Biophysical Journal
Article

Biophysical Society

Evidence against a Role of Elevated Intracellular Ca^{2+} during *Plasmodium falciparum* Preinvasion

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ABSTRACT Severe malaria is primarily caused by *Plasmodium falciparum* parasites during their asexual reproduction cycle within red blood cells. One of the least understood stages in this cycle is the brief preinvasion period during which merozoite-red cell contacts lead to apical alignment of the merozoite in readiness for penetration, a stage of major relevance in the control of invasion efficiency. Red blood cell deformations associated with this process were suggested to be active plasma membrane responses mediated by transients of elevated intracellular calcium. Few studies have addressed this hypothesis because of technical challenges, and the results remained inconclusive. Here, Fluo-4 was used as a fluorescent calcium indicator with optimized protocols to investigate the distribution of the dye in red blood cell populations used as *P. falciparum* invasion targets in egress-invasion assays. Preinvasion dynamics was observed simultaneously under bright-field and fluorescence microscopy by recording egress-invasion events. All the egress-invasion sequences showed red blood cell deformations of varied intensities during the preinvasion period and the echinocytic changes that follow during invasion. Intraerythrocytic calcium signals were absent throughout this interval in over half the records and totally absent during the preinvasion period, regardless of deformation strength. When present, calcium signals were of a punctate modality, initiated within merozoites already poised for invasion. These results argue against a role of elevated intracellular calcium during the preinvasion stage. We suggest an alternative mechanism of merozoite-induced preinvasion deformations based on passive red cell responses to transient agonist-receptor interactions associated with the formation of adhesive coat filaments.

INTRODUCTION

Most cases of severe malaria in humans are caused by the malaria parasite *Plasmodium falciparum* (*Pf*), one of the five malaria parasite species infecting humans. It is the asexual reproduction cycle of the parasite within human red blood cells (RBCs), initiated by merozoite invasion, that is responsible for the symptoms in malaria disease. *Pf* merozoites are pear-shaped spheroids of ~1.0–1.2 μm in diameter, with an apex structure that has to become aligned perpendicular to the RBC membrane for initiating parasite penetration (1,2).

In studies of *Pf* growth using cultures sustained with RBCs of different densities to reflect different hydration states, it was found that the invasion efficiency decreased progressively with the increase in RBC density (3). Because disease severity is associated with high parasitemia, the density effect contributes protection by preventing the development of high parasitemia in all inherited RBC abnormalities associated with the presence of dense RBC subpopulations (3). The search for clues to the possible mechanisms of this density effect focused attention on the events taking place between the instant a merozoite makes first contact with an RBC and the time when it becomes apically aligned, ready for invasion—the preinvasion stage.

The preinvasion stage is very brief, variably reported as lasting between 2–50 s (4–6). Microscopy, electron microscopy (7), and video microscopy (4,6,8,9) records of preinvasion and invasion stages have collectively documented the following sequence of dynamic events during most of the preinvasion periods observed so far: 1) random initial merozoite-RBC contacts away from the merozoite apex elicit reversible interactions between merozoite coat agonists and RBC membrane receptors (1), with coat filaments of 20–150 nm length joining the two surfaces (7); 2) dynamic RBC deformations of variable intensity emanating from merozoite contact points; 3) a positional progression of the merozoite toward an irreversible apical contact driven by a gradient of increasing adhesin concentrations on the merozoite coat (10–12); 4) cessation of RBC deformations

Submitted September 13, 2017, and accepted for publication February 9, 2018.

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Editor: H. Wiley.
https://doi.org/10.1016/j.bpj.2018.02.023

with restoration of normal biconcave shape (4,8); and 5) apex alignment of the irreversibly attached merozoite perpendicular to the RBC surface with formation of a tight junction structure (1,4,8,13,14). Merozoite penetration is frequently, but not always, accompanied by echinocytic shape changes of variable duration, usually ~5–15 min, after which the invaded cell regains its preinvasion shape with a ring-shaped parasite within (4,6). The membrane area and volume of host RBCs were shown to remain essentially unchanged during all these shape changes (15,16).

The preinvasion period remains one of the least understood stages of the malaria invasion process. Much progress has been made on the molecular and genetic identity of the variety of agonist families on the merozoite coat and of the receptors on the RBC surface that mediate the reversible and irreversible interactions operating during preinvasion and invasion stages (1,12,17–19). This contrasts with the meager progress made in the understanding of the mechanistic dynamics at play during preinvasion.

The only working hypothesis advanced so far on the mechanism of the merozoite-induced RBC deformations involves calcium mediation (5). The hypothesis was based on two critical assumptions: 1) that the merozoite-elicited RBC deformations were an active response of the RBC membrane aimed at speeding up apical contacts (4), thus increasing invasion efficiency, a response progressively inhibited in dense RBCs; and 2) that the deformations were caused by transients of local intracellular calcium concentration ($[Ca^{2+}]_i$) increase at the inner membrane surface, based on evidence that invasion was strongly dependent on the presence of calcium in the medium (10,20–22).

Weiss et al. (10) carried out a thorough investigation of the role of calcium during preinvasion and invasion stages by adding purified schizonts to RBCs loaded with the calcium-sensitive fluorescent dye Fluo-4. In 248 invasion events, recorded on time-lapse sequences alternating bright field and fluorescence frames, Ca^{2+} signals were detected only in 45% of instances. When present, the Ca^{2+} signals appeared toward the end of deformations and displayed a characteristic sequence starting with an intense punctate signal localized to the merozoite, followed by a variable diffusion pattern within invaded RBCs undergoing echinocytic transients (10).

At face value, these results suggest that $[Ca^{2+}]_i$ elevations play no role in the dynamic deformations assumed necessary for apical alignment, which is against the tenets of the calcium hypothesis. However, a number of technical and methodological issues prompted the need for a reassessment of the evidence and for further research to resolve the role of $[Ca^{2+}]_i$ during preinvasion, penetration, and immediate postinvasion stages. We consider these issues next.

A main methodological concern applies to the correct use of Fluo-4 in the conditions of merozoite invasion tests. Fluo-4 is loaded into cells with the use of its acetoxymethyl derivative, Fluo-4 AM, but AM derivatives do not permeate membranes. The hydrophobicity of the X-AM complexes allows them to rapidly partition into the hydrophobic core of cell lipid bilayers when added dissolved in dimethyl sulfoxide (DMSO) into cell suspensions. From there, esterases operating at the inner membrane surface break down the AM residues, releasing free X into the cell cytoplasm. In their original work, Tsien et al. (23–27) assumed that the formaldehyde released as a byproduct of AM hydrolysis diffused away from the cells with no toxic side effects. But Tiffert et al. (28) showed that all the formaldehyde released remains retained within the cells, and that for cells that depend on glycolytic metabolism for ATP synthesis, such as RBCs, formaldehyde exerts a powerful metabolic block on glycolytic ATP production. In substrate-free media, formaldehyde has no effect on the ATP content of the cells (28). In the presence of glucose, X-AM or formaldehyde treatments cause a sharp fall in cell ATP (28). This happens because ATP is rapidly consumed by hexokinase-mediated phosphorylation during the initial steps of glycolytic metabolism, whereas downstream ATP synthesis is blocked.

The formaldehyde-induced glycolytic block can be easily prevented by the inclusion of pyruvate in incubation or culture media (29,30). In the experiments of Weiss et al. (10), Fluo-4 AM exposure was in glucose-containing RPMI without pyruvate. Therefore, target RBCs may have been depleted of ATP, a necessary cofactor for invasion (31), rendering the assumed normality of the reported invasion responses questionable.

Additional issues of concern in the experiments of Weiss et al. (10) relate to the possibility of false negative Ca^{2+} signals from cells with low Fluo-4 loads and of relatively prolonged time gaps in time-lapse records, missing fleeting and potentially relevant events. The distribution of Fluo-4 in the RBC population was not investigated, leaving open the possibility that Ca^{2+} signals from low-Fluo-4 RBCs were below detectable levels. In the sample of time-lapse images, alternating bright-field and fluorescence images, critical periods of observation were missing. Records with higher time resolution are clearly needed to convincingly rule out transient Ca^{2+} signals during preinvasion. In the experiments reported here, we address each of these issues in detail.

MATERIALS AND METHODS

Chemicals and solutions

The experiments were performed using the following solutions referenced in the text. All chemicals were obtained from Sigma-Aldrich (Gillingham, UK), if not otherwise specified. Solution A: NaCl, 145 mM; KCl, 3 mM; Na-HEPES (pH 7.5 at 37°C), 10 mM; and $MgCl_2$, 0.15 mM. Solution AE: as A, plus Na-EGTA, 0.1 mM. Solution AIP: as A, plus inosine, 5 mM, and Na-pyruvate, 5 mM. Solution HKIP: NaCl, 60 mM; KCl, 90 mM; Na-HEPES (pH 7.5 at 37°C), 10 mM; $MgCl_2$, 0.15 mM; $CaCl_2$, 0.20 mM; inosine, 5 mM; and Na-pyruvate, 5 mM. Wash medium (WM): RPMI-1640 supplemented with HEPES, 40 mM; D-glucose, 10 mM; glutamine, 2 mM; and gentamicin sulfate, 25 mg/L. Wash medium with pyruvate

(WMP): as WM, plus Na-pyruvate, 5 mM. Culture medium (CM): as WM, plus AlbumaxII, 0.5% vol/vol. Culture medium with pyruvate (CMP): as CM, plus Na-pyruvate, 5 mM.

Malaria culture

Pf A4 (32) and 3D7 parasites were cultured in human RBCs from healthy volunteers under low-oxygen atmosphere (1% O_2, 3% CO_2, 96% N_2) according to standard protocols (33–35); the culture medium was changed daily. The RBCs were isolated from leukocytes and platelets using Lymphoprep (STEMCELL Technologies, Cambridge, UK) and used within seven days. *Pf* cultures were synchronized by the sorbitol lysis method (36) as needed; mature trophozoites and schizonts were selected from cultures by gelatin flotation (27,28,37,38) or by magnetic separation (39). Parasitemia was assessed by microscopic inspection of Giemsa stain blood smears (40).

Incorporation of Fluo-4 in RBCs

Fluo-4 was incorporated nondisruptively into RBCs using the acetoxymethyl derivative Fluo-4 AM (Invitrogen, Paisley, UK). The stock solution of Fluo-4 AM in DMSO was prepared to a concentration of 0.5 mM. Fresh RBCs were washed twice in AE, once more in AIP, and resuspended in AIP at 10% Hct. Fluo-4 AM in DMSO was added to the cell suspension to provide a final concentration of 5 μM. The suspension was incubated at 37°C for 45 min, washed twice in WMP, and finally suspended in CMP. The suspension was incubated for a further 15 min to enable the complete deesterification of the Fluo-4 AM molecules, as suggested in the product manual. The entire Fluo-4 loading procedure was performed under minimal light exposure.

Formaldehyde loading of RBCs

Fresh RBCs were washed and suspended at 10% Hct in solution A with no metabolic substrates. Formaldehyde was added from a 1 M stock solution to half of the RBC suspension to a final concentration of 0.4 mM, and both suspensions were incubated at 37°C for 1 h. After the incubation time, RBCs from each suspension were washed twice in A, resuspended in CM at 2% Hct, and distributed in two flasks. Four different suspensions were obtained: control (C), control + pyruvate (C + Pyr), formaldehyde (FA), and formaldehyde + pyruvate (FA + Pyr). For the experiments, an aliquot of *Pf* A4 clone suspension (32) with ~80% parasitemia of mature trophozoites and schizonts was added to each flask to obtain an initial parasitemia of around 3%. This was followed by incubation of the flasks at 37°C under low O_2 for ~28 h, at which time parasitemia was assessed by inspection of Giemsa-stained culture smears. Parasitemias were measured by counting 2000 RBCs in triplicates, with replicate percentages agreeing within 5%. The results are reported and analyzed in Effects of FA and Pyruvate on *P. falciparum* Invasion and Growth and Fig. 1 *a*.

Parasite culture in Fluo-4-loaded RBCs with pyruvate

Fresh RBCs, suspended in WM at 2% Hct, were loaded with Fluo-4 by adding Fluo-4 AM to a final concentration of 10 μM in the suspension (10). In these conditions, full Fluo-4 incorporation into the small 2% fraction of RBCs would generate a Fluo-4 concentration of 0.5 mmol/L cells. With a stoichiometry of four molecules of FA released per molecule of Fluo-4 incorporated, the concentration of FA experienced by the cells would be ~2 mmol/L cells. Half of the cells were resuspended in WM and half in WMP, all incubated at 37°C for 1 h and washed three times in 10 volumes of WM (10). Finally, the cells were loaded in chambers labeled as Fluo-4 and Fluo-4 + pyruvate (Fluo-4 + Pyr). Enriched 3D7 strain schizonts isolated by magnetic separation were added to both cultures and to a C sample of untreated RBCs (RBCs without Fluo-4 at 2% Hct) to obtain an initial parasitemia of 3%. Parasitemias in Fig. 1 *b* were estimated after 28 h from four experiments, and *p*-values were calculated using an unpaired *t*-test.

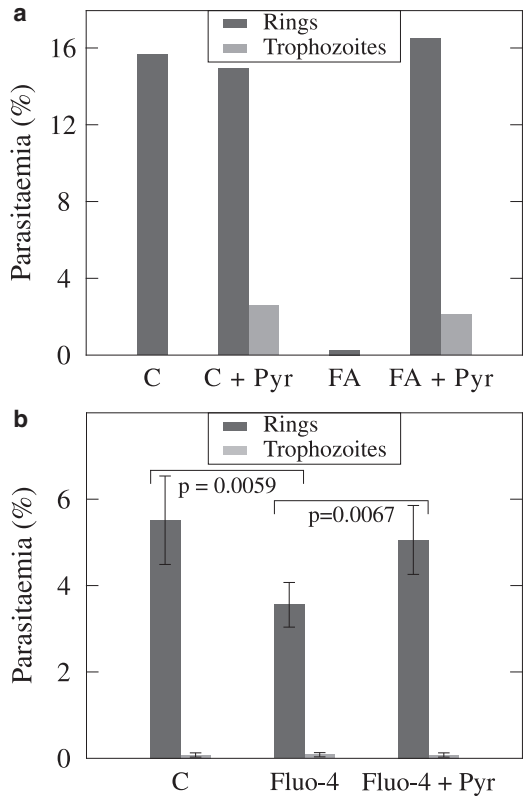

FIGURE 1 Effects of FA and Fluo-4-AM on *Pf* invasion in the presence or absence of pyruvate. (*a*) RBCs were exposed to FA in the absence (FA) or presence of pyruvate (FA + Pyr) as detailed in Formaldehyde Loading of RBCs. The results were compared with FA-free controls in the absence (C) or presence of pyruvate (C + Pyr). *Pf* A4 clone parasitemias were measured after 28 h, and triplicates agreed within 5%. (*b*) This panel shows the effects of Fluo-4 loading, following the experimental protocol of Weiss et al. (10), as reported in Parasite Culture in Fluo-4-Loaded RBCs with Pyruvate. *Pf* 3D7 parasitemias of four experiments were measured after 28 h culture in controls not exposed to Fluo-4-AM (C), and in Fluo-4-AM-treated RBCs in the absence (Fluo-4) and presence of pyruvate (Fluo-4 + Pyr). Significant differences ($p < 0.05$) are shown in the graph.

Ionomycin-treated RBCs

Fluo-4-loaded RBCs as described in Incorporation of Fluo-4 in RBCs were washed twice and resuspended at 10% Hct in HKIP. Ionomycin stock solution in DMSO (2 mM) was added to a final concentration of 0.2 μM. The entire procedure was performed at room temperature.

Vanadate-treated RBCs in low-K^+ and high-K^+ media

1 mL of RBCs was loaded with Fluo-4 in AIP as described in Incorporation of Fluo-4 in RBCs. A 0.1 mL aliquot was used as a C, and to the remaining 0.9 mL, vanadate and $CaCl_2$ were added to render final concentrations of 1 mM each from stock solutions of vanadate (100 mM) and $CaCl_2$ (200 mM).

A similar protocol was applied for vanadate-treated RBCs in high-K^+ medium: Fluo-4-loaded RBCs were washed twice and resuspended in HKIP at 10% Hct. Vanadate was added to the suspension to a concentration of 1 mM. Samples from C and vanadate-treated suspensions in low-K^+ and high-K^+ media were loaded in chambers for observation.

Imaging of the calcium egress-invasion assay

A 3D7 *Pf* suspension at 0.2% Hct with at least 80% parasitemia was prepared for imaging by mixing Fluo-4-loaded uninfected RBC (see Incorporation of Fluo-4 in RBCs) with an aliquot of highly concentrated (97–100%) parasitized RBCs obtained by magnetic separation. Imaging was done in SecureSeal Hybridization Chambers (Sigma-Aldrich). A custom-built temperature-control system was used to maintain the optimal culture temperature of 37°C during imaging experiments. The sample was placed in contact with a transparent glass heater driven by a proportional-integral-derivative temperature controller in a feedback loop with the thermocouple attached to the glass slide. A Nikon Eclipse Ti-E inverted microscope (Tokyo, Japan) was used with a Nikon 60× Plan Apo VC, NA 1.40, oil-immersion objective, kept at 37°C through a heated collar. Motorized functions of the microscope were controlled via custom software written in-house. Images were acquired using a CMOS camera (model GS3-U3-23S6M-C, Point Gray Research/FLIR Integrated Imaging Solutions (Richmond, Canada)). Focus was maintained throughout experiments using Nikon Perfect Focus hardware.

To record invasion events in bright field and Ca^{2+} signals under fluorescence with high time resolution, the microscope was equipped with a custom-built light-emitting diode (LED)-based illumination system. The system allows synchronizing camera frames with different LEDs (Mouser Electronics, High Wycombe, UK) of the illumination system with a predefined camera driven sequence. We used an alternating sequence of green LEDs (LED Engin LZ4-24MDCA-0000, 523 nm peak wavelength) for bright-field illumination and blue LEDs (Lumileds LXZ1-PB01, 470 nm peak wavelength) for epifluorescence illumination with fluorescence filter block (GFP-3035D, exciter FF01-472/30, dichroic FF495-Di03, emitter FF01-520/35; Semrock, Rochester, NY). In recorded events, frames were acquired in bright field and fluorescence in an alternating fashion with an exposure time of 200 ms.

We found that recording events at five frames per second (fps) optimized the fluorescent signal from invaded cells loaded with Fluo-4 and provided a detailed resolution of the preinvasion and invasion process. Each experiment lasted ~2 h to enable recording of a sufficient number of events and was performed in darkness to prevent photobleaching and to avoid signals from the environment.

RESULTS

Effects of FA and pyruvate on *P. falciparum* invasion and growth

The aim of these experiments was to establish whether *Pf* invasion could be affected by the FA released during the incorporation of AM-compounds into RBCs, and, if so, whether pyruvate could prevent these effects (29). Fluo-4 AM was added to RBC suspensions to generate a final concentration of 1–2 mmol/L cells of Fluo-4, assuming full release of the free dye into the cell (6,28,29). The concentration of FA released and trapped by the cells after Fluo-4 loading reached 4–8 mmol/L cells on full ester hydrolysis (28), and 4 mmol/L cells was the concentration tested in the experiments of Fig. 1 *a* following the protocol in Formaldehyde Loading of RBCs.

During the growth assay in glucose-containing RPMI medium, ATP was expected to fall rapidly in FA-treated cells, but only in the absence of pyruvate. Merozoites released during the first hours of incubation would thus encounter different ATP contents in RBCs under FA and FA + Pyr conditions. Under test was the comparison of growth in these two conditions. The results (Fig. 1 *a*) showed that parasite growth was comparable in controls and in FA-treated cells in the presence of pyruvate (Fig. 1 *a*: C, C + Pyr, and FA + Pyr). Growth was almost fully inhibited in the culture with FA-treated cells in the absence of pyruvate (Fig. 1 *a*: FA). The near-total absence of infected red blood cells or of Giemsa-stained residual parasite material in this condition suggested that invasion was minimally consummated in these cells. The fact that pyruvate fully prevented this effect indicated that ATP must have been depleted to levels incompatible with invasion in the FA-treated cells by the time most merozoites had egressed. These results support the early conclusions of Dluzewski et al. (31), based on experiments with resealed ghosts, that ATP depletion prevents invasion.

To evaluate the extent to which the FA effects reflected those caused by Fluo-4 incorporation when using the experimental protocol of Weiss et al. (10), we investigated the effects of pyruvate on growth by replicating their experimental conditions (see Parasite Culture in Fluo-4-Loaded RBCs with Pyruvate). We compared growth in RBCs loaded with Fluo-4 in the presence or absence of pyruvate, and the results are shown in Fig. 1 *b*. In the absence of pyruvate (Fig. 1 *b*: Fluo-4), growth was reduced by ~30% relative to Fluo-4-free C and Fluo-4 + pYR (Fig. 1 *b*: C, Fluo-4 + Pyr), confirming that the invasion efficiency was reduced in ATP-depleted RBCs. Once invasion occurs, no difference was noticed in the development of the parasites at ring stage between Fluo-4 and Fluo-4 + Pyr conditions.

When comparing the results in Fig. 1, *a* and *b*, it is important to note that with the protocol in Fig. 1 *a*, FA was delivered instantly and uniformly to all the cells at the maximal intended concentration, whereas with the protocol of Weiss et al. (10) in Fig. 1 *b*, FA would have been released more slowly, at the rate of AM-ester breakdown in each cell during Fluo-4 incorporation. Moreover, as documented below in Figs. 3 and 5, Fluo-4 loads varied substantially among the cells and hence also the extent of FA trapped by each cell, causing variable rates and extents of ATP depletion in the RBC population. Thus, the limited growth inhibition observed with the protocol of Weiss et al. (10) relative to that of Fig. 1 *a* could be explained by the slower and reduced FA release from cell subpopulations with varied esterase activity incorporating submaximal levels of Fluo-4 (Fig. 3).

Distribution of Fluo-4 in treated RBCs

To ascertain the reliability of Fluo-4-loaded RBCs to report Ca^{2+} signals in invasion assays avoiding false negatives, it

was necessary to investigate the population distribution of the fluorescent Ca^{2+} dye and confirm that all cells contained enough dye to generate detectable signals. In physiological conditions, RBCs maintain $[Ca^{2+}]_i$ of ~10–50 nM by a balance between inward Ca^{2+} leak (P_{Ca}) and active Ca^{2+} extrusion via the ATP-fueled plasma membrane calcium pump (PMCA) (Fig. 2) (41). The physiological pump-leak turnover rate varies within the range of 10–50 μmol/(L cells•h), depending on cell age and medium conditions (26,42,43). The K_d of Fluo-4 for Ca^{2+} is ~345 nM, so that fluorescent signals are expected to become detectable in RBCs containing sufficient dye when $[Ca^{2+}]_i$ increases above 80–100 nM (44).

In the current study we used ionomycin, a nonfluorescent Ca^{2+} ionophore, and vanadate, a cell-permeant, irreversible inhibitor of ATP-fueled pumps, to elevate $[Ca^{2+}]_i$ and thus elicit Fluo-4 fluorescent signals (45,46).

The interplay of these agents with the transport systems relevant to RBC Ca^{2+} homeostasis is illustrated in Fig. 2. With ionomycin, it is possible to increase the Ca^{2+} permeability of the plasma membrane to levels exceeding the maximal Ca^{2+} extrusion capacity of the PMCA, generating a uniform high-Ca^{2+} load in all the cells of a given sample, thus saturating the Fluo-4 light-emission intensity from every cell in the population. In these conditions, variations in the fluorescence signal report the true distribution of incorporated Fluo-4 in the RBC population. With vanadate,

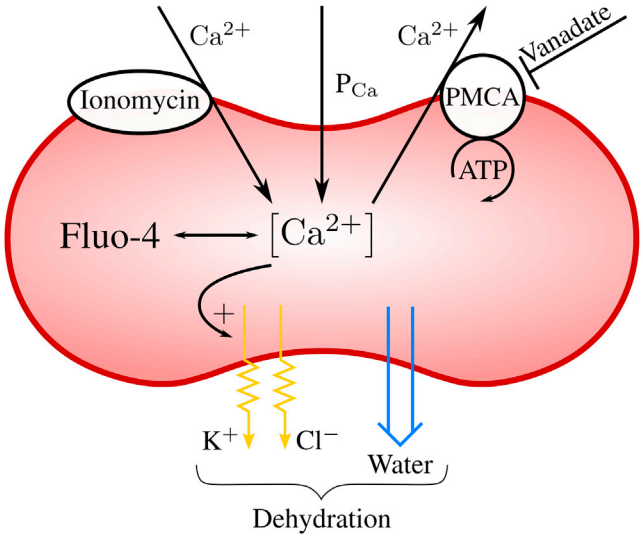

FIGURE 2 Illustration of the effects of ionomycin and vanadate on the calcium homeostasis of human RBCs. In physiological conditions, Ca^{2+} ions enter RBCs through low-permeability pathways (P_{Ca}) and are extruded by the ATP-fueled PMCA. Free Fluo-4 binds to Ca^{2+} ions with a K_d around 345 nM, generating a fluorescent signal (44). Physiological $[Ca^{2+}]_i$ levels ($\leq$50 nM) remain below the detectable threshold. Increasing the Ca^{2+} permeability with ionomycin or inhibiting the PMCA with vanadate elevates $[Ca^{2+}]_i$, enhancing the fluorescence signal. Elevated $[Ca^{2+}]_i$ activates Ca^{2+}-sensitive K^+-channels in the RBC plasma membrane, leading to KCl and water loss with cell dehydration and shrinkage. To see this figure in color, go online.

the intensity distribution of the generated fluorescent signals is a composite of the distributions of Fluo-4 and of the physiological Ca^{2+} permeability (P_{Ca}) in the RBC population (28,47). Fluorescence intensity distributions may be explored with the RBCs suspended in low-K^+ (plasma-like) or high-K^+ media. In low-K^+ media, activation of the Ca^{2+}-sensitive K^+ channels of RBCs (48–50) hyperpolarizes the cells and causes the net loss of KCl and water (Fig. 2). This leads to cell dehydration and shrinkage, easily detectable under bright-field observation, offering a Fluo-4-independent visual estimate of the distribution of $[Ca^{2+}]_i$ when high enough to activate the Gardos channels ($[Ca^{2+}]_i$ > 70–80 nM) (43,51)). A comparative analysis of the fluorescence distributions and of the dehydration response elicited by ionomycin and vanadate was expected to allow a rough estimate of the stochastic probability of invasion events in Fluo-4-loaded RBCs failing to produce detectable fluorescent signals (false negatives).

Representative bright-field and fluorescence images of Fluo-4-loaded RBCs exposed to ionomycin or vanadate are shown in Figs. 3 and 4, respectively. Under bright field, the C is largely dominated by normal-looking biconcave cells; using fluorescence, no signal is detected from any of the RBCs in the corresponding field (Fig. 3). The isolated strong signals visible at higher magnifications in the corresponding inset in bright field (Fig. 3) can be attributed to the tiny proportion (<0.1%) of contaminant lymphocytes retained in isolated RBC preparations.

Ionomycin-treated RBCs, suspended in low-K^+ medium for observation, appear uniformly shrunken in bright field (Fig. 3), as expected with RBCs in dehydrated conditions with uniform Ca^{2+}-saturation of their Gardos channels. The distribution of fluorescence intensities in the ionomycin-treated cells (Fig. 3) show a wide variation, reflecting the actual Fluo-4 distribution in the RBC population. A careful comparison with the corresponding bright-field image shows Ca^{2+} signals emanating from all the cells. Thus, despite the large variation in Fluo-4 contents, all the cells in the population generate detectable Ca^{2+} signals at Fluo-4-saturating $[Ca^{2+}]_i$ levels.

Bright-field images of vanadate-treated cells (Fig. 4) show typical fields of dehydrated, shrunken cells in low-K^+ medium, and of nondehydrated cells with largely preserved discocyte shapes in high-K^+ medium. In fluorescence (Fig. 4), Ca^{2+} signals are detected in the majority, but not in all, of the cells of the corresponding bright fields. This is particularly noteworthy for the cells suspended in high-K^+ medium. Compared with ionomycin-treated cells (Fig. 3), vanadate-treated cells show overall reduced fluorescence levels and sharper cell-to-cell differences, reflecting wider variations in Ca^{2+} gain. The distribution of fluorescent intensities assessed 3 h later showed no significant difference, suggesting that the intracellular calcium concentration had already reached saturation levels for the Fluo-4 signal in most cells. The shown intensity distribution

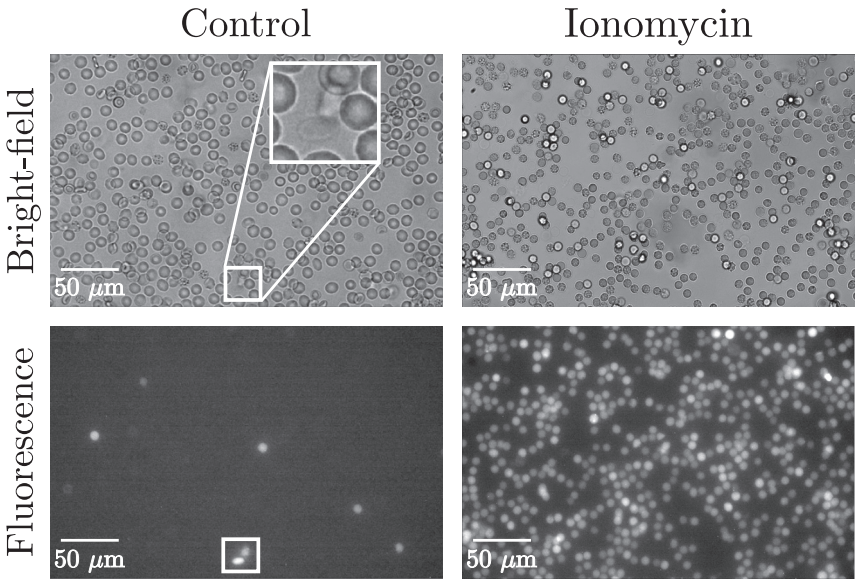

FIGURE 3 Effects of ionomycin-induced calcium loads on the bright-field appearance and fluorescence signal from Fluo-4-loaded RBCs. The results are representative of four similar experiments. Note the dominant normal biconcave discocyte appearance of the C RBCs (*top left*) and the lack of fluorescent signal (*bottom left*). The isolated intense fluorescent spots do not relate to intact RBCs, as illustrated for one such spot in the inset. The dominant appearance of the ionomycin-treated RBCs is that of profoundly shrunken and crenated RBCs (*top right*). Individual fluorescent signals (*bottom right*) can be traced to each corresponding cell in the bright-field image (*top right*). Thus, at saturating Ca^{2+} loads the presence of Fluo-4 is revealed in all cells, but the cell-load distribution appears substantially uneven.

approximates best the true fluorophore distribution in the RBC population. $[Ca^{2+}]_i$ levels appear higher in cells suspended in low-K^+ than in high-K^+ media (Fig. 4) for two reasons. Firstly, cell shrinkage in low-K+ conditions increases $[Ca^{2+}]_i$ at comparable total calcium concentrations. Secondly, a substantial component of the Ca^{2+} leak (P_{Ca}, Fig. 2) is electrodiffusional. The hyperpolarization generated by Gardos channel activation in low-K^+ media increases the driving gradient for Ca^{2+} influx, tending to elevate $[Ca^{2+}]_i$.

The fluorescence distributions obtained in these different conditions are quantified in the histograms of Fig. 5. The images in Figs. 3 and 4 were segmented into regions that identified every single cell in bright field, and partial cells at the edges were excluded using a mask. This segmentation was then superimposed on the fluorescence image of the same field of view, and after background subtraction, the average intensity of the pixels within each cell was measured to construct an intensity distribution across cells (Fig. 5). The fluorescence intensity distributions for ionomycin- and vanadate-treated RBCs are significantly above background for the vast majority of the cells. The distribution of Fluo-4 in ionomycin-treated cells is very broad, with a standard deviation of 31% of the mean, considerably higher than the 20% previously recorded for fura-2 incorporation (52). The distributions of fluorescence intensities in vanadate-treated cells are much narrower, with substantially lower means, reflecting permeability-restricted Ca^{2+} influx,

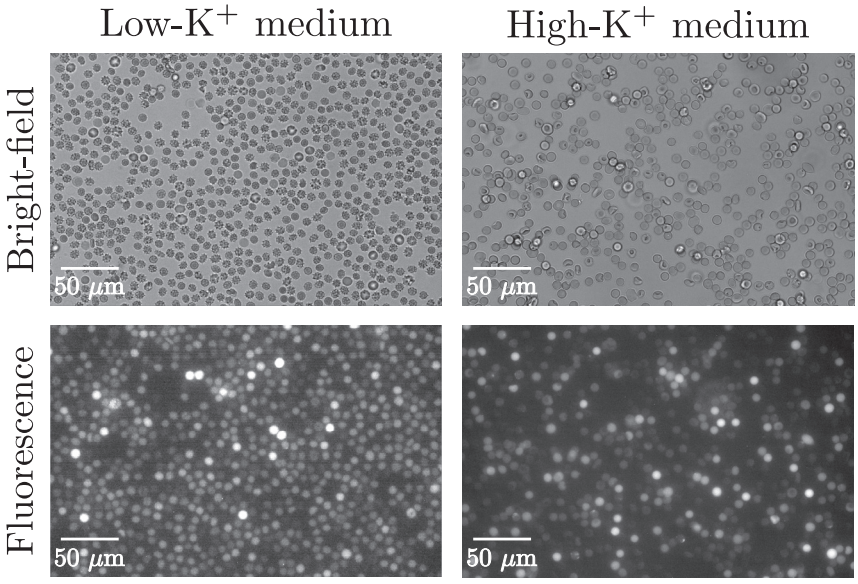

FIGURE 4 Effects of vanadate-induced PMCA inhibition on the bright-field appearance and fluorescence signal from Fluo-4-loaded RBCs in low-K^+ and high-K^+ media. The results are representative of six similar experiments. The resulting fluorescence distributions are a composite of true variations in Fluo-4 contents and differences among cells in calcium leak (P_{Ca}). In low-K^+ media, the dominant appearance is that of dehydrated RBCs (*top left*), contrasting with the dominant normal discocyte appearance of the cells in high-K^+ media (*top right*), where dehydration is prevented. Fluorescence intensities (*bottom panels*) vary sharply among the cells, with no signal at all from a substantial fraction of cells in both conditions.

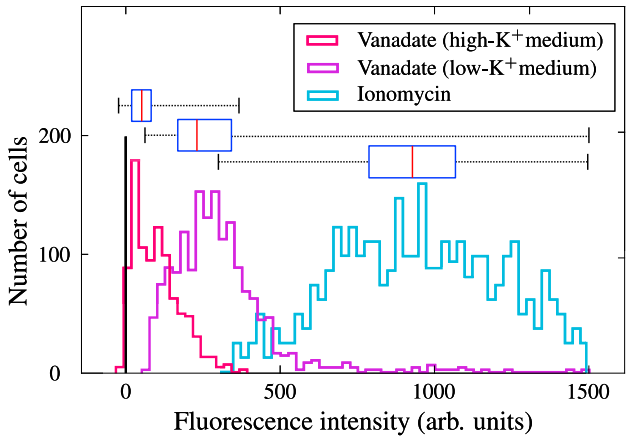

FIGURE 5 Distributions of fluorescence signal intensities from Fluo-4 loaded RBCs treated with ionomycin or vanadate. Mean background signal intensity was estimated from the controls, and it was set as the *x* axis zero. The total fluorescence was calculated by subtracting the background mean from each individual cell's intensity. Fluorescence intensity from low-K^+ vanadate and ionomycin distributions is distinctively higher than the C (RBCs with Fluo-4 only). In the high-K^+ condition, the fluorescence intensity is lower than in the low-K^+ condition, reflecting a permeability-restricted Ca^{2+} influx. In the box plots, the red line indicates the median, the box indicates the 25th and 75th percentiles of the samples, and whiskers denote total data range. To see this figure in color, go online.

more severe in the high-K^+ condition in which around 3% of the cells are below the background.

Ca^{2+} signals were detected from most of the vanadate-treated shrunken cells suspended in low-K+medium (Fig. 4). The mean physiological $[Ca^{2+}]_i$ level within human RBCs suspended in plasma is ~50 nM (26). In the absence of precise in situ calibrations of the Fluo-4 signal, the Fluo-4 detection level for $[Ca^{2+}]_i$ remains unknown. It is therefore important to note that $[Ca^{2+}]_i$ elevations between physiological levels and the Fluo-4 threshold would remain undetected. However, there is strong evidence that the Ca^{2+}-sensitive Gardos channels of the RBC membrane (Kcnn4) (48,53,54) remain viable but inactive during invasion (55,56). This offers an independent estimate of the top limit to which $[Ca^{2+}]_i$ may increase when undetected by Fluo-4. Based on early calibrations of the Ca^{2+} sensitivity of the Gardos channel in human RBCs (51,57), this top limit is ~80–100 nM. Therefore, our results cannot rule out $[Ca^{2+}]_i$ increases below this limit during invasion.

Video microscopy recordings of egress-invasion sequences

We followed the invasion process in 20 Fluo-4-loaded RBCs, from merozoite egress to postinvasion echinocytosis, by video recording under bright field and fluorescence at 5 fps (see Imaging of the Calcium Egress-Invasion Assay). Ca^{2+} signals were not detected in 11 out of 20 experiments. Weiss-Gilson et al. (10) also reported ~55% negative results. However, the probability that this is due to undetectable signals from cells with poor Fluo-4 loads, given the Fluo-4 distributions shown in Figs. 3, 4, and 5, is vanishing small.

In all nine cells with a positive fluorescent response, the fluorescent Ca^{2+} signals were fully confined to the postalignment stages.

All Ca^{2+} signals detected were of the punctate modality described in detail by Weiss-Gilson et al. (10). Fig. 6 shows selected frames of Video S1, representative of a typical punctate response in which the intensity of the Ca^{2+} signal was high, indicating provenance from cells with high Fluo-4 loads, recorded with higher time resolution (10 fps). More than 2 s after the first deformation response to merozoite contact (shown on bright field at 1.4 s postegress) a peak of intense fluorescence, entirely localized to the body of the merozoite, appears within the 0.1 s transition from baseline fluorescence to the next video frame. The following frames show a gradual increase in fluorescence within the boundaries of the invaded RBC toward a homogeneous fluorescence distribution reached after ~5 s postegress, as shown in Fig. 6. The changes in fluorescence intensity gradients clearly point to the merozoite as the main source of elevated RBC Ca^{2+}. In all 20 experiments of this series, no Ca^{2+} signal was seen to originate from locations other than the merozoite. In the 11 punctate-negative experiments, absence of Ca^{2+} signals included all echinocytic periods. These results suggested no increase in the calcium permeability of the RBC membrane throughout invasion, and that elevated $[Ca^{2+}]_i$ was not required for echinocytosis.

An example of invasion processes in which RBCs show weak Ca^{2+} signals from low Fluo-4 loads is reported in Video S2 and in the analysis of Fig. S3. No signal was detected during preinvasion periods both in the case of high and low $[Ca^{2+}]_i$ (Figs. 6 and S3; Videos S1 and S2), thus ruling out false negative results in this series. Taken together, these results made a strong case against the hypothesized role of calcium in preinvasion deformations. Ca^{2+} signals were only detected as an episodic occurrence during postalignment events.

In conclusion, the constant features in all the nine records with positive Ca^{2+} signals were the punctate response to merozoite alignment and the sustained increase in Ca^{2+} signal intensity postinvasion. Variable, inconstant, or uncertain features were 1) the original $[Ca^{2+}]_i$ level within individual target cells (compare background signals in Videos S1 and S2), 2) the duration of the preinvasion stage, 3) the presence and duration of postinvasion shape-quiescent periods, and 4) the delay and morphological progression to echinocytosis from gradual to explosive.

Deformation response of RBCs to initial merozoite contacts

In the original formulation of the calcium hypothesis (5), deformations were assumed to be calcium-driven active

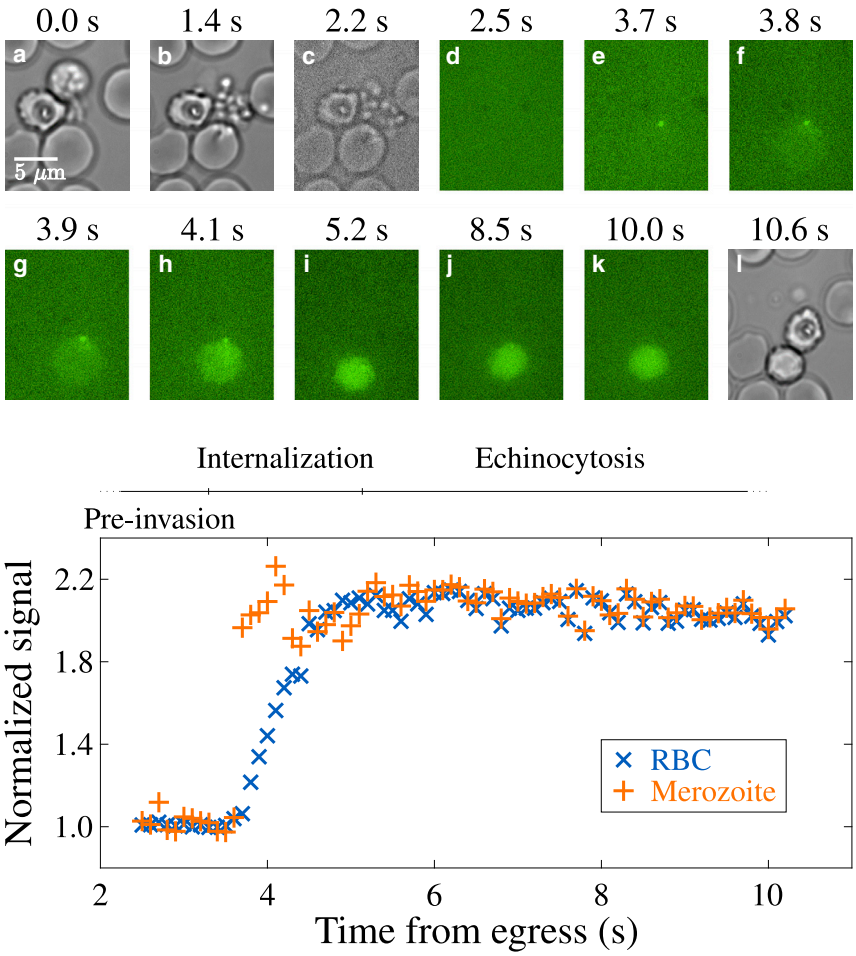

FIGURE 6 Video recording of an egress-invasion sequence in Fluo-4 loaded cells (Video S1) with a high fluorescent intensity punctate response. Selected snapshots are shown in the top panel; the bottom plot quantifies the changes in fluorescent intensities of merozoite and RBC regions over time, normalized to the surrounding background in each frame. Snapshots show as follows: (*a* and *b*) a merozoite upon contact with a healthy RBC triggers cell deformation at 1.4 s after egress; (*c*) switch from bright-field to fluorescence channel; (*d*) the first frame in fluorescence is recorded at 2.5 s but no fluorescence signal is visible until (*e*) a strong signal at 3.7 s is almost entirely confined to the merozoite area and appears as a Fluo-4 saturating intensity, 2.3 s after merozoite contact and local deformation in frame (*b*); (*f–h*) rapid diffusion of the fluorescent signal from the invading merozoite to the RBC in ~0.4 s; (*i–k*) merozoite fluorescence merges with the uniform RBC fluorescence, signaling parasite internalization; and (*l*) echinocytic condition of invaded RBC at the end of recording, on return, to bright-field imaging. The bottom plot gives the time sequence of merozoite and target-cell Ca^{2+} signals during a typical punctate response. It shows the absence of a Ca^{2+} signal during the preinvasion period and the extended duration of the high Ca^{2+} signal during the echinocytic stage. To see this figure in color, go online.

RBC-membrane responses required for apical alignment. In the absence of detectable calcium signals during the preinvasion period, are deformations still active and relevant to merozoite alignment? Could deformation intensity still be correlated with late positive Ca^{2+} signals, potentially associated with subliminal $[Ca^{2+}]_i$ elevations during preinvasion stages? Using the approach developed by Weiss et al. (10), we scored the preinvasion deformations observed under bright field in each of the 20 experiments of this series. The results in Fig. 7 showed no preferential correlation with presence (*green*) or absence (*red*) of Ca^{2+} signals at any of the deformation intensities scored.

DISCUSSION

We investigated the hypothesized role of elevated $[Ca^{2+}]_i$ on the deformation responses that merozoite contacts elicit in RBCs during the preinvasion period (5). We sought to overcome methodological uncertainties from earlier studies concerning the ATP depletion status of the RBCs targeted for invasion, the possibility of false negatives from low-Fluo-4 containing RBCs, and the possibility of brief events being missed during the relatively large gaps in early time-lapse video recordings (10). Ca^{2+} signals were recorded from Fluo-4-loaded RBCs in conditions that ensured preservation of their normal ATP contents (Fig. 1). The distribution of Fluo-4 in the RBC population was measured under a variety of conditions and found to vary widely, but all RBCs were shown to contain sufficient Fluo-4 to elicit detectable Ca^{2+} signals at saturating Ca^{2+} loads (Figs. 3, 4, and 5). Egress-invasion sequences were followed and video-recorded under bright field and fluorescence in Fluo-4-loaded RBCs at frequencies of between 5 and 10 fps, a 10–15-fold improvement on the time-resolution of previous time-lapse recordings (Figs. 6 and S3; Videos S1 and S2). Our results resolve lingering concerns and gaps from earlier studies (10), provide strong evidence against the calcium hypothesis (5), and offer, to our knowledge, a novel insight on the mechanics of merozoite-RBC interactions during the preinvasion stage.

In the 20 egress-invasion assays reported here, Ca^{2+} signals were recorded only in nine (Figs. 6 and S3; Videos S1 and S2), all of the punctate modality originally described by Weiss et al. (10). Ca^{2+} signals were never detected during preinvasion stages regardless of presence, absence or intensity of late fluorescent signal (Figs. 6 and S3; Videos S1

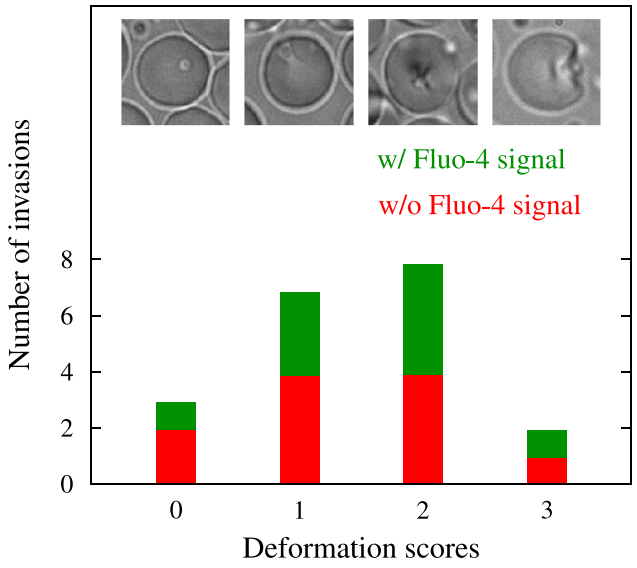

FIGURE 7 Scoring the deformation intensities associated with presence or absence of calcium signals during the 20 experiments of this series. Our scoring was derived from the original Weiss et al. (10) classification. Samples of the zero to three scores used here are shown at the top. Note the absence of correlation between the deformation level and the presence (*green*) or absence (*red*) of Ca^{2+} signal. To see this figure in color, go online.

and S2) or of the intensity of the deformation response (Fig. 7). Taken together, these results argue against the hypothesized role of $[Ca^{2+}]_i$ elevations on merozoite-elicited deformations (5)), unless confined to submembrane microdomains within levels below Gardos channel activation, undetectable by Fluo-4.

The conclusions concerning calcium agree with those of McCallum-Deighton and Holder (22) that the role for calcium in merozoite invasion is extracellular (10). Results of Gao et al. (58) demonstrate that calcium is required by merozoites for Ca^{2+} signaling of EBA-175 discharge, leading to apical junction formation, and indicate that all merozoites poised for invasion are in a high Ca^{2+}-signaling condition (19,59). The interaction between PfRh5 and basigin was shown to be essential for establishing the tight junction between merozoite and host during invasion, an event associated with Fluo-4 signals of elevated Ca^{2+} in merozoite and host cells (60,61). In the study by Volz et al. (61), Ca^{2+} signals were detected in only 41 out of 178 merozoite contacts associated with host cell deformations, and 36 of the 41 progressed to invasion (61). The Ca^{2+} signal for 3D7 in their Fig. 5 a shows the typical punctate response associated with events following irreversible apical alignment, hard to attribute to preinvasion events. The study by Aniweh et al. (60) provides elegant evidence for the essential role of the PfRh5-basigin interaction in merozoite invasion. But the implicit assumption that the elevated Ca^{2+} signals they detected for the postalignment period occur in all invasion instances is not supported by their evidence, which was based on population signals from a fluorescence plate reader or by isolated observations on single-invasion events. The episodic occurrence of postalignment Ca^{2+} signals reported in our casuistic and in that of Weiss et al. (10) may result from 1) stochastic permeability pathway configurations affecting diffusional patterns for Ca^{2+} and Fluo-4 between merozoite and host; 2) a Ca^{2+} signal required for successful invasion of age-discriminated target RBCs; or 3) false negatives due to poor documentation of successful invasion among some of the Ca^{2+}-negative results.

On the possible function of punctate responses

With this in mind, the lack of Ca^{2+} signals in 55% of invasions recorded in Fluo-4-loaded RBCs could only have resulted from the lack of free Fluo-4 access to Ca^{2+}-activated merozoites. Other than presence or absence of Ca^{2+} signals, there were no alternative features that could help distinguish the dynamics of preinvasion and invasion patterns between the two groups. Free Fluo-4 was present initially only within the RBC cytoplasm (Figs. 3 and 4). Therefore, access to merozoites in the 45% of responses with detectable Ca^{2+} signals must have been through the activation of a diffusional path connecting RBC and merozoite compartments. To be able to elicit a saturated Ca^{2+} signal to emerge within a single frame transition of 0.1 s (Fig. 6; Video S1), a high-permeability pathway would have had to be generated soon after junction formation. Such a diffusional pathway would also allow other solutes to equilibrate across, including Ca^{2+} ions among others. The spatial and temporal patterns of the $[Ca^{2+}]_i$ increase documented in the punctate responses (Fig. 6; Video S1) are consistent with and support the view that a down-gradient flow of Ca^{2+} from merozoite to RBC can account for all the characteristics of the Ca^{2+} signals recorded from RBCs (Fig. 6).

Activation of the connecting pathway must have taken place in 45% of egress-invasion events, regardless of whether or not Fluo-4 was there to visualize it. It may simply represent a premature or early formation of a membranous patch at the apical junction, precursor of the high-permeability parasitophorous membrane (62–64) in a fraction of invasion events, of indifferent significance to its dynamic course. Alternatively, the connection may have evolved as a way of increasing invasion efficiency in selected RBC subpopulations. For instance, merozoites invading aging RBCs may activate early path formation to improve invasion efficiency, a point which future research may help resolve by investigating whether punctate-response frequencies vary in a systematic way in age-segregated RBCs during invasion assays.

Together with the evidence that host calcium originated from the merozoite in the 45% of instances with punctate Ca^{2+} signals, the total absence of Ca^{2+} signals from Fluo-4-loaded RBCs in the 55% of Ca^{2+}-negative assays clearly argues against increases in the Ca^{2+} permeability of host

RBCs during invasion and echinocytosis. Hence, the suggestion that rhoptries release factors that permeabilize host cells to Ca^{2+}, secondarily triggering echinocytosis (10), is not supported by the available evidence. In addition, absence of late Ca^{2+} signals during the echinocytic stage, when the internalized parasite is surrounded by the parasitophorous vacuolar membrane, suggests that Fluo-4 diffusing from host cytoplasm toward the ring-stage parasite cannot access parasite domains of high-Ca^{2+} concentration any more.

On the mechanism of apical alignment

Demise of the calcium hypothesis rekindles the search for alternative mechanisms that could account for the dynamics of apical alignment. A few critical clues based on recent and earlier observations may be used to build a new coherent hypothesis amenable to theoretical and experimental tests. We can outline these clues as follows: 1) only weak local deformations correlate with invasion efficiency (10,12); 2) merozoite-host agonist-receptor interactions form reversible coat filaments of between ~20–150 nm in length, capable of generating passive local membrane deformations on attachment and detachment (7,65,66); 3) certain agonist-receptor binding interactions (i.e., EBA-175 and glycophorin A) activate signaling cascades that alter the physical properties of the host cell membrane, priming it toward an increased invasion efficiency (19,59); 4) the apex of the merozoite is positively charged relative to its base and to the negatively charged RBC surface (67); and 5) apex-directed concentration gradients of agonists develop on the coat of activated merozoites (1,12).

With these elements, the dynamics of the preinvasion stage leading to apical alignment may be envisaged as proceeding along the following sequence. Egress dispersal generates random and mostly apex-distant proximities between merozoites and target RBCs. When distances approach less than ~200 nm, agonist-receptor binding interactions (ARBIs) trigger the transient formation and contraction of "Bannister coat filaments" (7) of long (~150 nm) and short (~20 nm) varieties, generating local bending deformations on target RBCs by passive compliance of the RBC membrane. The intensity of the effects caused by these transient adhesions will depend on the nature and surface density of ARBIs, on the bending modulus condition of the RBC membrane, and on the thermal and flickering fluctuations on its surface (68–71). The strength of each ARBI and associated Bannister coat filament cluster is assumed to peak on formation and decay rapidly along an exponential time course, thus allowing merozoites to detach and reassociate further with the same or other target RBCs. Crick et al. (66) observed that spent merozoites with lost invasive capacity attached irreversibly to RBCs, as if the dissociation reaction had become blocked or inactivated—reminiscent of the condition of dehydrated RBCs surrounded by attached merozoites unable to invade (3). The irreversible attachment of spent merozoites offered the opportunity to measure the force of attachment. Using optical tweezers, Crick et al. (66) calculated that a force of 40 ± 8 pN was needed to detach spent merozoites, probably near the peak force in a normal biphasic agonist-receptor binding reaction. Progress toward alignment will take place when successive merozoite attachments advance along the apex-directed agonist concentration gradient and electric field. Important modulating factors, with influence on apical alignment and invasion efficiency, will be those affecting cytoskeletal tension and the viscoelastic and bending properties of the membrane (19,59,68,71–73). These factors may be good candidates to account for the gradual decrease in invasion efficiency with increasing RBC density because of the density-associated decrease in RBC deformability (74).

Essential components of the sequence just outlined as a mechanism of apical alignment were envisaged long ago by Bannister et al. (7), summarized in this quote from their paper: "Individual filaments are anchored to the membrane strongly enough to maintain attachment to red cells and to mediate considerable bending forces, although they allow re-orientation of the merozoite on the red cell, or even detachment, if effective apical contact is not made."

The passive compliance hypothesis of apical alignment outlined above can account for local deformations, but it offers no explanation for the large and distal dynamic deformations with which target RBCs often respond to merozoite contacts or proximities (4,8). Without calcium mediation, the mechanism of these large deformation responses remains a challenging open question for future research.

SUPPORTING MATERIAL

Four figures and two videos are available at http://www.biophysj.org/biophysj/supplemental/S0006-3495(18)30255-8.

AUTHOR CONTRIBUTIONS

V.L.L., P.C., and T.T. formulated the project and, together with V.I., designed the research. V.I., A.J.C., T.T., and Y.C.L. cultured malaria parasites. V.I., A.J.C., and T.T. performed the experiments. J.K. developed the microscopy setup. V.I. processed and analyzed the data. V.I. and V.L.L. drafted the manuscript. P.C. and T.T. contributed in reviewing and editing the manuscript.

ACKNOWLEDGMENTS

We are grateful to Julian C. Rayner for providing 3D7 parasites and insightful comments. V.I. is funded by Engineering and Physical Sciences Research Council and the Raymond and Beverly Sackler Foundation. J.K. and P.C. were funded by EU-ERC CoG HydroSync.

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Supplemental Information

Evidence against a Role of Elevated Intracellular Ca^{2+} during *Plasmodium falciparum* Preinvasion

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Supplementary material to: Evidence against a role of elevated intracellular calcium during *Plasmodium falciparum* invasion

V. Introini, A.J. Crick, T. Tiffert, J. Kotar, Y.-C. Lin, P. Cicuta, V.L. Lew.

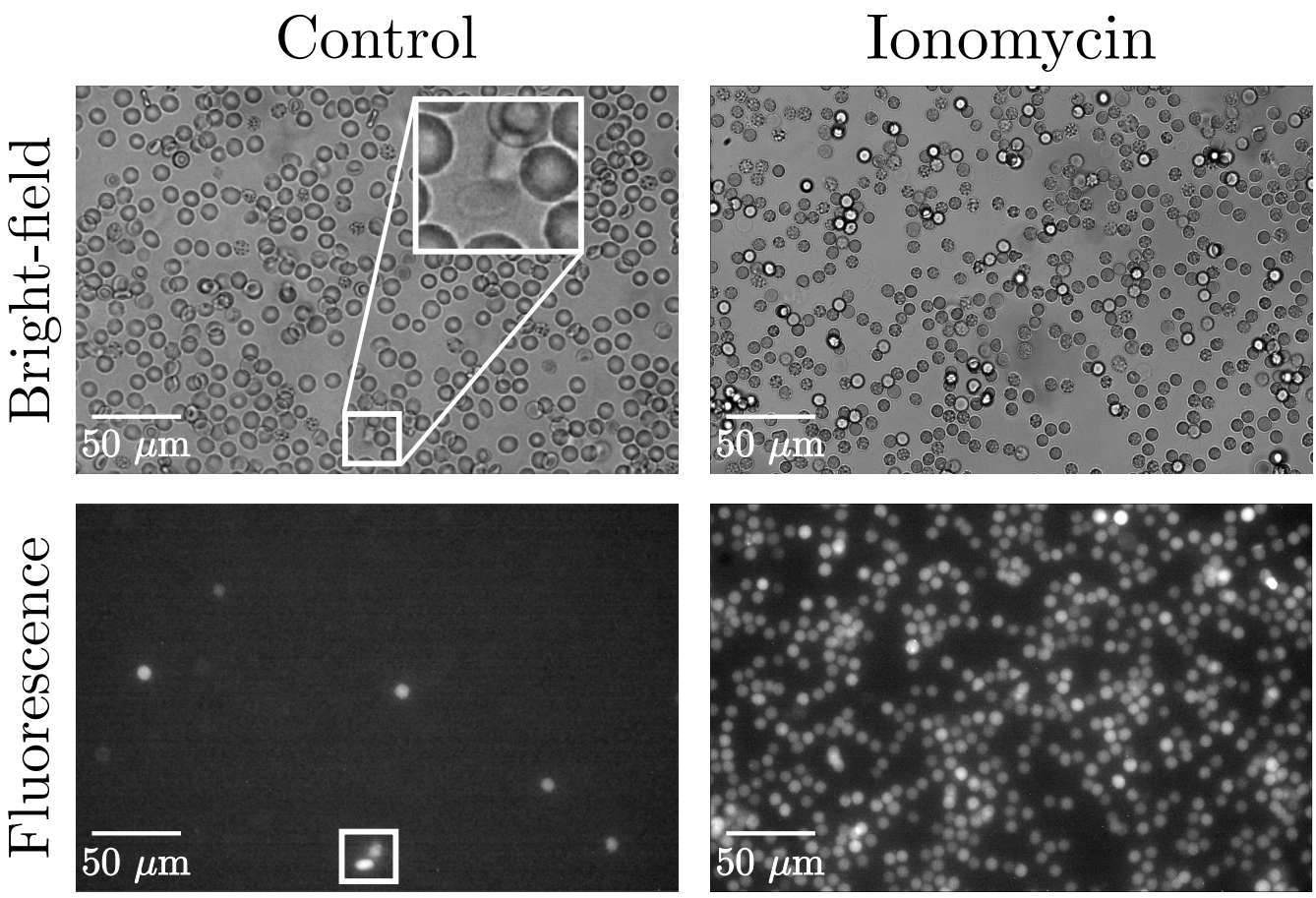

Figure S1: Figure 3 from the manuscript at higher magnification.

0006-3495/08/09/2624/12 $2.00

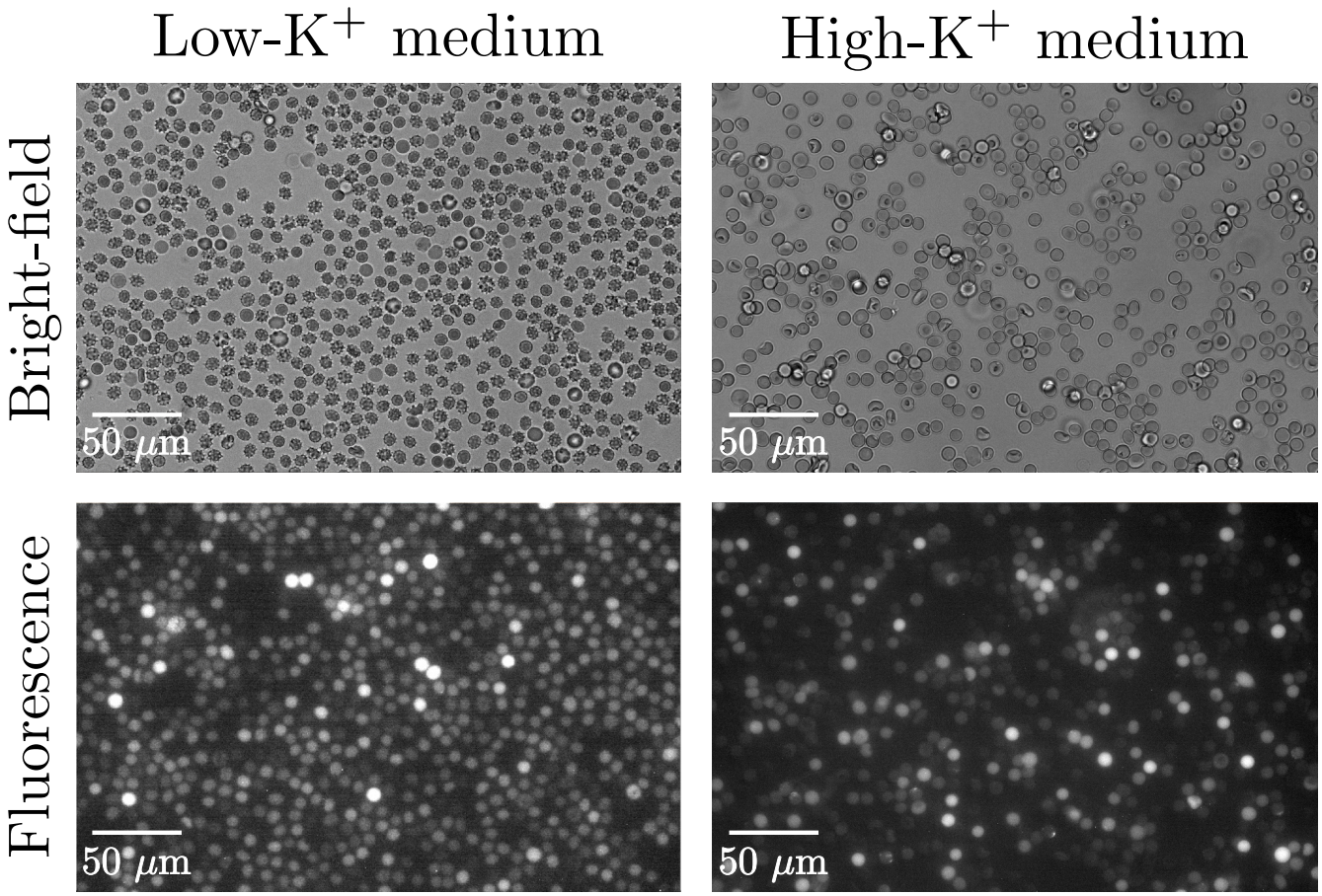

Figure S2: Figure 4 from the manuscript at higher magnification.

Caption for Video S1 A merozoite invasion of an erythrocyte loaded with the Ca^{2+}-dependent marker Fluo-4 AM (10 fps).

Caption for Video S2 Video representative of weak Ca^{2+}signals during merozoite invasion (5 fps). Bright field images document a sequence of merozoite egress, followed by weak local deformations induced by a multiple invasion at 4.8 s (top right) and at 6.0 s (top left), ring forms are visible during a shape-quiescent period of about 8 s duration, ending in a sharp echinocytic transformation recorded for a further 20 s. The fluorescence sequence starts at 4.2 s with a weak but clear Ca^{2+}signal from the full volume of the invasion-targeted RBC suggesting an aging RBC with an elevated $[Ca^{2+}]_i$ level on the borderline of the Fluo-4 detection threshold. Two punctuate images of lighted merozoites poised for invasion appear in sequence within the fluorescent boundary of the cell starting from 5.0 s (top right) and 6.6 s (top left). From then on, despite the low signal-to-noise levels, the Ca^{2+}signal intensity within the RBC increases towards a constant value.

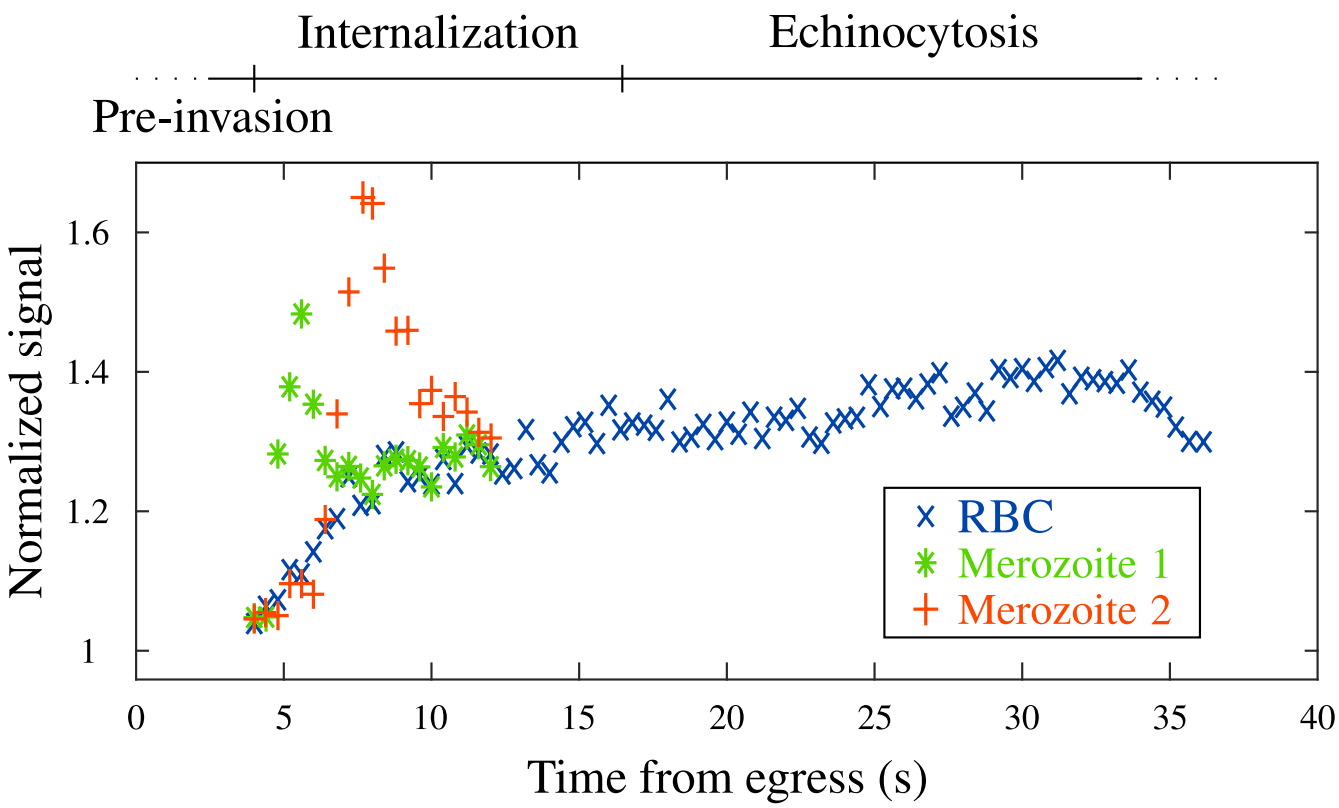

Figure S3: Plot of fluorescence intensity from the cell and invading merozoites normalized by the background at each frame. The analysis starts with the first frame in fluorescence at 4.2 s post egress, a first merozoite lights up at 5.0 s and after a narrow pick of intensity, the signal of the merozoite remains stable. A second merozoite invades the same cell at 6.6 s post egress, showing a sharp fluorescent signal that lasts around 2 s. The RBC signal increases linearly until reaching a plateau in about 5 s, that lasts for other 20 s before beginning to decrease, possibly due to fluorescence bleaching. The signals of the merozoites overlap the one from the cell when the parasites are completely inside the RBC. Data from Video S2.

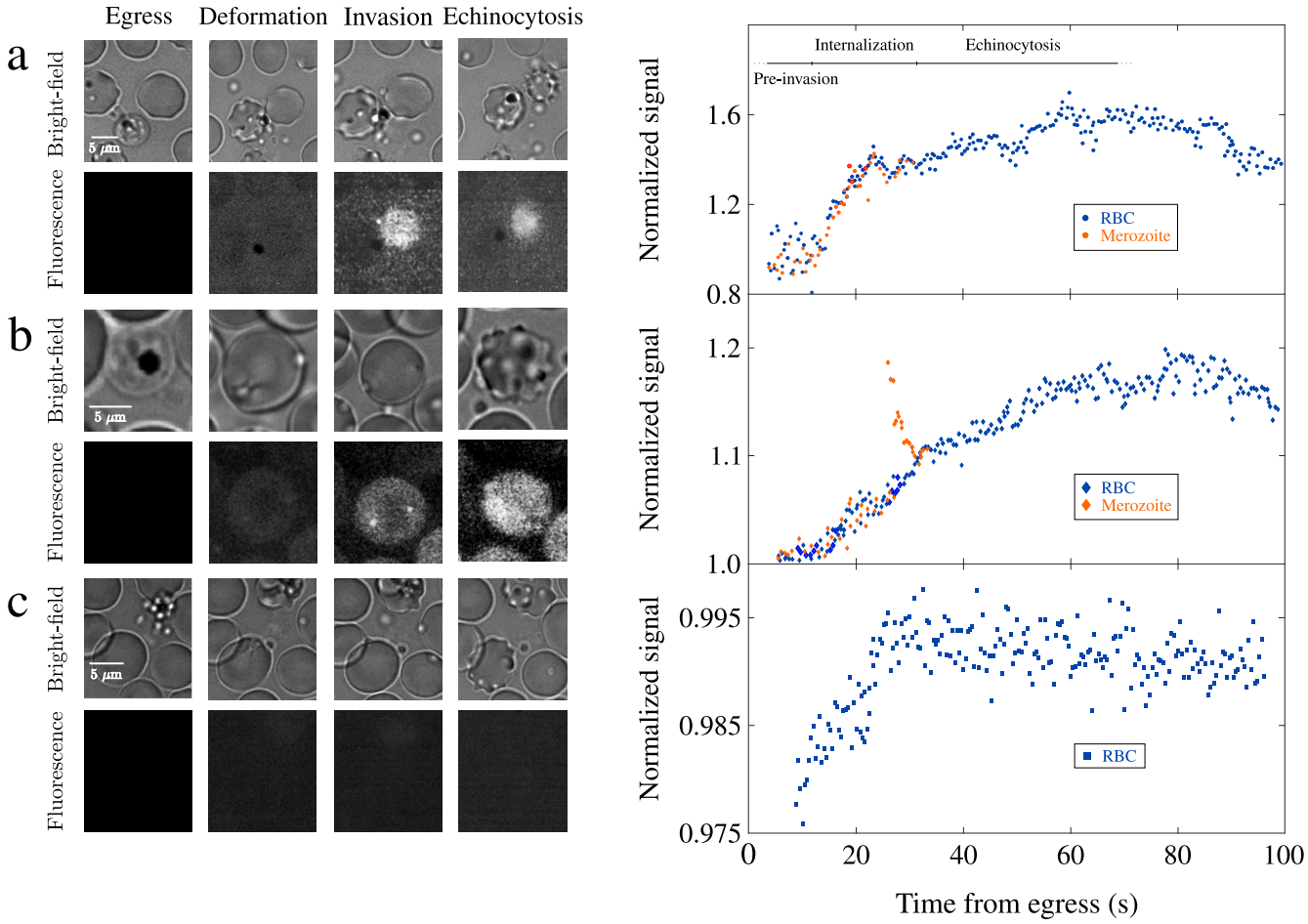

Figure S4: Overview of different egress-invasion typologies in Fluo-4 loaded cells. Selected images of three experiments are shown on the left; the plots on the right quantify the fluorescent intensities of merozoite and RBC regions over time, normalized to the surrounding background in each frame. **a**: the merozoite lights up at the same time as the invaded erythrocyte. **b**: multiple invasion in which the merozoites light up first showing a peak of intensity, while the erythrocyte signal continues to increase after the onset of echinocytosis. **c**: no calcium-related signal appears during an entire successful invasion. The signal scatters and remains under the detectable threshold.