Observation of spin and orbital rotation of red blood cell in dual-beam fibre-optic trap with transverse offset

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Abstract
The spin and orbital rotation of the red blood cell (RBC) are achieved simultaneously by introducing a transverse offset to the dual-beam fibre-optic trap. The motion type of the captured RBC could be controlled by adjusting the offset distance. When the offset distance is relatively small, the RBC is observed to spin in the trap centre, with the spin frequency increasing linearly with the offset distance. Once the offset distance is above a critical value, the RBC will rotate along an elliptic orbit, together with the spin motion. The orbital rotation frequency and spin frequency both decrease with the increased offset distance. This technique allows mixing and viewing living cells from different perspectives concurrently without exposing them to any mechanical contact, and is generally applicable to biological and medical research.

Supplementary material for this article is available online

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(Some figures may appear in colour only in the online journal)

1. Introduction
Since first proposed by Arthur Ashkin in 1970 [1], optical traps have become versatile tools for the micromanipulation of biological objects [2–4]. They are widely used to rotate [5], stretch [6], sort [7] and binding cells [8]. The rotational control can provide better insights into the three-dimensional subcellular structures of biological samples, and is generally applicable to biological and medical area [5, 9–11].

The rotational control includes spin and orbital rotation. The controllable rotation of objects is commonly realised by laser beams carrying net angular momentum, including spin [11, 12] and orbital angular momentum [13, 14]. The spin or orbital angular momentum is transferred from the special optical field to the objects, leading to the spin motion or orbital rotation of objects. However, this approach can only be used for birefringent or absorbing material. This strongly limits its application in the biological realm. In 2008, Blakely et al achieved the orbital rotation of polydimethylsiloxane (PDMS) microsphere by combination of two upstream-angled fibres and fluid drag [15]. Subsequently, Watanabe et al proposed another optical orbital rotation technique by controlling the laser power emerging from two transversely misaligned optical fibres [16]. Black and associates demonstrated controlled spin of smooth muscle cells based on transversely misaligned dual-beam fibre-optic trap [17]. These orbital rotation and spin methods are
widely applicable and not limited by the sample’s birefringent properties. Recently, we analysed the transformation process and mechanism of the possible motion type of the captured microsphere in a dual-beam fibre-optic trap with transverse offset [18, 19], and firstly demonstrated the orbital rotation of the microsphere without any additional controls of fluid drag or laser power [20]. However, because the suspended microsphere was spherical, no spin motion of the microsphere was observed along with the orbital rotation. To date, the spin and orbital rotation motion of trapped particle were achieved by transversely misaligned dual-beam fibre-optic trap, separately. Nevertheless, the simultaneous spin and orbital rotation still have not been observed yet.

Observing and studying the single red blood cell (RBC) are of great significant in prediction and diagnostic of diseases, such as malaria [21], diabetes [22] and leukemia [23]. In this paper, we captured a single RBC by the dual-beam fibre-optic trap. Through adjusting the offset distance between two fibres, we successfully observed the spin and orbital rotation of the RBC, concurrently. The RBC span as it rotated around the trap centre along an elliptical orbit. This work will contribute to controllable motion of biological cells in localised environment, and is generally applicable to many applications, such as microfluidic mixing biology imaging and cell manipulation.

2. Experimental methods

The optical layout for the experiment is shown in figure 1. The experimental device was made up of a PDMS chip housing two transversely misaligned fibres (OZ Optics, core diameter: 6 μm) across a microfluidic flow channel. Each fibre was attached to a translation stage (Thorlabs, resolution: 1 μm) to adjust the offset distance. Each fibre was coupled with different laser diode source (BWT Beijing Ltd, continuous wave, 980 nm) to avoid the generation of coherent interference. In each optical path, a fibre optical attenuator (OZ Optics) was used to adjust the laser power. The final laser powers emitted from two fibres were both 100 mW. The laser power was monitored by a 90/10 fibre optical couple (OZ Optics) and a photodiode (Thorlabs). The RBCs were separated by centrifugation and diluted by phosphate buffered saline. The ethylenediamine-tetra-acetic acid was used as anticoagulant. The PDMS chip was sterilised by autoclaving before experiment for biological applications. Spin and orbital rotation of the RBCs were achieved by adjusting the offset distance through the translation stages. The RBCs were imaged using a microscope objective (Nikon Ltd, E Plan ×10, NA = 0.25). Still images at 15 fps are obtained by a CCD camera (Watec, resolution: 640 × 480 pixels). A notch filter (Thorlabs) was inserted to prevent the laser light of 980 nm from entering the CCD. The acquired images are exported to MATLAB to get the paths and postures of the RBCs.

Figure 2 illustrates the principles of the spin and orbital rotation of RBCs in the dual-beam fibre-optic trap with transverse offset. As shown in figure 2(a), when introducing a small transverse offset between the two fibres, the scattering forces from each beam ($F_{s1}$, $F_{s2}$) generate a torque on the trapped RBC. The RBC spins in the trap centre about an axis perpendicular to the optical axis and the offset direction. The spin direction could be applied along different axes by creating desired directional offset between the two fibres. That allows viewing the RBC in three dimensions simultaneously without exposing them to any mechanical contact. When the offset distance $d$ is above a critical value, the trap centre turns to be an unstable equilibrium point [18]. The RBC will break away from the centre position and begins to
rotate along an approximate elliptic orbit, as shown in figure 2(b).

3. Experimental result and discussion

3.1. Spin

Figure 3 shows the spin of the RBC in the dual-beam fibre-optic trap with transverse offset. The shape of the trapped RBC is a flattened biconcave disk whose diameter is about 7 μm. The distance between each fibre end is approximately 250 μm. The offset distance is set as 10 μm. The trapped RBC was observed to spin clockwise in the trap centre with an approximate frequency of 0.2 Hz. The time-lapse images of the posture change of the RBC are shown in the inset.

3.2. Orbital rotation

When the offset distance is above a critical value, the centre position is no longer a stable equilibrium positions, and the trapped RBC cannot be stably captured and spin there [18]. The critical value is verified to be 13 μm in this situation. Figure 4 shows the time-lapse images of the dynamic trajectory and posture change of the trapped RBC, with the offset distance set as 15 μm. Instead of spinning in the centre position, the RBC rotated along an elliptic orbit in the optical trap, as the red solid curves indicated. The orbital rotation frequency and perimeter were about 0.42 Hz and 31.2 μm, respectively. Meanwhile, the posture of RBC changes along with the orbital rotation, as the insets show. The spin frequency was observed to be about 0.159 Hz.

The orbital rotation trajectory and velocity can be affected by the offset distance. The orbital rotation perimeter and frequency of the RBC versus the offset distance is shown in figure 5. As the offset distance increases, the experiment data show an increasing of the orbital rotation perimeter, with the orbital rotation frequency decreasing.

4. Discussion

When rotating in the optical trap along an elliptic orbit, the RBC is still affected by the torque created by the two misaligned fibres. Therefore the RBC will spin itself along with

Figure 3. Spin of the RBC when the offset distance is 10 μm. The main panel shows the schematic of dual-beam fibre-optic trap with transverse offset. The inset shows the time-lapse images of the posture change of the RBC.
the orbital rotation. Figure 6 shows the spin frequency as a function of the offset distance for different RBCs. In order to verify the repeatability of the measurements, three RBCs were tested in the experiment. For different RBCs, their sizes, shapes, and optical properties are diverse from each other. The spin frequency varies for different RBCs, so does the critical value of the offset distance. However, as shown in figure 6, for all RBCs, the spin frequency versus the offset distance follows the same tendency. When the offset distance is smaller than the critical value, the RBC spins in the trap centre. The torque exerted on the RBC increases with the offset distance, leading to a larger spin frequency. The spin frequency increases with the offset distance. Once the offset distance is above the critical value, the trapped RBC begins to rotate along an approximate elliptic orbit, together with the spin motion. When the offset distance increases, the orbital rotation perimeter increases. The RBC will be farther away from the centre area, resulting in the decreasing of torque, which leads to a smaller spin frequency. The concomitant spin frequency decreases with the offset distance.
5. Conclusion

We observe and describe the spin and orbital rotation of a trapped RBC concurrently by a dual-beam fibre-optic trap with transverse offset. We change the offset distance between two fibres by adjusting the translation stage on which each fibre stick. The experiments show that, as the offset distance increases, the motion type of the RBC translates from spin to orbital rotation. When the offset distance is smaller than a critical offset distance, the RBC is observed to spin in the trap centre. The spin frequency increases with the offset distance. When the offset distance is above the critical value, the RBC rotated along an elliptic orbit in the optical trap. The orbital rotation amplitude increases with the offset distance, with the orbital rotation frequency decreasing. In addition, along with the orbital rotation, the RBC still spin itself in the orbit. The spin frequency decreases with the offset distance.

In conclusion, we have introduced a technique that allows spin and orbital rotation of living cells simultaneously. The motion type of the captured cell could be controlled by adjusting the offset distance. This technique allows mixing (orbital rotation) and viewing (spin) living cells in three dimensions simultaneously without exposing them to any mechanical contact. We suggest that it may become a useful tool in cellular mixing and imaging.

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