evaluate DV directly from the results of experiments. Analogous procedure had been developed, for example, in goniophotometry in 1990 [11]. There is in the goniophotometry a so called *far zone* of diffraction. In a real experiment, its value is not known *a priori*, but is very important to evaluate all results of the experiment. So, the special procedure with the use of final numeric results of the experiment was developed to verify whether the condition of the far zone was reached in the experiment or not. In the future something similar is represented

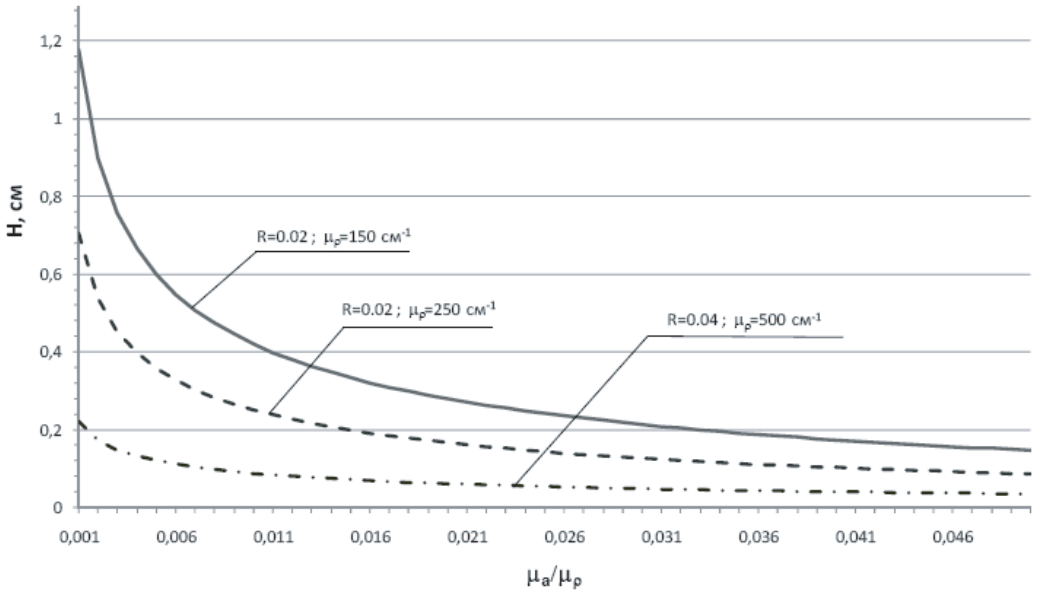

Figure 2: Results of calculations of H as a function (6) for different sets of R, μ_a, μ_ρ under $\gamma = 0.95$.

expedient to be developed for DV in NMS as well. Like it follows from (1)–(5), the decreasing of registered backscattered flux from the tested tissue will inform doctors about corresponding decreasing of DV. So, the less signal is registered the less DV exists in a tissue.

4. CONCLUSION

Today, with the development of noninvasive medical spectrophotometry (NMS), it appears a necessity to evaluate the so called "*diagnostic volume*" (DV) of the human soft tissues being studied during the experiment. Various authors today have under consideration different aspects of DV in NMS. However, up to now, the notion of DV has not been strictly determined and widely accepted yet in a modern biomedical optics. So, the goal of our study was: The looking for a convenient theoretical definition and description of the DV.

To reach our goal, we have defined the notion of DV in the strict terms of Radiation Transport Theory (RTT). This definition basing on a concept of the counting of backscattered radiation potentially allows anyone to evaluate DV which is reached in experiments using the classic RTT theoretical approaches. As theoretically, the backscattered flux is described and calculated in frameworks and terms of the RTT, the definition connects the concept of DV to a magnitude of a stream of radiation registered by a diagnostic system.

Numeric calculations show that for typical human soft tissues effective DV in a simplest 1D theoretical case turn out to be approximately lying in a range of 1–8 mm of a depth of the 1D both scattering and absorbing medium. But if transport optical properties of a tested biological tissue are not known *a priori*, the only way out while defining DV is to evaluate DV directly from the results of the experiments.

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