Proceedings - 19th International Conference - IEEE/EMBS Oct. 30 - Nov. 2, 1997 Chicago, IL. USA

A LIGHT SCATTERING CUVETTE FOR THE MEASUREMENT OF THROMBOEMBOLI TYPE IN FLOWING WHOLE BLOOD

Jungkuk Kim*, Woong Huh**, and Chul Soo Bae***
*Guidant Corporation (CPI), 4100 Hamline Avenue North, St. Paul, Minnesota, 55112
**Electronic Engineering Department, Myong Ji University, Yongin, Korea
***Electronic Communication Engineering Department, Kwan Dong University, Kangneung, Korea
*E-mail: jungkuk.kim@guidant.com

Abstract- A recent light scattering cuvette has been successful in differentiating the type of microemboli in flowing whole blood. However, since the technique was designed assuming the microemboli are concentrated near the center of the scattering medium, it is necessary to investigate the effect of off-center locations on discrimination. The scattering intensities from 5 off-center locations were investigated and the type discrimination parameter (ratio of two forward scattering intensities) was calculated. The perturbation solution of radiative transport equation was used to describe the scattered intensity distribution in the scattering medium. In each location the parameter used for discrimination was not significantly altered since the overall cuvette geometry compensates for the scattered intensity variation caused by off-center locations. Therefore, the scattering cuvette is reliable for differentiation of microemboli type.

INTRODUCTION

The light scattering cuvette method has been a useful tool to detect the microemboli located in whole blood in real-time [1,2]. Recently, the method has been improved to differentiate the nature of microemboli [3,4]. A pair of detectors were added in the forward scattering directions (5° and 20°) and their measured intensity ratio was used to differentiate the type. Although the scattering cuvette geometry was designed to reduce the effects of microemboli location on the scattered intensities at the detectors, it is not clear how much intensity variation is related to the actual location of flowing microemboli during measurement, because the detectors are fixed to face the center of scattering medium and a small deviation in scattering angle can cause a big difference in scattered intensity, particularly in the forward direction. Also it is very difficult to locate microemboli because the nature of fluid dynamics is unclear in the scattering measurement system [5,6].

In this paper, a theoretical investigation is attempted to evaluate the ratio variations of the scattered intensities by locating a microembolus at 5 different positions that are maximally separated from the center of the scattering medium. A radiative transport equation is used to describe the flux distribution in the multiple scattering medium of erythrocytes and the microemboli are represented as a source. The ratios of off-center locations of polystyrene spheres, air bubbles, and clots are compared to that of center location in the scattering medium. Also, the calculated ratios of polystyrene sphere of 90μm are compared to those of measurement.

METHOD

The light scattering cuvette developed for microemboli type discrimination is shown in Figure 1. A laser beam illuminates a flowing whole blood within a silastic tubing located inside a cuvette through an optical fiber. Four optical fibers are positioned in the forward direction to detect scattered intensities. The size of silastic tubing at the measurement site is 2.216 mm (outer diameter) and 1.016 mm (inner diameter). The distance between the center of tubing and the detectors is 10 mm and the angle of acceptance of the detectors is 3.2° in the geometry. The angles of the detector positions for D1 and D2 are 20° and 5° to the incident direction, respectively. In particular, the angles are selected because the intensity ratios at the two scattering angles (intensity at D1's / intensity at D2's) for each type of microemboli are all different and easily distinguishable [3].

In Figure 2, the magnified cross section of tubing within the cuvette is shown with 5 different microemboli positions that are separated 0.408mm from the center and 45° each other. Since the geometry is symmetrical, only the upper half of the medium is considered.

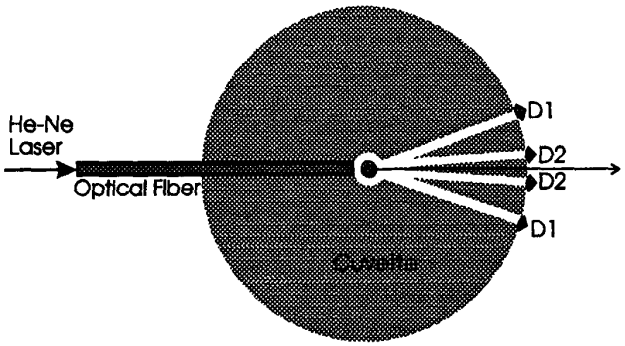

Figure 1. Light scattering cuvette for microemboli type differentiation. For size determination, a 90° detector can be added (not shown).

(0-7803-4262-3/97/$10.00 (C) 1997 IEEE)

In order to describe the scattered intensity in the geometry, the radiative transport equation for unpolarized light is used [7]

$$\left(\frac{\partial}{\partial s}+\Sigma_t\right)\varphi(\bar{r},\hat{\Omega})=\int \Sigma_s(\bar{r},\hat{\Omega}'\cdot\hat{\Omega})\varphi(\bar{r},\hat{\Omega}')d\hat{\Omega}'+S(\bar{r},\hat{\Omega})=Q(\bar{r},\hat{\Omega}) \quad (1)$$

where the angular flux $\varphi(\bar{r},\hat{\Omega})$ propagating through a multiple scattering medium is described at the position $\bar{r}$ and direction $\hat{\Omega}$, with the total macroscopic extinction cross section Σt, the source of light within the scattering volume V and the differential scattering function of the continuum $\Sigma s(\bar{r},\hat{\Omega}'\cdot\hat{\Omega})$ describing the probability of light scattered into the direction $\hat{\Omega}$ from incident direction $\hat{\Omega}'$.

A general perturbation solution is obtained from Eq. (1) with the assumption that the light scattered from the continuum scatterers (erythrocytes) can be decomposed into two components, one component entirely in the incident direction and the other component isotropically scattered into whole space. It is also required and has been verified [8] that the isotropic component be significantly less than the forward component. In the perturbation solution [1,3], the multiple scattering by red blood cells is approximated by the transport approximation [8] and the microemboli are considered as a secondary source by assuming only one microembolus exists in a measurement moment. The source term becomes

$$S(\bar{r},\hat{\Omega}) = \varphi_i\Sigma_{ss}f_s(\hat{\Omega}_0\cdot\hat{\Omega})e^{-\bar{\tau}_s} \quad (2)$$

where Σ_{ss} is the scattering cross section of a microembolus and $f_s(\hat{\Omega}_0\cdot\hat{\Omega})$ is the scattering phase function of the microembolus.

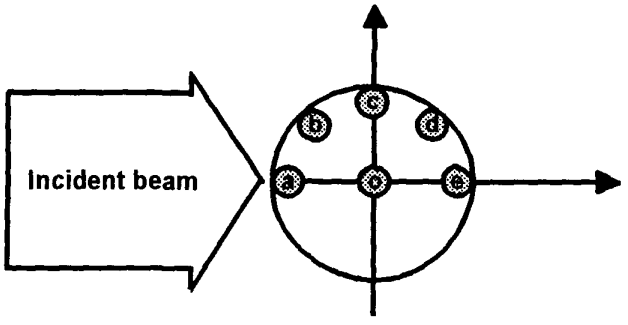

Figure 2. Six microemboli locations used to calculate the scattered intensity ratio in the scattering cuvette geometry.

The theoretical calculation for scattered intensities from microemboli at the 6 different locations is based on Eq. (2). The scattering angle to the detectors from a microembolus at each location is obtained and the scattered intensities at the detectors are calculated. For scattered intensity calculation of microemboli, the approximate two-parameter phase function is used [9].

First, a 90μm polystyrene sphere is positioned at the 6 locations and the scattered intensities at the detectors are calculated. Then, the intensity ratios are obtained as shown in Figure 3 with the ratios actually measured by the scattering cuvette system.

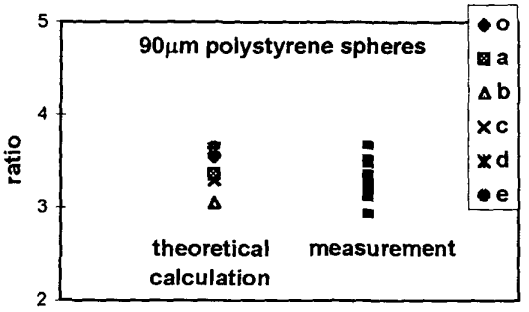

Figure 3. Scattered intensity ratio distribution for a 90μm polystyrene sphere located in 6 different positions in the scattering medium of whole blood.

Also, the scattered intensity ratios from air bubbles and clots of 30μm and 60μm are calculated by positioning them at the 6 locations. The calculated ratios are shown in Figure 4.

RESULT AND DISCUSSIONS

There is good agreement between theoretical calculation and measurement for 90μm polystyrene sphere as shown in Figure 3. The calculated ratios are from 3.05 to 3.65 while the measured ratios are from 2.92 to 3.63. The ratios of air bubbles and clots are also clustered together as shown in Figure 4. The minimum ratio in clot distribution is 5.12 while the maximum ratio in air bubbles is 4.96.

From the distributions in Figure 3 and Figure 4, the order of ratios is b, c, a, o, d, and e, from lowest to highest regardless of microemboli type. When a microembolus is located at position b, the scattering angles for the upper detectors become smallest, and produce the lowest ratio, because the 5° detector does not increase the scattering intensity as much as the 20° detector does. In the scattering phase functions of polystyrene spheres, air bubbles, and clots, the scattering variation around 5° is smaller than around 20°. Fortunately, the detectors in the lower half of the scattering medium produce a higher ratio and compensate for the low ratio. In the case of a 90μm polystyrene sphere at position b, the ratio of upper detectors

is 2.94 and the ratio of lower detectors is 3.73, while the combined ratio is 3.05. Although the ratio of lower detectors is much higher than that of upper detectors, the longer optical path in the scattering medium for lower detectors attenuates more scattering intensity, and therefore, the combined ratio depends more on the intensities at upper detectors.

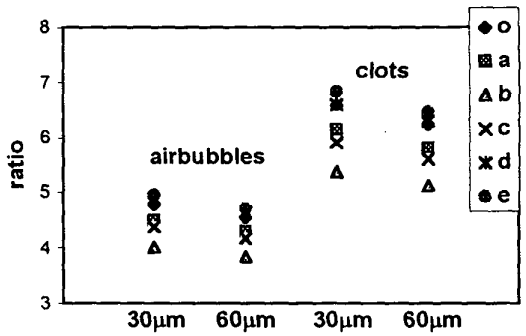

Figure 4. Scattered intensity ratio distribution for air bubbles and clots of 30 and 60μm located at 6 different positions.

CONCLUSION

The light scattering cuvette method developed for microemboli type differentiation is evaluated theoretically. The effect of 5 off-center microemboli locations on the differentiation parameter is investigated. The result of theoretical calculation of the scattered intensity ratio shows that the location effect of microemboli is not significant and the proper microemboli type differentiation is possible in the light scattering cuvette geometry. It is found that the scattering geometry along with the scattering phase functions of microemboli compensates for intensity ratio variation caused by the off-center locations of microemboli in the cylindrical scattering medium of whole blood.

REFERENCES

[1] L. Reynolds, K. A. Solen, S. F. Mohammad, G. M. Pantalos, and J. Kim, " Differential light scattering cuvettes for the measurement of thromboemboli in high shear blood flow systems," ASAIO Transactions, vol. 36, 1990.

[2] K. Solen, S. Mohammad, G. Burns, G. Pantalos, J. Kim, Y. Peng, W. Pitt, L. Reynolds, and D. Olsen, "Makers of thromboembolization in a bovine ex vivo left ventricular assist device model," ASAIO Journal, M602-M608, 1994.

[3] J. Kim, J. Lin, and L. Reynolds, "A laser scattering method for characterization of thromboemboli in whole blood," Proc. of the 16th Annual International Conference of the IEEE EMBS, Baltimore, Nov. 1994.

[4] J. Kim, C. S. Bae, and H. S. Jo, "Determination of blood clot composition in real-time by laser scattering method," Proc. of the 17th Annual Conference of the IEEE EMBS, Montrèal, Canada, Sept. 1995.

[5] Chandran, K. B., Cardiovascular biomechanics, New York University Press, New York, 1992.

[6] Karino T. and Motomiya, M., "Flow visualization in isolated transparent natural blood vessels," Biorheology, vol. 20, pp. 119-127, 1983.

[7] J. J. Duderstadt and W. R. Martin, *Transport Theory*, New York, A Wiley-Interscience, 1979.

[8] G. D. Pedersen, N. J. McCormic, and L. O. Reynolds, "Transport calculations for light scattering in blood," Biophysical J., vol. 16, pp. 199-207, 1976.

[9] L. O. Reynolds and N. J. McCormick, "Approximate two-parameter phase function for light scattering", J. Opt. Soc. Am., vol. 70, no. 10, 1980.