Measuring erythrocyte deformability with fluorescence, fluid forces, and optical trapping

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1 Introduction

Manipulation of micron- and submicron-size matter by optical forces from a single laser beam has been a subject of continuing interest after its first demonstration by Ashkin et al.1 The possibility of contactless manipulation under physiological conditions has widespread implications in biology, and consequently, the optical trap has been extensively used for manipulation of cells.2 Deformability of red blood cells (RBCs) and their properties, such as like membrane elasticity, are of long standing interest. Changes in the RBC deformability exhibit a strong correlation with several blood disorders. Deformability of RBC population is currently measured using automated rheoscopes and ektacytometers.3–5 Changes in deformability of a single RBC are assessed through micropipette aspiration,6 automated rheoscopes,7 and with optical traps using two beads fixed on either side of an RBC.8 Each of these single-cell techniques is cumbersome, especially if one needs to study a small, specific subset of the population. Whether through automated rheoscopes or through bead entrapment, the measurements can currently be made only for a random subset of cells.

In previous work on the optical trapping of healthy and malaria-infected (Plasmodium falciparum) RBCs,9 we have shown that as an RBC moves toward the laser focus, trapping occurs; this is accompanied by shape distortion (buckling) such that the original disklike RBC buckles, by folding action, into a rodlike shape. On removal of the laser light, the cell unfolds to its original biconcave shape.10 Our particular interest is to probe the trapping characteristics of healthy and malaria-infected RBCs. Single-cell studies of normal and Plasmodium-infected RBCs have assumed considerable importance in recent years.11 It is established that malaria-induced organ failure is associated with capillary blockage and the enhanced rigidity of infected RBCs. Elastometric microchannels of micron-sized diameters have been utilized to establish differences in deformability of normal and infected RBCs.11 We have succeeded in combining a liquid flow cell with a laser optical trap and a fluorescent set up to measure the shear modulus of fluorescence-labeled RBCs, both healthy and malaria-infected, under liquid flow conditions. We describe here a simple technique “optical trap-assisted folding-unfolding behavior of RBC” (OTAFUR) to analyze the buckling-unbuckling behavior of specific single RBCs. The OTAFUR value in Folding (F) (in milliseconds) and unfolding (UF) (in seconds) are measures of the intrinsic deformability and recovery of a single RBC. The UF-recovery parameter, in particular, is independent of any flow or shear stress and measured without having to immobilize the RBC on any solid surface. Although

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Abstract. A laser-based method has been developed for experimentally probing single red blood cell (RBC) buckling and determining RBC membrane rigidity. Our method combines a liquid flow cell, fluorescence microscopy, and an optical-trap to facilitate simple measurements of the shear modulus and buckling properties of single RBCs, under physiological conditions. The efficacy of the method is illustrated by studying buckling behavior of normal and Plasmodium-infected RBCs, and the effect of Plasmodium falciparum–conditioned medium on normal, uninfected cells. Our simple method, which quantifies single-RBC deformability, may ease detection of RBC hematological disorders. © 2008 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3037342]

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all the previous experiments (see Refs. 3–8, and references therein) have yielded useful information on cell deformability, we present here an alternative experimental approach that has a direct link to the mechanical properties of cell membranes. The efficacy of the method is illustrated by studying (i) the buckling behavior of normal and Plasmodium-infected red blood cells and (ii) the effect of P. falciparum–conditioned medium on normal, uninfected cells. Specifically, we have utilized optically induced folding and unfolding times of single cells as a measurable parameter with a mechanical connection to examine the deformation rate of the cell under a constant load and its subsequent relaxation/recovery time when the load is removed.

2 Experimental Details

2.1 Optical Trap and Flow Cell Setup

The experimental set up is shown in Fig. 1. We use single-beam optical tweezers to trap RBCs under both static and flow conditions. Our tweezers setup has been described earlier. In brief, it consists of a 120-mW Nd:YAG laser with a 2-mm beam that is expanded to 8 mm. This beam is coupled to an inverted microscope (Nikon TE 2000U) that is equipped with a fluorescence attachment. Trapping of a single cell is achieved using either a 100X (1.3 NA) oil-filled objective or a 60X (0.75 NA) long-working-distance objective. Typical values of laser power measured using an integrating sphere after the objective are ~20 mW in the present series of experiments (variation of cell folding and unfolding with laser power has been characterized by us in an earlier study). A CCD camera is used to capture the cell trapping events in the form of a real-time movie interfaced to a computer. The RBCs are placed either on a cover slip (static case) or in a parallel-plate liquid flow cell mounted on a translation stage attached to the microscope (Fig. 1). Care was taken to ensure that the trapped cells were always in the same focal plane (10 μm above the cover slip), ensuring constant trapping force at each instant. The flow cell was constructed using a glass slide of dimensions 75 × 25 × 1 mm and a cover slip of dimensions 60 × 22 × 0.17 mm, with 0.17-mm thick spacers in-between to form the flow channel. The effective inner dimensions of the flow channel were 55 × 10 × 0.17 mm. A peristaltic pump (Pharmacia LKB-Pump P-1) was used to maintain continuous flow of the red cell suspension through the chamber at a constant flow of 1.4 mL/min. The fluid flow was laminar, and the Reynolds value was typically of order 10⁻².

2.2 Sample Preparation

Asexual stages of P. falciparum 3D7 strain were maintained in vitro in 5% hematocrit in Roswell Park Memorial Institute (RPNI) 1640 medium containing 0.5% albumax and 80-mg/mL gentamycin sulphate in a humidified chamber containing 5% CO₂ at 37°C in human RBCs of serological type O+. To obtain synchronized cultures, sorbitol treatment was performed. The P. berghei ANKA and P. yoelli strains were maintained by passaging asexual stages through BALB/c mice. Tail bleeds were collected from mice showing approximately 20–40% peripheral blood parasitemia, and diluted 1:10 in incomplete RPMI. About 100 μL of this dilution was injected intraperitoneally into naïve BALB/c mice for the expansion of parasites. Parasitemia was monitored by microscopic examination of blood smears stained with Giemsa. Blood samples from humans and mice were collected in a sterile tube containing the anticoagulant ACD and centrifuged at 3000 rpm for 10 min. The plasma and buffy coat containing white blood cells were aspirated out and purified RBCs were washed with sterile RPMI (Life Technologies, Inc.) medium with 28 mM NaHCO₃, 25 mM HEPES, and 80 mg/mL gentamycin sulphate. The RBCs were resuspended in sterile RPMI medium containing 0.5% albumax (Life Technologies, Inc.) as a 50% v/v suspension, and diluted for use. In case of P. berghei–and P. yoelli–containing samples, normal RBCs (NRBCs) were obtained from uninfected mice and infected RBCs (IRBCs) from infected mice. Before running in the flow cell, cells were incubated with 10 μg/mL DAPI in either PBS or RPMI for 10 min, pelleted at 3000 rpm, and resuspended in phosphate-buffered saline with 1% bovine serum albumin (BSA). Cells were used at a concentration of 10⁶ cells/mL.

2.3 Conditioned Medium

IRBCs were synchronized by sorbitol treatment. Freshly treated IRBCs were cultured at 5% haematocrit and 1% parasitemia as described above. After every 8 h, the spent medium was collected after the cells settled down and fresh medium was added. The spent medium collected was pelleted at 3000 rpm for 10 min; the pH was adjusted to 7.4 and was filter sterilized. This medium was called conditioned medium (CM). For the experiment, fresh NRBCs were incubated for 24 h each in CM from different stages. As a control, NRBCs were kept in RPMI. After 24 h, all sets of RBCs were washed and incubated for another 24 h in CRPMI.
2.4 Assessment of Folding and Unfolding

For folding and unfolding analysis, the RBCs were stained with DAPI, washed twice in RPMI and diluted to \( \sim 10^6 \) cells/mL in complete RPMI (CRPMI). During the experiment, about 10–20 \( \mu \)L of suspension was placed on a coverslip. Infected cells were identified by strong fluorescent in UV light (340–380 nm). Typically, an RBC in the vicinity of the trap experiences an attractive force, causing it to move toward the trap focus and subsequently deforms (folds) into a rod shape. Furthermore, when the trap is removed by blocking the laser beam path, the RBC regains its original shape by unfolding. These events were recorded for several RBCs. Subsequent analysis was done by converting the videos to frames and counting the number of frames taken to fold. Unfolding, which takes several seconds could also be typically measured using real-time movies captured by a CCD camera.

2.5 Statistical Analysis

The data sets were first checked for normality by Kolmogorov and Smirnov’s method. Most of them failed the normality test; hence, significance testing was done using the Kruskal–Wallis test followed by Dunn’s nonparametric test. The data sets that passed the normality test (shear modulus experiment and unfolding data in the \( P. yoelli \) experiment) were further tested using one-way ANOVA followed by Tukey–Kramer’s multiple comparison tests. All tests were two tailed. The statistical significance of our data is quantified in terms of \( P \) values.

3 Results and Discussion

We have earlier proposed a model based on Euler buckling that rationalizes the experimentally observed folding and unfolding of RBCs that occur upon their placement in an optical trap. Such buckling phenomena have been related to the elastic properties of the cell membrane; the model successfully predicts that folding actions occur much more rapidly than unfolding and also establishes the functional relationship between folding time and incident laser power. However, there is, as yet, no simple formulation of how such buckling phenomena might be related to the shear modulus of the RBC. Here, we investigate the folding and unfolding behavior of NRBCs, parasite-infected RBCs (PRBCs), and uninfected RBCs (URBCs) within an infected population under flow conditions. URBCs represent those uninfected RBCs that are exposed to PRBCs, while NRBCs are RBCs that have never been exposed to PRBCs. Infected cells were labeled with DAPI, a membrane-permeable fluorescent nuclear dye. Control experiments on a population of infected and uninfected RBCs conducted with and without DAPI did not reveal any change in the buckling phenomena. Initially, a gentle flow with a fluorescence scan is used for sampling of appropriate red cells. Once a desirable cell is viewed, the cell is trapped by switching on the laser trapping field. The flow is then stopped, and the folding (F) and unfolding (UF) time-values are measured. Figure 2(a) shows the folded RBC. Unfolding occurs upon removal of the laser trapping field. These F and UF values are robust and do not change for up to 1–2 min of trapping and untrapping of the same RBC, repeatedly. Typical F and UF states of a normal RBC are shown in Fig. 2(b), Video 1, and Video 2. The intraerythrocytic stages of the human malaria parasite \( P. falciparum \) take \( \sim 48 \) h to complete one cycle as they progress through ring, trophozoite, and schizont stages.

It is known that the shear modulus and the deformability of infected red cells increase as they progress to the schizont stages. It is difficult to distinguish between infected and uninfected RBCs through simple bright-field imaging, especially during the early ring stages (0–16 h) of the parasite. Therefore, a synchronization of the \( P. falciparum \) culture, along with use of the fluorescence attachment to our optical trap, enabled us to assess OTAFUR values for unequivocally identified parasitic stages as detected by DAPI staining [Fig. 3(a)]. It was observed that the F and UF values for different parasitic stages changed distinctly during the late ring to early trophozoite stage at \( \sim 16 \) h (Fig. 3). It is to be noted that the currently employed technique of micropipette aspiration does not work well with mature stages of malaria-infected RBCs.

Our measurements show that the F and UF parameters can help resolve the buckling properties of different stages of malarial infection [Fig. 3(b) and 3(c)]. UF values show greater...
resolution to distinguish various stages, and the maximal change occurs at $\sim 32$ h which approximately represents the early schizont stage. Earlier, a recovery parameter was reported in red cells (time constant), which was determined by stretching red cells immobilized at one end and allowing the cell to recover. The OTAFUR unfolding time is reflective of the inherent membrane properties comparable to this time constant. However, unlike earlier methods, the buckling is caused by a definitive laser power and remains constant in a setup. Moreover, the unfolding time is in seconds, which allows for far greater temporal resolution [Fig. 3(a)]. We observe similar behavior of mouse RBCs in murine models of malaria ($P.$ bergheri ANKA and $P.$ yoelii), where stage-specific assessments of RBC deformability have not been reported previously (Fig. 4). It is apparent from Figs. 3(b) and 3(c) that uninfected RBCs in the population also show distinct changes in F and UF values, indicating a trans-effect of parasitized cells on the uninfected cells. We used OTAFUR to explore the effects of PRBCs on neighboring RBCs. It has been documented that a small percentage of PRBCs (5%), as detected in the peripheral blood of patients, can influence the mechanical properties of uninfected cells, possibly resulting in severe anemia.16,17

Measurements of cell deformability have been carried out earlier on malaria-infected RBC populations using a laser-assisted optical rotational cell analyzer (LORCA).16 In this assay, a diffraction pattern of the ellipticity of the population was evaluated, from which it was possible to deduce the deformability of a population of RBCs. We have assessed the effects of conditioned parasite CM on NRBCs. A schematic of our experiment is shown in Fig. 5(a). The medium is removed after requisite time periods, and NRBCs are treated for 24 h with the CM. The cells are then washed, and one aliquot is immediately analyzed using OTAFUR [Fig. 5(b)], while the

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**Video 1** Real-time movie clip of a single, healthy, human red blood cell undergoing folding action as soon as the laser optical trap is switched on. Note that the other two cells in the frame simply undergo Brownian-like motion, their overall disk-like shape remaining intact. (QuickTime 758 kb).

**Video 2** Real-time movie clip showing the unfolding of a healthy, human red blood cell into its normal biconcave disk-like shape upon removal of the optical trap. (QuickTime, 699 kb).

**Fig. 3** (a) Images of DAPI-stained uninfected (U) and $P.$ falciparum infected RBCs at respective time points postsynchronization as seen in (a) bright field and (b) through fluorescent attachment. (b) F and (c) UF times of different RBCs versus time after synchronization of $P.$ falciparum culture containing 1% parasitemia. N: normal RBCs; U: uninfected RBCs from synchronized culture at 8–16 h time point. Each point represents a single RBC, and horizontal bars represent the mean of each group R: ring; T: trophozoite, and S: schizont ($P$ value: $^*<0.05$, $^{**}<0.01$, $^{***}<0.001$).
Fig. 4 Folding time and unfolding time of different RBCs from *P. berghei* ANKA infected (a) and *P. yoelli* infected (b) BALB/c mice (*P* values: *< 0.05, **< 0.01, ***< 0.001*).

Fig. 5 Effect of *P. falciparum* CM on folding and unfolding of normal NRBCs. (a) Schematic for collection of CM from different stages post synchronization. F and UF times of (b) RBCs incubated with different CM for 24 h and (c) after recovery in normal medium for another 24 h N: normal RBCs incubated in normal medium (*P* values: *< 0.05, **< 0.01, ***< 0.001*).
remaining cells are put back with normal medium for 24 h and then tested using OTAFUR/H20851. It is apparent that the medium of parasitized culture contains one or more components that mediate measurable changes in normal RBCs/H20849. The effects are transient, and the cells recover/H20850. Our experiments in Fig. 3 did reflect these changes between URBCs and NRBCs, but did not show statistical significance perhaps because the cells were subjected to the CM only for 8 h. Our detailed observations indicate that 24-h incubation shows significant effects on the URBCs, and is indeed also dependent on the percentage parasitemia data not shown. Moreover, control experiments were conducted to establish that normal RBCs do not show any change in folding/unfolding for up to 48 h of incubation in normal medium. It is pertinent to note that preliminary experiments have been conducted by us to explore possible mediators in the CM; our results indicate that proteins might not be active mediators because measurements indicate the effects to be heatstable. There might be a possible role played by ionic flux as ion chelators and channel blockers appear to reverse the changes.

In order to place our findings in a proper perspective, we make a comparison of shear modulus values that we determine with those obtained using standard rheological and optical stretcher methods. For determining shear modulus in the present experiments, the trap was focused near the surface of the flow cell. Typically, the flow was stopped and an RBC was trapped. Once the RBC was trapped and folded, flow was started.

Because of the viscous drag experienced by the trapped RBC, it elongated and at a critical flow speed, escaped the trap. Velocity of the escaped RBC was measured by counting the number of frames it took to escape from the field of view after getting released from the trap. Calculation of shear modulus was done by the following formula:

\[ \mu = \frac{\eta L_0^2}{Z_{eq}} \]

where \( \eta \) denotes the medium viscosity, \( L_0 \) is the length of the folded RBC prior to the start of the fluid flow, \( \Delta L \) is the maximal change in the length upon application of fluid action, and \( V \) is the escape velocity of the RBC. \( 1/Z_{eq} = 1/Z_1 \)

Video 3 Trapping of a flowing healthy, human red blood cell (NRBC) by an optical trap. Note how the flow of the medium elongates the trapped cell. The periodic variations that are observed are due to the non-constant action of the peristaltic pump used in our experiments. (QuickTime, 1.4 MB) [URL: http://dx.doi.org/10.1117/1.3037342.3].

Video 4 Trapping of a flowing, malaria-infected red blood cell (PRBC) by an optical trap. The flow of the medium leads to considerably less elongation of the cell, compared to a healthy cell, due to its enhanced rigidity that accompanies Plasmodium infection. (QuickTime, 831 kb) [URL: http://dx.doi.org/10.1117/1.3037342.4].
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