Measurement of Magnetic Susceptibility of a Particle Suspended in a Liquid Phase

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It was proposed that a method to measure the magnetic susceptibility of a particle such as the biological cell suspended in a liquid phase without any kind of contact with the apparatus. This method utilizes the magnetic force acting on the particle under the high magnetic field gradient, which is balanced by the viscous force controlled by the fluid velocity. The magnetic susceptibility can be determined from the value of the fluid velocity when the suspended particle is stopped against the fluid motion by the magnetic force. An experimental result for a polystyrene micro-sphere proved a possibility of the *in vivo* assay and separation of the living cells by using this method.

The assay and separation of living cells such as blood cells and lymphocytes are of great importance in the biological and medical fields.[1] The flow-cytometry (FCM) using antibody marked by fluorescent dye is effective for this porpose.[1-5] FCM, however, can not be applicable if suitable antibodies are not provided. Mechanical and electrostatic damages of the cells by the high-speed and high-voltage separator are also pointed out.

To overcome these difficulties, a new method by use of the magnetic force can be introduced: The magnetic force is yielded by the magnetic susceptibility of the cell and the magnetic field gradient, so that this method is applicable to all kinds of cells. The magnetic field does not interact so strongly with usual cells, *i.e.*, even for the order of 10T, the magnitude of the magnetic force is in the same level as the gravity force.[6-9] So, if some suitable configuration for the detection of the magnetic susceptibility of the cell is possible, we can expect not only the high selectivity but also the high survival ratio of the cells during the assay process.

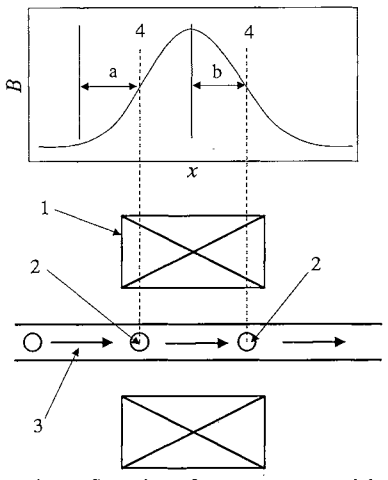

Figure 1. Schematic configuration of apparatus. a and b indicate the areas where the diamagnetic and paramagnetic particles are trapped, respectively. 1, magnet; 2, trapped sphere; 3, liquid flow; 4, maximum points of the magnetic force.

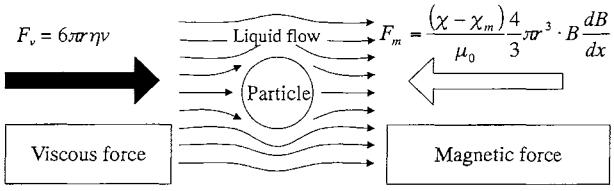

Figure 2. Two different forces acting on a suspended particle.

In the present paper, as the first step, a new method to determine the magnetic susceptibility of a small particle suspended in a solution is examined. At the end of this paper, the possibility of the application of the magnetic field to the *in vivo* assay and separation is discussed.

Figure 1 is the schematic configuration of the apparatus. The main part is a tube placed in a high magnetic field; inside of it a liquid flows accompanying the particles of which the susceptibility is to be measured. The laminar flow, as shown in Figure 2, drags each particle by the viscous force, which is approximated by the following Stokes equation

$$F_v = 6\pi r\eta v \tag{1}$$

where F_v viscous force, r radius of particle, η viscosity of liquid, and v is relative velocity of particle for the liquid.

However, under the high magnetic field gradient, against the drag force the magnetic force resulting from the difference of the magnetic susceptibilities between the particle and the solution is generated as follows,

$$F_m = \frac{(\chi - \chi_m)}{\mu_0}\frac{4}{3}\pi r^3 \cdot B\frac{dB}{dx} \tag{2}$$

where F_m the magnetic force, χ the magnetic susceptibility of particle per unit volume, χ_m the magnetic susceptibility of the liquid per unit volume, μ_0 the space permeability, r the particle radius, B the magnetic flux density, x is the distance along the axis of the bore of the magnet.

Then, using the value of the velocity when the particle is trapped and the following equation obtained from Eqs. (1) and (2), we can calculate the susceptibility of the particle

$$\chi = \frac{9}{2}\frac{\mu_0\eta v}{r^2}\left(B\frac{dB}{dx}\right)^{-1} + \chi_m \tag{3}$$

From the above discussion, according to the difference of the susceptibilities it may be also possible to separate the particles without any contact with the apparatus.

As a test particle for the measurement, a polystyrene micro-sphere of 92.9 μm in diameter (DYNOSPHRES SS-922-P, Japan Synthetic Rubber Co.) was used. The particle was injected by a micro-syringe into a solution containing 0.3 mol dm^{-3} copper sulfate and saturated oxygen. The copper sulfate and oxygen were added to obtain the large difference of the susceptibilities between the particle and the solution and remove the effect of

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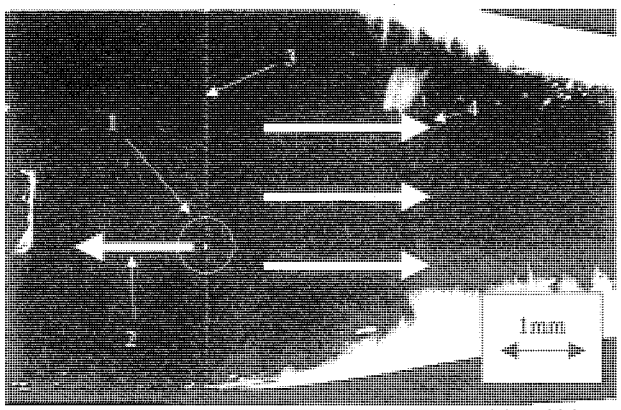

Figure 3. The photomicrography of the polystyrene particle, which was trapped in the measuring point. 1, trapped sphere; 2, magnetic force direction; 3, maximum point of $B(dB/dx)$=180 T^2m^{-1}; 4, direction of fluid motion.

the dissolved oxygen from the atmosphere, respectively. The temperature of the solution was kept at 300±1 K. The velocity of the solution was regulated within the accuracy of 1 μms^{-1}. To observe the trapping of the particle, a CCD camera connected to an external monitor was introduced inside the bore. For improving the precision, the measurement was carried out in the point where have the maximum value of $B(dB/dx)$= 180 T^2m^{-1} in the bore of the magnet.

Figure 3 is a photo exhibiting such trapping of the polystyrene particle. By the velocity determined v=3.16×10^{-4} ms^{-1}, together with other data, μ_0=4π×10^{-7} Hm^{-1}, η=1.09×10^{-3} Pa s, r=92.9 μm, $B(dB/dx)$=180 T^2m^{-1}, and χ_m=-3.41×10^{-6}, we can finally obtain the magnetic susceptibility of the particle per unit volume as –8.39×10^{-6} in SI unit. This value is in good agreement with the value, -8.21×10^{-6}, from reference data.[10]

Under the present experimental conditions, the precision of the measurement is estimated as 3.16×10^{-8}, which will be improved if higher magnetic field and more precise control of the fluid flow are introduced.

On the other hand, the velocity to trap a particle of 100 μm is calculated as 3.64×10^{-4} ms^{-1}, whereas in the present case of a particle of 92.9 μm, the velocity is 3.16×10^{-4} ms^{-1}. The difference of these two velocities is thus about 5.0×10^{-5} ms^{-1}, so that from the precision of the velocity control, *i.e.*, 5 μms^{-1}, we can expect good separatability for the difference in size of 10 μm (normal size of a living cell).

As to susceptibilities of living cells, *e.g.*, the red and white cells have the difference of the volume susceptibility of the order of 10^{-6}, which can be easily detected for separation.[11] We have now preparing a new type of the separator to separate living cells by this method.

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