Role of Calcium in Phosphatidylserine Externalisation in Red Blood Cells from Sickle Cell Patients

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1. Introduction

Patients with sickle cell disease (SCD) display a range of symptoms which include chronic anemia together with ischemic pain and organ damage [1]. The underlying cause is the presence in patients’ red blood cells (RBCs) of the abnormal hemoglobin, HbS [2]. HbS polymerises into rigid rods on deoxygenation, changing RBC shape from biconcave disc into the characteristic sickle appearance [3]. RBC membrane permeability is markedly abnormal [4] whilst HbS is also unstable, representing an oxidative threat [5]. Altered behaviour of these HbS-containing RBCs (here termed HbS cells), other circulating cells, and the endothelium combine to reduce RBC lifespan (hence the anemia) and also result in microvascular occlusion (hence the ischemia) [6]. Although the exact pathogenesis remains unclear, an important feature is considered to be increased exposure of phosphatidylserine (PS) on the outer bilayer of the RBC membrane [7–10]. Externally PS is prothrombotic, and also provides a potential adhesion site for both macrophages and activated endothelial cells, contributing to both reduced HbS cell lifespan and vascular occlusion [11–13].

Two membrane phospholipid transporters represent the major determinants of PS exposure in RBCs: the ATP-dependent aminophospholipid translocase (APLT or flipase) transports aminophospholipids (APs), including PS, from outer to inner leaflet, whilst the Ca2+-dependent scramblase moves APs rapidly in both directions thus disrupting phospholipid asymmetry [14]. In normal RBCs, PS is largely confined to inner leaflet, through the dominant action of the flipase whilst the scramblase remains quiescent. A small, but variable, proportion of HbS cells from sickle cell patients, however, show exposure of PS ranging from about 2–10% [7, 9, 15, 16]. Both flipase inhibition and activation of the scramblase are probably involved [17]. Flipase inhibition could follow oxidative stress [18, 19], whilst scramblase activation could be caused by raised intracellular Ca2+ (e.g., [19, 20]) or other stimuli (e.g., [21]). The exact mechanisms, however, remain uncertain.

It is also well established that deoxygenation of HbS in vitro results in increased PS exposure [22, 23] but, again, the mechanism is not clear. Possibilities include disruption of the spectrin cytoskeleton [24], ATP depletion [25], decrease in intracellular Mg2+ [26], and also a rise in intracellular Ca2+...
In many reports concerning PS exposure, however, Ca^{2+} is not controlled or is present at unphysiological levels, making it difficult to assess its role definitively. In addition, whilst a more recent study correlated PS exposure in HbS cells with flippase inhibition, rather than elevation of intracellular Ca^{2+}, the effects of deoxygenation were not determined [9].

Deoxygenation of HbS cells as well as causing HbS polymerisation and shape change, also activates a permeability pathway termed P_{sickle} [4, 27]. P_{sickle} is often described as a deoxygenation-induced cation conductance, apparently unique to HbS-containing red cells. A major importance of P_{sickle} entry via this pathway is the obvious link between HbS polymerisation and the deoxygenation-induced PS exposure, estimates suggest that the magnitude to which Ca^{2+} may be elevated is still relatively modest (around 100 nM) [29], and several orders of magnitude below that required for scramblase activation (around 100 μM) is usually cited [20, 30–32]. The present work is aimed at assessing the role of Ca^{2+} in PS exposure in RBCs from sickle cell patients.

2. Materials and Methods

2.1. Blood. Anonymised, discarded, routine blood samples (taken into the anticoagulant EDTA) were collected from individuals homozygous for HbS (HbSS genotype, n = 62) with approval from the local Ethics committee. After withdrawal, blood samples were kept refrigerated until used. (RBCs from HbSS individuals are here termed HbS cells).

2.2. Salines and Chemicals. HbS cells were washed into low (LK) or high potassium- (HK-) containing saline, comprising (in mM) NaCl 140, KCl 4, glucose 5, HEPES 10 for LK saline, and NaCl 55, KCl 90, glucose 5 and HEPES 10 for HK saline, all pH 7.4 at 37°C, with different extracellular [Ca^{2+}]_o ([Ca^{2+}]_o) as indicated. When required, inhibitors (clotrimazole, DIDS, and dipyridamole) were added from stock solutions in DMSO. In these experiments, DMSO (clotrimazole, DIDS, and dipyridamole) were added from stock solutions in DMSO. Unless otherwise stated, data are presented as means ± S.E.M. for blood samples from n patients. Statistical significance of any differences was tested using paired Student’s t-test (with P < .05 taken as significant).

3. Results

3.1. The Effect of Ca^{2+} on PS Exposure. PS exposure in HbS cell samples taken from SCD patients and immediately labelled with FITC-annexin ranged from 0.4 to 16.0% with a mean of 2.3 ± 0.5% (n = 36). The effect of different [Ca^{2+}]_o (0.1, 0.5, 1.1, 2 and 5 mM) on the percentage of HbS cells showing PS exposure was then investigated. In oxygenated (20% O_2) HbS cells, PS exposure was lower and although the extent of exposure was augmented when RBCs were incubated at higher [Ca^{2+}]_o, the effect was small and not significant (Figure 1). When cells were deoxygenated (1% O_2), PS exposure was always higher than that observed in oxygenated HbS cells.
extracellular Ca$_2^+$'s (0.5, 1.1, 2.0 and 5.0 mM) after which they were labelled with FITC-annexin (as described in Section 2). Histograms representing mean percentage of positive RBCs were labelled with FITC-annexin (as described in Section 2). Histograms represent means ± S.E.M. for 5 different patients. *P < .01 deoxy compare to oxy; 1*P < .05 cf. 0.5 mM Ca$^{2+}$ deoxy; 2*P < .01 cf. 0.5 mM Ca$^{2+}$ deoxy.

Figure 2: Effect of inhibitors on phosphatidylserine (PS) exposure in red blood cells (RBCs) from sickle cell patients. RBCs were incubated under deoxygenated conditions (1% O$_2$) for 3 hours (5 mM extracellular [Ca$^{2+}$]) after which they were labelled with FITC-annexin. Four conditions (all with 0.5% DMSO) are shown: MAPTAM-treated RBCs (loaded with 5 μM MAPTAM prior to deoxygenation), clotrimazole (10 μM), dipyridamole (50 μM), and DIDS (50 μM). Results are presented as percentage PS exposing RBCs relative to control RBCs exposed to 0.5% DMSO only. Histograms represent means ± S.E.M. (n = 3). *P < .01 and *P < .0001 cf DMSO controls.

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PS at the higher [Ca$^{2+}$]$_o$ (Figure 1). This effect was present within 30 min, with longer incubation periods increasing the effect. To determine whether Ca$^{2+}$ was acting extracellularly or intracellularly, HbS cells were loaded with the Ca$^{2+}$ chelator MAPTAM prior to deoxygenation (Figure 2). Over a 3 hour period, MAPTAM decreased the percentage of positive HbS cells (P < .01). This inhibitory effect did not persist over an 18 hour incubation, probably because the available cytoplasmic MAPTA becomes saturated with Ca$^{2+}$.

3.2. Effect of Partial P$_{sickle}$ Inhibitors on PS Exposure. Although there are no specific inhibitors of P$_{sickle}$, dipyridamole is partially effective [40]. When present during deoxygenation, dipyridamole (50 μM) reduced PS exposure in deoxygenated HbS cells (Figure 2; P < .01), consistent with Ca$^{2+}$ entry via P$_{sickle}$ stimulating exposure. DIDS, although better known as a band 3 inhibitor, is also a partial P$_{sickle}$ inhibitor [41]. Addition of DIDS (50 μM), however, produced a marked increase in PS exposing RBCs with percentage of positive RBCs increasing several folds (Figure 2; P < .01). When DIDS was added to RBCs from normal HbA/A individuals, PS exposure was also similarly increased: to 95.0 ± 0.3% in oxygenated conditions, and to 98.7 ± 0.1% in deoxygenated cells (both means ± S.E.M., n = 3). These findings suggest that annexin binding was caused by DIDS reacting with its target on the RBC membrane. HbS cells exposed to DIDS, but not subsequently treated with FITC-annexin, did not fluoresce (e.g., 0% DIDS-treated without FITC-annexin cf 50% DIDS-treated with annexin), indicating that the high values were not due to fluorescence from DIDS itself.

3.3. PS Exposure and Red Cell Shrinkage. Elevated intracellular Ca$^{2+}$ activates the Gardos channel and leads to K$^+$ loss with Cl$^-$ following through separate Cl$^-$ channels [4]. PS exposure could therefore be secondary to the ensuing cell shrinkage [37]. To investigate this possibility, HbS cells were suspended in high K$^+$-containing saline (90 mM) to remove any gradient for K$^+$ efflux. The deoxygenation-induced increase in PS exposure was abolished (Figure 3), with values reduced to those observed in oxygenated samples (P < .001 deoxy HK cf oxy HK; N.S. deoxy HK cf oxy HK). An estimate of RBC size is provided by FACS forward scatter measurement. Forward scatter was 487 ± 8 (means ± S.E.M., n = 3) in oxygenated HK saline, falling to 439 ± 4 in deoxygenated HK saline (P < .005). In deoxygenated HK saline a value of 497 ± 3 was obtained (N.S. cf oxygenated HK saline). PS exposure following deoxygenation in HK saline was therefore accompanied by cell shrinkage. This was not observed during deoxygenation in high K$^+$ saline. A second method of inhibiting the Gardos channel, treatment with
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3.4. PS Exposure and Direct Manipulation of Intracellular \([Ca^{2+}]\). Treatment of RBCs with the divalent cation ionophore bromo-A23187 was used to alter intracellular \([Ca^{2+}]\) directly [34, 35]. RBCs were initially treated with vanadate (1 mM), to inhibit both the plasma membrane Ca\(^{2+}\) pump and also the aminophospholipid translocase (flippase) before addition of bromo-A23187 (1.2 \(\mu\)M, 1% haematocrit) and requisite extracellular \([Ca^{2+}]\)s for 30 min. They were then treated with \(Ca^{2+}\) (0.4 mM) before labelling with FITC-annexin. Intracellular \([Ca^{2+}]\) is calculated from extracellular \([Ca^{2+}]\) \(\times r^2\), where \(r^2\) was taken as 2.05 [36]. Results presented are from a single experiment representative of 5 others.

3.5. Modulation of PS Exposure. In the preceding section, although high affinity \(Ca^{2+}\)-induced scrambling was present, it was noticeable that nevertheless only a minority of all RBCs stained positively for PS using FITC-annexin—as is also found in many literature reports, for example, [39]. That \(Ca^{2+}\) loading was complete and homogeneous was first ascertained using intracellular fluo-4 (Figure 5). It is apparent that the majority of RBCs (98 \(\pm\) 1\%, \(n = 3\)) were \(Ca^{2+}\)-loaded. Uneven \(Ca^{2+}\) loading can therefore be discounted. As K\(^+\) has been reported to inhibit PS scrambling [42], the effect of 30 min incubation in LK saline compared to HK was determined in the presence of bromo-A23187 and different \([Ca^{2+}]\). LK saline was found to increase the percentage of positive cells (Figure 6(a)), an effect again partially inhibited by clotrimazole (10 \(\mu\)M) which, for example, reduced percentage of positive cells from 44\% to 28\% at 10 \(\mu\)M \(Ca^{2+}\). Finally, the effect of the calmodulin inhibitor W-7 was tested (Figure 6(b)). In this case, the percentage of positive RBCs increased. It was noticeable, however, that in all these manoeuvres, \(Ca^{2+}\) affinity was unaffected (Figure 6).
4.1. Role of Ca$^{2+}$ and P_sickle on PS Exposure. Altering extracellular Ca$^{2+}$ levels had little effect on PS exposure in oxygenated HbS cells. Under deoxygenated conditions, however, PS exposure increased with [Ca$^{2+}$]. This effect was partially inhibited by dipyridamole [40] and by intracellular Ca$^{2+}$ chelation with MAPTAM treatment [34]. These findings are consistent with Ca$^{2+}$ entering via the deoxygenation-induced pathway P_sickle [4, 27] and acting intracellularly. Intracellular Ca$^{2+}$ can have several actions. First, it will activate the Gardos channel leading to RBC shrinkage [43]. Second, it may stimulate the Ca$^{2+}$-dependent scramblase whilst inhibiting the ATP-dependent flippase [14]. Third, it may stimulate cysteine proteases [44]. Any of these events may lead to PS exposure [21]. Several manoeuvres were tested to separate these possibilities. The most effective way of inhibiting PS exposure was incubation in high K$^+$ saline. Removal of the electrochemical gradient for K$^+$ efflux abolished the deoxygenation-induced increase in PS exposure. The Gardos channel inhibitor clotrimazole also partially inhibited PS exposure. Findings are consistent with the hypothesis that activation of P_sickle, by deoxygenation mediates Ca$^{2+}$ entry, elevating [Ca$^{2+}$], which then promotes PS exposure by Gardos channel activation, loss of intracellular solutes, and red cell shrinkage. Importantly, high K$^+$ salines were effective over all incubation times (up to 18 hours). Shrinkage has been shown previously to stimulate PS exposure in both normal RBCs and HbS cells [37, 45] and would appear to be involved in deoxygenation-induced PS exposure in sickle cells.

4.2. Ca$^{2+}$ Dependence of PS Exposure. A major aim of this work was to determine unequivocally the intracellular Ca$^{2+}$ required to elicit PS exposure in HbS cells. This was investigated using RBCs loaded with different [Ca$^{2+}$]s using bromo-A23187. RBCs were first treated with vanadate (to inhibit both the plasma membrane Ca$^{2+}$ pump and
the flippase) and subsequently with Co2+ (which blocks A23187 so that the relatively high [Ca2+] required for annexin binding, 2.5 mM, could not gain access to the cytoplasm). Results showed that PS exposure was stimulated by micromolar Ca2+ concentrations with an EC50 of about 1.2 μM. This concentration is similar, though slightly higher, compared with that required for half-maximal activation of the Gardos channel activation [46, 47] and for inhibition of the flipase [26]. A similar high affinity for Ca2+ was also observed in RBCs incubated in LK saline indicating that high K+ levels are not responsible for these observations. Calmodulin is known to interact with RBC cytoskeleton and influence PS exposure [48, 49]. Incubation with the calmodulin antagonist W-7 again showed a similar high Ca2+ affinity for PS exposure. In this case, the percentage of positive cells was also increased so that the majority of RBCs became positive, showing that most RBCs are capable of PS scrambling at these low Ca2+ levels. Previously reported values for activation of the scramblase are considerably higher than those given here, with values of 25–100 μM quoted [14, 32]. Previous measurements, however, were made largely on resealed RBC ghosts, inside-out vesicles, or purified PLSCR1 [30, 31, 50, 51], which may not in fact represent the RBC scramblase [52]. These preparations will also necessarily lack much of the cytoplasmic contents which may result in reduction in Ca2+ affinity of the scrambling process. Furthermore, several previous reports were carried out in the presence of high concentrations of extracellular Mg2+ (1 mM) [20, 30, 50], which with the ionophore A23187 would set intracellular Mg2+ at over 2 mM, considerably in excess of the normal RBC [Mg2+] [53], and which might be expected to dampen any Ca2+ driven process. We speculate that having a similar Ca2+ level for Gardos channel activation, flipase inhibition and activation of scrambling would coordinate eryptotic events [21] and facilitate removal damaged RBCs in normal individuals, whilst in SCD patients, hyperactivity of these processes may contribute to disease pathogenesis.

Authorship Contributions

The paper was designed by J. S. Gibson and D. C. Rees and carried out by E. Weiss, E. Weiss and J. S. Gibson analysed the data. J. S. Gibson wrote the paper.

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