Laser Original

Improvement of Lambert-Beer Law Dynamic Range by the Use of Temporal Gates on Transmitted Light Pulse Through a Scattering Medium

Hironori YOSHINO *, Kenji WADA *, Hiromichi HORINAKA *, Yoshio CHO *,
Tokuo UMEDA ** and Masahiko OSAWA ***

(Received May 30, 1995)

The Lambert-Beer law holding for pulsed lights transmitted through a scattering medium was examined using a streak camera. The Lambert-Beer law dynamic range is found to be limited by floor levels that are caused by scattered photons and are controllable by the use of a temporal gate on the transmitted pulse. The dynamic range improvement obtained for a scattering medium of 2.8 cm^{-1} scattering coefficient of a thickness of 80 mm by a temporal gate of 60 ps was as much as 50 dB and the Lambert-Beer law dynamic range reached to 140 dB.

Key Words: Scattering medium, Optical CT, Lambert-Beer law, Light pulse, Temporal gate

There has been a growing interest in investigating the realizability of an optical CT, which is expected to offer more specific diagnostic information concerning the physiological activities and defects than from the morphologic information obtainable from X-ray CT. The living tissue, however, is a highly scattering medium for the probing light. In a thick object of living body, photons of visible or near IR light, candidate wavelengths of optical CT, normally experience the multiple scattering. Accordingly, straightforward-propagating scattering-free photons, often called ballistic photons¹⁾, seem to be unrealistic to exist in a thick object. To reconstruct a CT image, we need projection data that are integrated absorption distributions over straight lines. Thus, as for those photons

that are expected to serve to acquire the projection data, quasi-straightforwardly-propagating (QSP) photons, photons experiencing the multiple scattering but still keeping their bouncing trajectories eventually around a straight line, called snake photons²⁾, are the subject of recent interest. Scattering property of the living tissue causes another problem that the above QSP photons are masked by scattered photons. Therefore, the establishment of an efficient extraction technique of the QSP photons from scattered photons is a crucial task for the realization of the optical CT.

To exist the QSP photons out of dominantly strong scattered photons, various techniques have been proposed and tested. They can be categorized largely into two different approaches

* Department of Physics and Electronics, Faculty of Engineering, Osaka Prefecture University (1-1 Gakuen-cho, Sakai, Osaka 593)

** Hiroshima Prefectural College of Health and Welfare, Department of Radiological Sciences and Technology (1-1 Gakuen-cho, Mihara, Hiroshima 723)

*** Biomedical Laboratory, Sumitomo Electric Industries Ltd. (1-1 Shimaya, Konohana-ku, Osaka 554)

aches of spatial^{3,4)} and temporal⁵⁻⁸⁾ discrimination techniques. Detailed influence of the gate duration in the temporal discrimination approach was investigated recently⁹⁾.

In either approach, spatial or temporal, the main problem in the realization of the optical CT is how large dynamic range, or equivalently, how thick object can be handled. The CT algorithm widely used for the X-ray CT depends on the Lambert-Beer law which holds for the X-ray absorption reflecting the morphologic character of the living body. For the light in place of X-ray, however, the Lambert-Beer law holds only while the scattered light component can be ignored comparing with the QSP-photon component as in the case of a thin object. Thus the reachable thickness of an object is determined by the dynamic range in which the Lambert-Beer law holds. A main cause, other than the detector sensitivity, that limits the dynamic range is the scattered component incident on a detecting system.

The light intensity W transmitted (along z -axis) through a scattering object of a thickness d having an enough lateral dimension and having a distribution of scattering coefficient $\mu_s(z)$ and detected by a detector having a collimator in front of it is approximately express as,

$$W = W_0 \left[\exp \left(\int_0^d -\mu_s(z) dz \right) + q \left(1 - \exp \left(\int_0^d -\mu_s(z) dz \right) \right) \right] \quad (1)$$

where W_0 is the incident light intensity and q (< 1) is a factor at which the scattered component is incident on the detector. The factor q is a function of the acceptance angle of the collimator and the detector area. Although Eq.(1) was originally derived for the cw light based on the light scattering theory¹⁰⁾, it is expected to hold also for the pulsed light if we assume W as

the pulse total energy (time-integrated intensity over whole pulse duration). For the pulsed light, the first term on the right-hand side of Eq.(1) may be assumed to represent a component comprising the QSP photons whose logarithmic conversion is to be used as the projection data in the CT algorithm, whereas the second term to be the contribution from the total scattered light into the detected component. In this case, if we give a time gate of a short duration of t_g commencing at the leading edge (temporal) of pulse onto the incident pulse, and if we take W in Eq.(1) to be $W = \int_0^{t_g} I(t) dt$, where $I(t)$ is the pulse shape, and having a short enough t_g , it is also expected that the q -factor is controllable by t_g , because the QSP photons arrive at the detector earlier than the scattered photons. This is the basis of the temporal discrimination scheme and its validity was already provide experimentally^{11,12)}. Thus, it is understood from Eq.(1) that the first term comprises the component for holding the Lambert-Beer law, while the second term (term having the q -factor) forms a floor level that limits its dynamic range. Now the problem in widening the dynamic range of the Lambert-Beer law is how to suppress the second term of Eq.(1) by controlling the q -factor.

In this letter, we report the result of our experimental verification of the validity of Eq.(1) for the pulsed light, in particular stressing the existence of floor level due to the scattering light component, and our effort to widen the dynamic range of the Lambert-Beer law by keeping the q -factor small via the application of temporal gates on transmitted pulses through a turbid sample.

The experimental setup is shown in Fig.1. Pulses incident on a sample cell were obtained from a mode-locked Ti:sapphire laser tuned to 830 nm (This wavelength is suitable for con-

Fig. 1 Experimental setup.

structuring an optical CT for mapping the oxygenation state of blood in the living body). Pulse width is 1.5-2.0 ps which is assumable to be a deltafunction for our experiment. Average power used ranged around 100-500 mW. Scattering sample used is "Intralipid-10%" (Kabi Pharmacia AB, Uppsala) aqueous solution held in acrylic cells, meaning $\mu_s(z) = \mu_s (= \text{const.})$. Cells used have traversal depths (sample thickness) of 20-80 mm with a fixed cross-sectional area of $100 \times 100 \text{ mm}$. In this experiment, no absorbing medium was added intentionally to see only the influence of the scattering medium separately, meaning $\mu_a(z) = 0$. A pinhole placed at the center on the output-side face of the cell and input diaphragm ($100 \times 100 \text{ }\mu\text{m}$) of a monochromator placed at a fixed distance (600 mm) from the pinhole act as a double-pinhole collimator spatial discriminator. The monochromator relays the input diaphragm image onto a photo-cathode of a streak camera and at the same time it acts as a filter to exclude broadband background components. The streak

camera (Hamamatsu Photonics C4332-02, temporal resolution 15 ps) was operated in the single-photon coupling mode. The integration time for averaging normally used was 30 sec. Since the single-photon counting mode of operation of the used streak camera system has a limited dynamic range as much as 30 dB due to its limited photon counting speed and its finite accompanying memory size, to accommodate an expected much wider dynamic range, a stack of calibrated attenuators was placed on the input beam. A part of incident beam was separated by a beam-splitter placed on the input beam to give a time reference.

Examples of observed pulse shape after the transmission through the cell are shown in Fig. 2. Notable changes when the scattering medium concentration is increased that are seen from the figure are; 1) delays in the pulse leading edge, 2) delays in the peak position, and 3) spreadings of the trailing part of the pulses. These mean respectively that 1) ballistic photons, which are expected to show no delay

Fig. 2 Examples of observed pulse shape change depending on the scattering medium concentration. The cell length is 40 mm. Each peak intensity is normalized.

Fig. 3 Observed transmitted pulse energy variation as a function of the scattering medium concentration at a fixed cell length with changing the gate duration as a parameter. Dotted lines roughly indicate Eq.(1).

depending on the scattering medium concentration, do not exist or cannot be detected, 2) QSP photons, which are expected to show a proportional delay on the rising part of the pulse depending on the concentration, are seen to be

present mainly in the early rising part of the pulse, and 3) scattered photons start increasing already in the latter rising part of the pulse and spreading over mainly in the trailing part of the pulse.

The above result justifies the use of a temporal gate for selecting only those photons in the early rising part of the pulse to reduce the q -factor and thereby to widen the dynamic range of the Lambert-Beer law. Observed transmitted pulse energy variation as a function of the scattering medium concentration at a fixed cell length with changing the gate duration as a parameter is shown in Fig. 3. In experiment, as the cell-output photon collection efficiency of the detection system for the case of zero scattering medium concentration was not optimized to 100%, hereinafter W_0 in Eq.(1) is assumed to be the detected pulse energy for the zero scattering medium concentration instead of the input pulse energy. Also, in Eq.(1), since the scattering coefficient μ_s is proportional to the concentration of the scattering medium, the observed result of Fig. 3, in which the concentration is changed instead of sample thickness, can serve to verify the validity of Eq.(1). Dotted lines indicate Eq.(1). All the observed data verify the holding of Eq.(1) for the pulsed light. That is, while the scattering medium concentration is low, data points are clustering on a single descending line (the Lambert-Beer law region where the first term of Eq.(1) is dominant) regardless of the gate duration, and at higher concentrations data points start showing saturations and lining on "floors" (floor region where the second term of Eq.(1) is dominant) after particular concentrations determined by the gate duration and accordingly by the q -factor. Here, for the observed data points, the gate duration is the time interval counted stating from the leading edge of each transmitted pulse.

The Lambert-Beer law region gives a scattering coefficient/%-concentration of $2.8 \text{ cm}^{-1}/\%$ (%-concentration: 10 ml of "Intralipid-10%" in 1000 ml water). This result should be compared with the result of $3.86 \text{ cm}^{-1}/\%$ already measured for Intralipid-10% aqueous solution at 633 nm by cw He-Ne laser light¹³⁾. The same observations were tried also on different cell lengths of 20 mm, 40 mm, and 60 mm. The scattering coefficients obtained from different cell lengths concentrated around the above value. Standard deviation of observed values was less than $0.22 \text{ cm}^{-1}/\%$. From the observed data, the dynamic range improvement obtained for a 1% concentration sample of a thickness of 80 mm is read to be approximately 50 dB by a temporal gate of 60 ps (starting from the leading edge of the transmitted pulse) comparing to without temporal gate and the dynamic range is widened to 140 dB. Under an average input light level of 500 mW, further shorter gate duration did not give reliable floor levels due to streak camera shot-noise counting fluctuations even with longer integration times than normally used of 30 sec. The cell-output photon collection efficiency was not optimized, as mentioned before, there is a room for a further improvement of the dynamic range. Small slants seen on the floor region of the data points are considered to be caused by lateral escapings of scattered photons due to a rather small lateral size ($100 \times 100 \text{ mm}$) of the used cell comparing with its traversal depth (80 mm). The maximum scattering coefficient under which we could observe was 28 cm^{-1} (10% case in Fig. 2 for 4 cm-cell length). This corresponds to the lightest part in scattering coefficients of living tissues.

In conclusion, we could show experimentally the validity of Eq.(1) using pulsed light and in

particular the existence of the floor level due to the scattered photons. The dynamic range improvement achieved by the use of a temporal gate was as much as 50 dB and the Lambert-Beer law dynamic range reached up to 140 dB.

Acknowledgement

This research was conducted as a part of Super Dynamic Response Research Project supported by a grant from Osaka Prefecture.

References

- 1) K. M. Yoo and R. R. Alfano: *Opt. Lett.*, **15** (1990) 320.
- 2) L. Wang, P. P. Ho, C. Liu, G. Zhang and R. R. Alfano: *Science* **253** (1991) 769.
- 3) M. Toida, M. Kondo, T. Ichimura and H. Inaba: *Appl. Phys.* **B52** (1991) 391.
- 4) Y. Cho, T. Shiota, K. Wada, T. Umeda and M. Osawa: *Int'l Conf. on Lasers and Electro Optics*, Tech. Dig. Vol.11 (Optical Society of America, Baltimore, 1993) paper CTuK7.
- 5) Y. Cho and M. Kanda: Japanese Pat. 63-206655, U.S. Pat. 4, 832,035, EPC 0280986 (1988).
- 6) J. Reintjes, M. D. Duncan, R. Mahon, L. L. Tankersley and Eric Mazur: *Int'l Conf. on Lasers and Electro Optics*, Tech. Dig. Vol.10 (Optical Society of America, Baltimore, 1991,) paper CTuH3.
- 7) G. Jarry, J.-P. Lefebvre, S. Debray and J. Perez: *Med. & Biol. Eng. & Comput.* **31** (1993) 157.
- 8) B. B. Das, K. M. Yoo and R. R. Alfano: *Opt. Lett.* **18** (1993) 1092.
- 9) Feng Liu, K. M. Yoo and R. R. Alfano: *Opt. Lett.* **19** (1994) 740.
- 10) A. Ishimaru: *Wave Propagation and Scattering in Random Media*, Vol.2, Chap.14, (Academic Press, New York, 1978).
- 11) K. M. Yoo, Qirong Xing and R. R. Alfano: *Opt. Lett.* **16** (1991) 1019.
- 12) K. M. Yoo, B. B. Das and R. R. Alfano: *Opt. Lett.* **17** (1992) 958.
- 13) J. C. Moes, M. J. C. van Gemert, W. M. Star, J. P. A. Marijnissen and S. A. Prahl: *Appl. Opt.* **28** (1989) 2292.