A Comprehensive Review on Eryptosis

Etheresia Pretorius   Jeanette N. du Plooy   Janette Bester

Department of Physiology, University of Pretoria, Pretoria, South Africa

Key Words
Erythrocytes • Eryptosis • Membrane changes • Flow cytometry • Confocal microscopy • Scanning electron microscopy

Abstract
Erythrocytes (RBCs) are extremely sensitive cells, and although they do not have nuclei and mitochondria, are important health indicators. This is particularly true because, during inflammation, whether it is systemic or chronic, the haematological system is constantly exposed to circulating inflammatory mediators. RBCs have a highly specialized and organized membrane structure, which interacts and reacts to inflammatory molecule insults, and undergo programmed cell death, similar to apoptosis, known as eryptosis. Over the past years, eryptosis studies have focussed on determining if membrane changes have occurred, particularly whether a phosphatidylserine (PS) flip, $\text{Ca}^{2+}$ leakage into the cell, changes to ceramide and cell shrinkage have occurred. Mostly, flow cytometry is used, but confocal microscopy and ultrastructural studies also confirm eryptosis. Here, we provide a comprehensive overview of eryptosis, where we revisit the biochemical process of the process, review all literature in PUBMED, that is shown under the search word, “eryptosis”, and also discuss current methodologies to determine the presence of eryptosis; included in the discussion of the methodologies, we discuss a pitfalls section for each method. This paper is therefore a comprehensive synopsis of current knowledge of eryptosis and discusses how RBCs may provide an essential in vivo cell model system to study not only inflammation in disease, but also track disease progression and treatment regimes.

Introduction
Erythrocytes (RBCs) are extremely sensitive cells, and although they do not have nuclei and mitochondria, form an important component of the human body as health indicator. This is particularly true because, during inflammation, whether it is systemic or chronic the haematological system is constantly exposed to circulating inflammatory mediators. RBCs have a highly specialized and organized membrane structure, which interacts and reacts to inflammatory molecule insults. Although it does not have a nucleus or mitochondria, it undergoes programmed cell death, similar to apoptosis, and this is called eryptosis. The basis for eryptosis is discussed in various publications by the Lang group e.g. [1-9], and it is known...
to contribute to conditions like anaemia, metabolic syndrome, diabetes, malignancy, hepatic failure, heart failure, uraemia, hemolytic uremic syndrome, sepsis, fever, dehydration, mycoplasma infection, malaria, iron deficiency, sickle cell anaemia, thalassemia, glucose-6-phosphate dehydrogenase deficiency and Wilson's disease [10].

In this paper, we provide a comprehensive overview of eryptosis, revisit the biochemical process of eryptosis, review all literature in PUBMED that is shown under the search word, “eryptosis” and also discuss current methodologies to determine the presence of eryptosis. We conclude by providing a comprehensive synopsis of current knowledge of eryptosis and discuss how RBCs may provide an essential in vivo cell model system to study not only inflammation in disease, but also track disease progression and treatment regimes. The next paragraphs will review the structure of the RBC membrane, and how it is changed during eryptosis.

### The RBC membrane

The mature RBC consists of a complex plasma membrane, containing a specialized lipid bilayer that interacts through protein interactions with integral membrane proteins. The membrane lipids that form the double-layered surface of all cells are categorized as phospholipids, glycolipids, and cholesterol. Cholesterol is commonly spread equally throughout the 2 leaflets, while the 4 major phospholipids are asymmetrically arranged. The preservation of this asymmetric arrangement of phospholipids, especially the localization of PS and phosphoinositides to the inner leaflet, plays a major role on the integrity of the RBC. Disruption of this lipid asymmetry leads to displaying of PS on the outer leaflet and its externalization has been suggested to play a major role in premature destruction of RBCs [11]. For a detailed review see [12]. The cytosol contains highly enriched haemoglobin, and molecules like cytosolic Ca²⁺. The phospholipid bilayer facilitates enzymatic reactions, is involved in membrane transport and signal transduction pathways and these are all involved in maintaining of lipid homeostasis. There are hundreds of different phospholipid molecular species that differ with regards to their polar, hydrophilic heads and non-polar hydrophobic hydrocarbon tails. Glycerophospholipids have a glycerol backbone, while sphingomyelin has a sphingosine backbone.

Lipid species and proteins aggregate in domains in the membrane, called rafts that form specialized areas that act together and are involved in individual physiologic processes such as signal transduction. Membrane cholesterol is unesterified and lies between the two layers of the lipid bilayer [13, 14]. Lipid rafts enriched in cholesterol and sphingolipids are also in association with specific membrane proteins that include flotillins, stomatin, phospholipids are asymmetrically distributed across the lipid bilayer with the amino phospholipids, phosphatidylserine and phosphatidylethanolamine (PS and PE) on the inside and choline containing phospholipids, phosphatidylcholine and sphingomyelin (PC and SM) on the outer leaflet. SM is the most abundant sphingolipid, constituting a class of structural lipids with ceramide as the hydrophobic backbone [13, 16-22]. See Fig. 1 for an overview of the RBC membrane (adapted from [14, 23]).

Three integral types of proteins facilitate the transmembrane passage, as well as the structural arrangement of lipids in the RBC membrane, and they are flippases, floppases and scramblases. Floppase controls the reverse transfer of choline-containing phospholipids, PS and SL and cholesterol (against concentration gradients) from the inner leaflet to the outer leaflet. Flippase (aminophospholipidtranslocase) pumps the amino-containing phospholipids from the outer to the inner leaflet [24]. Scramblase initiates non-specific bidirectional transport of phospholipids down their concentration gradients in an energy independent manner across the RBC membrane. The activation of the phospholipid scramblase is known to be involved in loss and disruption of the asymmetry of the membrane phospholipids that is essential for maintaining lipid homeostasis in RBCs [14, 25].
The magnesium ATP dependent flippase, which transfers PS and PE from outer to inner monolayer at the expense of ATP, maintains the correct distribution of the phospholipid layer. Loss of phospholipid asymmetry and the exposure of PS are triggered by a phospholipid scrambling activity. PS is usually confined to the inner leaflet of the RBC and its externalization requires both inhibition of the flippase and activation of the scramblase and both may follow from elevation of intracellular Ca\(^{2+}\)[26]. Energy-independent flippases therefore allow common phospholipids to equilibrate rapidly between the two monolayers and also play a role in the biosynthesis of a variety of glycoconjugates such as glycosphingolipids, N-glycoproteins, and glycosylphosphatidylinositol (GPI)-anchored proteins [27]. Scramblase facilitates the flip-flop of lipids in a non-selective fashion from the inner, as well as the outer leaflet [28] – this process is a bidirectional process, down a concentration gradient. In the presence of calcium, scramblase behaves like a channel for lipids, allowing them to diffuse from one monolayer to the other, according solely to the concentration gradient. Structural proteins like Band 3 regulates the structure and function of the RBCs, as it facilitates anion transport via the RBC membrane and it is an important binding site for cytoskeletal and other RBCs proteins [29][30][31][32]. Band 3 is a multi-spanning ion transport channel or trans-membrane protein, and the tetramers tether the bilayer to the skeleton via an interaction between its cytoplasmic domain and ankyrin, which is associated with spectrin (see [12] for a detailed discussion).

What happens in the RBC membrane during eryptosis?

Eryptosis is characterized by cell shrinkage and cell membrane scrambling and is stimulated by calcium entry through Ca\(^{2+}\)-permeable, PGE\(_2\)-activated cation channels, by ceramide, caspases, calpain, complement, hyperosmotic shock, energy depletion, oxidative stress, and deranged activity of several kinases (e.g. AMPK, G\(_K\), PAK2, CK1\(\alpha\), JAK3, PKC, p38-MAPK) [33-39]. This process happens as follows: hyperosmotic shock, energy depletion, or removal of extracellular CI activates the non-selective Ca\(^{2+}\)-permeable cation channels in the membrane. This causes Ca\(^{2+}\) to enter and leak into the cell followed by the PS-flip to expose PS at the erythrocyte surface [40]. Also subnanomolar concentrations of prostaglandin E\(_2\) (PGE\(_2\)) lead to activation of erythrocyte cation channels and influx of Ca\(^{2+}\), calpain activation, and ankyrin-R degradation [40]. PGE\(_2\) is produced from membrane phospholipids by the sequential action of Ca\(^{2+}\)-independent...
phospholipase A₂ (PLA₂), cyclooxygenase (COX) and PGE-synthase (see Fig. 2, adapted from [35, 40, 41]).

When Cl⁻ is removed (1A), it causes the formation of PGE₂ (2A), and COX activation (2B) leading to arachidonic acid formation and PGE₂ efflux, followed by stimulation and opening of the membrane Ca²⁺-channels (3). Oxidative stress (1B) also causes the Ca²⁺ channel to open [41]. During osmotic stress (1C) RBC shrinkage also happens due to Ca²⁺ entry [42]. Increased cytosolic Ca²⁺ activates Ca²⁺-sensitive K⁺ channels resulting in the subsequent exit of KCl and cell shrinkage [35]. Energy depletion also causes Ca²⁺ entry [43] [44]. Ca²⁺ entry also stimulates sphingomyelinase to form ceramide (4) [42]; Ca²⁺ and ceramide then activate a scramblase (5) and this leads to the exposure of PS and breakdown asymmetry of the cell membrane [35]. As mentioned previously, PS is usually confined to the inner leaflet of the RBC and its externalization requires both inhibition of the flippase and activation of the scramblase and both may follow from elevation of intracellular Ca²⁺[26]. Elevated cytosolic free Ca²⁺ concentrations also activate μ-calpain (6), which degrades components of the cytoskeleton, like the ankyrin R complex (7), leading to membrane blebbing [40]. PS exposure (involvement of floppase) (8) may not necessarily be regulated by PGE₂ that is formed by stressed RBCs but also may be triggered by PGE₂ from other sources [40].

Compounds tested that prevent or induce eryptosis

The following section comprehensively reviews literature where researchers tested the effects of various molecules and compounds on eryptosis formation or inhibition. In various comprehensive investigations, the Lang group is the leading eryptosis researchers (see Table 1). Table 1 lists compounds that induce or inhibit eryptosis. The main methods used to determine this process were:

- Annexin V binding for PS exposure
- Fluorescence marker for cytosolic calcium
- DCF fluorescence for ROS
- Anti-ceramide antibody for ceramide formation/ anti-ceramide-FITC antibody and radioactive labelling
- Cell volume by forward scatter
- Cytosolic ATP levels using luciferin-luciferase-based assay
- Glutathione by CMF fluorescence/ mercury orange fluorescence
- ELISA methods
The individual methods will be briefly discussed in the next section. Table 2 lists literature that includes research by other groups and the Lang group, but utilizes also additional novel methods, while Table 3 lists literature where animal models were used and Table 4 lists literature where eryptosis were noted in specific diseases.

Table 1. Investigations by the Lang group, suggesting that products cause eryptosis in human RBCs

<table>
<thead>
<tr>
<th>Compound causing eryptosis</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinomycin</td>
<td>Cyclosporine [34, 37, 41]</td>
</tr>
<tr>
<td>Topotecan</td>
<td>Adenosine [43, 45-179]</td>
</tr>
<tr>
<td>Philinetein</td>
<td>Retinoic acid</td>
</tr>
<tr>
<td>Cryptotanshineine</td>
<td>Aluminum ions</td>
</tr>
<tr>
<td>Biacelein</td>
<td>Ciglitazone and PPARgamma</td>
</tr>
<tr>
<td>Salinomycin</td>
<td>Igg15deoxy-delta12,14-</td>
</tr>
<tr>
<td>Piperoxoglutamine</td>
<td>prostaglandin J2 [150-PGF2]</td>
</tr>
<tr>
<td>Saponin</td>
<td>Glucocorticin</td>
</tr>
<tr>
<td>Estramustine</td>
<td>Ribavirin</td>
</tr>
<tr>
<td>Embelin</td>
<td>Treosulan</td>
</tr>
<tr>
<td>Narasin</td>
<td>Sphingosine and sphingosine-1-</td>
</tr>
<tr>
<td>Zolofracit</td>
<td>phosphate</td>
</tr>
<tr>
<td>Amtriprilin-nylon: mice model</td>
<td>Vitamin K(3)</td>
</tr>
<tr>
<td>Bismuth</td>
<td>Resveratrol</td>
</tr>
<tr>
<td>Ruxolinib</td>
<td>Beesnavicine</td>
</tr>
<tr>
<td>Biosellatic acid</td>
<td>Dicumarol</td>
</tr>
<tr>
<td>PTXZ/20-anti-inflammatory drug</td>
<td>Xanthinesulfonyl</td>
</tr>
<tr>
<td>Alpha-lipoic acid Monensin</td>
<td>Thymoquinine</td>
</tr>
<tr>
<td>Phytadic acid</td>
<td>Valinomycin</td>
</tr>
<tr>
<td>Licochealane</td>
<td>Ipratropium bromide</td>
</tr>
<tr>
<td>PRIMA-1: antitumor drug</td>
<td>Sunitinib</td>
</tr>
<tr>
<td>Carcinol</td>
<td>Salinide sulfide</td>
</tr>
<tr>
<td>Caffeine Protease inhibitor: nelfinav</td>
<td>Zinc</td>
</tr>
<tr>
<td>Peptidoglycans (PGNs) from bacterial cell walls</td>
<td>Zidovudine</td>
</tr>
<tr>
<td>walls belong to pathogen-associated molecular patterns (PAMP)</td>
<td></td>
</tr>
<tr>
<td>Problucin</td>
<td>Pyrimethamine</td>
</tr>
<tr>
<td>Lipoxigenase inhibitor: haem5864</td>
<td>Rifas artificially aged by glycation</td>
</tr>
<tr>
<td>Cadmium ions</td>
<td>Benzethonium</td>
</tr>
<tr>
<td>Selenium compounds</td>
<td>Thioridazine</td>
</tr>
<tr>
<td>Silver ions</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>Gold</td>
<td>Blebbistatin</td>
</tr>
<tr>
<td>Carnosic acid</td>
<td>Paclitaxel</td>
</tr>
<tr>
<td>Trans-cinnamaldehyde</td>
<td>Novobiocin</td>
</tr>
<tr>
<td>Extracellular phosphate</td>
<td>Celecoxib</td>
</tr>
<tr>
<td>Synthetic lipopeptide Pam3CSK4</td>
<td>Celecoxib</td>
</tr>
<tr>
<td>Apigenin</td>
<td>Sunitinib</td>
</tr>
<tr>
<td>Flavonoids</td>
<td>Plumbagin</td>
</tr>
<tr>
<td>Pumaglillin</td>
<td>otenone</td>
</tr>
<tr>
<td>Gossypol</td>
<td>Pafalide</td>
</tr>
<tr>
<td>Methyl-6-lysine</td>
<td>Hexavalent (VI) chromium</td>
</tr>
<tr>
<td>Anamidamide</td>
<td>Gambogenic acid</td>
</tr>
<tr>
<td>Vanadate</td>
<td>Soraflin</td>
</tr>
<tr>
<td>Radioactive agents</td>
<td>Cisplatin</td>
</tr>
<tr>
<td>Mushroom tyrosinase</td>
<td>Methyldopa</td>
</tr>
<tr>
<td>Hemin-exposure</td>
<td>Arsenic</td>
</tr>
<tr>
<td>Philinetein</td>
<td>Thymol</td>
</tr>
<tr>
<td>Asahikizone</td>
<td>Anthomethicin B</td>
</tr>
<tr>
<td>Methylhydroxamate</td>
<td>Artistorical acid</td>
</tr>
<tr>
<td>Mitotane</td>
<td>Mitoxanilate</td>
</tr>
<tr>
<td>Tinn</td>
<td>Chimide</td>
</tr>
<tr>
<td>Amiodarone</td>
<td>Lithium</td>
</tr>
<tr>
<td>Anthoquinone B</td>
<td>Amoyl peptide Geldanamycin</td>
</tr>
<tr>
<td>Dimethyllumerate</td>
<td>The effect of temperature</td>
</tr>
<tr>
<td>Nitric Oxide</td>
<td>Anthamidine</td>
</tr>
<tr>
<td>Mitoxanine</td>
<td>RBC age</td>
</tr>
<tr>
<td>Cryptotanshineine</td>
<td>Phleomycin acid effect on intraerythrocytic growth of P. falciparum</td>
</tr>
<tr>
<td>Nitric Oxide</td>
<td>Methylglyoxal</td>
</tr>
<tr>
<td>Methyglyoxal</td>
<td></td>
</tr>
<tr>
<td>1,4-naphthoquinone derivative</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Papers on eryptosis using similar techniques as in Table 1, but with additional methods

<table>
<thead>
<tr>
<th>Compound</th>
<th>Technique</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fas</td>
<td>PhosphoEROS</td>
<td>(180)</td>
</tr>
<tr>
<td>Polyethylene D</td>
<td>Quantitative real-time pulse sequencing (TPPS) technology: determination of phosphatidyl ethanolamine functional test with annexin V-fluorescent binding</td>
<td>(181)</td>
</tr>
<tr>
<td>Uric acid and sodium salicylate</td>
<td>PhosphoEROS labeled with Alexa Fluor 488-labeled Annexin V: Progesterone activity was assessed by clumping time and purified organelles</td>
<td>(182)</td>
</tr>
<tr>
<td>Cinchonine</td>
<td>Calcium leakage: Flow cytometry</td>
<td>(183)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(184)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(185)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(186)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(187)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(188)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(189)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(190)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(191)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(192)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(193)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(194)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(195)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(196)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(197)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(198)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(199)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(200)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(201)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(202)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(203)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(204)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(205)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(206)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(207)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(208)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(209)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(210)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(211)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(212)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(213)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(214)</td>
</tr>
<tr>
<td>L-carnitine and L-arginine</td>
<td>L-carnitine and L-arginine</td>
<td>(215)</td>
</tr>
</tbody>
</table>
Methods to study eryptosis

From the above-mentioned tables, it is noted that there are a few basic techniques used in the study of eryptosis, and they mainly include flow cytometry with some researchers using confocal microscopy. The techniques are combined and summarized from the papers listed in the tables and particularly the Bissinger, Qadri and Lang papers give extensive information from the manufacturers.

### Externalization of PS

**Flow cytometry**

PS is externalized during eryptosis and this externalization can be measured using Annexin-V binding. In order to determine Annexin-V-binding, a small amount (2-5 µl) of
Table 4. Diseases associated with eryptosis

<table>
<thead>
<tr>
<th>Disease</th>
<th>Methods</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute cardiac failure</td>
<td>Phosphatidylycerine exposure was estimated from Annexin-V-binding,</td>
<td>[245]</td>
</tr>
<tr>
<td></td>
<td>calcium measured with Fluos3 fluorescence, ceramide abundance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tested with antibodies and ROS with 2',7'-dichlorodihydrofluorescein</td>
<td></td>
</tr>
<tr>
<td></td>
<td>diacetate (DCFDA) as determined by flow cytometry.</td>
<td></td>
</tr>
<tr>
<td>Lung cancer</td>
<td>Annexin-V binding for PS exposure, Fluos3 fluorescence marker for</td>
<td>[246]</td>
</tr>
<tr>
<td></td>
<td>cytosolic calcium, DCFDA fluorescence for ROS and anti-ceramide</td>
<td></td>
</tr>
<tr>
<td></td>
<td>antibody for ceramide formation, flow cytometry.</td>
<td></td>
</tr>
<tr>
<td>RBC from chronic kidney disease;</td>
<td>Flow cytometry</td>
<td>[247]</td>
</tr>
<tr>
<td>hemodialysis; patients and healthy controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperthermia in hereditary spherocytosis</td>
<td>PS exposure</td>
<td>[248]</td>
</tr>
<tr>
<td>Obese</td>
<td>CD47 expression and Caspase-3 and Caspase-9 activity (flow</td>
<td>[249]</td>
</tr>
<tr>
<td></td>
<td>cytometry); PS exposure</td>
<td></td>
</tr>
<tr>
<td>Anaemia in end-stage renal disease</td>
<td>PS exposure; Calcium measurement; Cell volume; Ceramide; ROS</td>
<td>[250]</td>
</tr>
<tr>
<td>Lead exposed individuals</td>
<td>(ATP) concentration; Calpain; Reduced/oxidized glutathione;</td>
<td>[251]</td>
</tr>
<tr>
<td></td>
<td>Thioluburilic acid-reactive substance (TBARS) concentration; PS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>exposure; Calcium measurement; δ-aminoenolic acid dehydratase (BDAAD)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>activity.</td>
<td>[251]</td>
</tr>
<tr>
<td>Hemolytic anaemia</td>
<td>Transmission electron microscopy; PS exposure; Wheat germ</td>
<td>[252]</td>
</tr>
<tr>
<td></td>
<td>agglutinin (WGA)-FITC</td>
<td></td>
</tr>
<tr>
<td>Hereditary spherocytosis</td>
<td>PS exposure; Cell surface glycoproteins using wheat germ agglutinin</td>
<td>[253]</td>
</tr>
<tr>
<td></td>
<td>using flow cytometry</td>
<td></td>
</tr>
<tr>
<td>Paroxysmal nocturnal hemoglobinuria and</td>
<td>PS exposure; Cell surface glycoproteins using wheat germ agglutinin</td>
<td>[254]</td>
</tr>
<tr>
<td>myoglobinlastic syndrome.</td>
<td>using flow cytometry</td>
<td></td>
</tr>
<tr>
<td>Human population exposed to arsenic</td>
<td>PS exposure; Calcium measurement; Ceramide measurement; Cell</td>
<td>[255]</td>
</tr>
<tr>
<td>through drinking water</td>
<td>volume</td>
<td></td>
</tr>
<tr>
<td>Type B diabetes with chronic kidney disease</td>
<td>GSH/GSSG ratio; Lipperoxidation; PS exposure</td>
<td>[256]</td>
</tr>
<tr>
<td>Sickle cell disease</td>
<td>PS exposure</td>
<td>[257]</td>
</tr>
<tr>
<td>Autoimmune haemolytic anaemia</td>
<td>PS exposure; Calcium measurement</td>
<td>[258]</td>
</tr>
<tr>
<td>Beta-thalassemia: splenectomized and</td>
<td>PS exposure</td>
<td>[259]</td>
</tr>
<tr>
<td>non-splenectomized individuals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5α-3β3, a clinical candidate for malaria</td>
<td>PS exposure</td>
<td></td>
</tr>
<tr>
<td>RBCs from healthy volunteers were exposed</td>
<td>PS exposure; Calcium measurement; Cell volume; Cell</td>
<td>[261]</td>
</tr>
<tr>
<td>to plasma of patients suffering from sepsis,</td>
<td>volume; Glutathione measurement</td>
<td></td>
</tr>
<tr>
<td>or to supernatants from sepsis producing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pathogens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RBCs from healthy volunteers were exposed</td>
<td>Ps exposure; Calcium measurement</td>
<td>[262]</td>
</tr>
<tr>
<td>to plasma from a patient with severe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>idiopathic recurrent haemolytic uremic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>syndrome secondary to factor H depletion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaemia in the elderly</td>
<td>PS exposure; Calcium measurement; ROD; Ceramide measurement;</td>
<td>[263]</td>
</tr>
<tr>
<td></td>
<td>Cell volume; Glutathione measurement</td>
<td></td>
</tr>
<tr>
<td>Type B diabetes</td>
<td>Non-protein-bound iron, methemoglobin and glutathione were determined</td>
<td>[36]</td>
</tr>
<tr>
<td></td>
<td>in RBCs; Non-protein-bound iron was determined in plasma; RBC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>caspase-3 activation was evaluated by an immunocorbet enzyme</td>
<td></td>
</tr>
<tr>
<td></td>
<td>assay</td>
<td></td>
</tr>
<tr>
<td>Parkinson’s disease</td>
<td>Ultrastructural analysis</td>
<td>[264]</td>
</tr>
<tr>
<td>Autoimmune haemolytic anaemia treated with</td>
<td>Serological tests</td>
<td>[265]</td>
</tr>
<tr>
<td>erythropoiesis-stimulating agents</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

freshly drawn citrated blood should be mixed in either 500 µl Annexin-V binding buffer or Ringer solution (containing 5 mM CaCl₂), subsequently stained with Annexin-V, conjugated with the appropriate fluorochrome according to the instrument that will be used. The Annexin-V-sample-mix should be diluted 1:200 in Ringer solution, containing 5 mM CaCl₂, or Annexin-V binding buffer at 37°C for 15-45 minutes (incubation time depends on manufacturer protocol) protected from light.

The Annexin-V abundance at the RBC-surface can then be determined on a flow cytometer. Annexin-V-binding can be measured with an excitation and an emission wavelength for the specific conjugated fluorochrome that will be specified in the manufacturer datasheet. A dot plot of forward scatter (FSC) vs. side scatter (SSC) should be set to linear scale for both parameters.

**Confocal microscopy**

For the visualization of eryptotic RBCs, 20-30 µl RBCs (1 × 10⁶ cells) stained with Annexin-V (with conjugated fluorochrome of choice), taken in a 1:100 dilution, in 200 µl Ringer solution, containing 5 mM CaCl₂, or Annexin-V binding buffer. The RBCs should be
washed twice and finally resuspended in 200 μl Ringer solution containing 5 mM CaCl₂ or Annexin-V binding buffer. There are two ways to prepare the sample before viewing under the microscope, all the steps should be done protected from light:

1. Spread 40 μl of the sample onto a glass slide and dry it for 15 min at room temperature, followed by covering of the slides with PROlong Gold antifade reagent. These samples can be viewed on any confocal laser-scanning microscope with a water immersion Plan-Neofluar 40/1.3 NA DIC objective.

2. A second method is to drop 10 μl of the sample on a glass slide and cover it with a coverslip. These samples can be viewed under any confocal microscope with a Plan-Apochromat 63x/1.4 Oil DIC objective.

**Pitfalls**

- RBCs are very sensitive cells and great caution should be taken not to induce damage to these cells during sample preparation.
- All the chemicals that will be used in the sample preparation should be at room temperature before use and at a pH of 7.4 to avoid osmotic shock.
- The blood sample taken should not be older than 4 hours, and should be stored at room temperature.
- The blood tube(s) should be centrifuged to obtain only the RBC fraction to avoid any possible cross reactivity from other cells (white blood cells and platelets).
- Vortexing of the cells should be avoided during sample preparation - rather re-suspend cells by agitation in solution or by tapping the tube (Eppendorf or microtube) that holds the sample.

The cells tend to move around in solution when on the glass slide, let the sample stand for 30 seconds before viewing under the microscope in order for the cells to settle. Slides can also be coated with poly-L-lysine to attach cells [267].

The cells tend to move around in solution when on the glass slide, let the sample stand for 30 seconds before viewing under the microscope in order for the cells to settle. Slides can also be coated with poly-L-lysine to attach cells [267].

**Reactive Oxygen Species (ROS)**

Oxidative stress is an important accelerator and inducer of eryptosis and increased ROS generation is an important indicator of oxidative stress. ROS can be determined by utilizing 2′,7′-dichlorodihydrofluorescein diacetate (DCFDA) [245]. 4 μl RBCs should be mixed in 1 ml Ringer solution or a solution containing 5 mM CaCl₂. 150 μl from the resulting cell suspension should be centrifuged at 1600 rpm for 3 min at room temperature. Cells should then be stained with 10 μM DCFDA in Ringer solution at 37°C for 30 min. Following staining, the cells should be washed three times in 150 μl Ringer solution. These washed cells should then be re-suspended in 200 μl Ringer solution, and the ROS-dependent fluorescence intensity measured by flow cytometry, at an excitation and an emission wavelength determined by manufacturer’s instructions.

**Pitfalls**

- The blood should be stained as soon as possible after blood donation to avoid false readings of ROS introduced after blood donation.
- As mentioned above, these cells must be handled with extreme care.

**Intracellular Ca²⁺**

An increase of intracellular Ca²⁺ is part of the initiation of eryptosis and further fuels cell membrane scrambling to externalize PS to the outer leaflet of the RBC membrane. The cell-permeable acetoxyethyl (AM) ester of the fluorescent Ca²⁺ indicator Fluo-3, is commonly used to detect changes in intracellular Ca²⁺ levels in a variety of cells. The basis of this marker, is the
fact that Fluo-3 AM is almost non-fluorescent, until it is hydrolyzed intracellularly to Fluo-3 in the presence of Ca\(^{2+}\) [114].

**Flow cytometry**

In order to quantify intracellular Ca\(^{2+}\), 2 \(\mu\)l of freshly drawn blood should be mixed in 500 \(\mu\)l Ringer solution, containing 5 mM CaCl\(_2\) or any buffer solution containing 5 mM CaCl\(_2\). The cells should then be stained in 5 \(\mu\)M Fluo-3/AM and incubated at 37°C for 30 min. Ca\(^{2+}\)-dependent fluorescence intensity can then be measured in a flow cytometer, with an excitation and an emission wavelength that is specific to the fluorochrome used.

**Ceramide Formation**

Ceramides are composed of a sphingosine and a fatty acid and are known to form part of the cell membrane of cells. Ceramide is primarily produced by means of a *de novo* synthesis pathway, or by hydrolysis of sphingomyelin, catalyzed by sphingomyelinases. When ceramide is generated in the plasma membrane, it augments membrane rigidity by stabilizing smaller lipid platforms known as lipid rafts. The amount of ceramide content is an affective indicator of eryptosis [266]. Increased ceramide content is therefore and affective indicator of eryptosis.

**Flow cytometry**

Currently there are not many techniques available to determine ceramide expression on the RBC surface, but a monoclonal antibody-based assay is most commonly used. Also, radioactive labelling may also be used to show ceramide formation in RBCs where sphingomyelin breakdown is measured, by labelling RBCs with radioactive choline followed by measuring the incorporation of [methyl-3H] choline into RBC lipids [268].

The monoclonal antibody assay involves mixing 4 \(\mu\)l of RBCs in 1 ml Ringer solution, followed by taking 100 \(\mu\)l from the resulting cell suspension and centrifuging at 1600 rpm for 3 min, at room temperature, to form a RBC pellet. Subsequently, the cells should be stained for 1 h at 37°C with 1 \(\mu\)g/ml anti-ceramide antibody in a 1:10 dilution phosphate-buffered saline (PBS) containing 0.1% bovine serum albumin (BSA). Cells should then be washed twice afterwards with 100 \(\mu\)l PBS-BSA, followed by staining of the cells for 30 min, with a secondary antibody conjugated with a specific fluorochrome. The unbound secondary antibody should be removed by repeated washing with 50 \(\mu\)l PBS-BSA. Followed by re-suspending the samples in 200 \(\mu\)l PBS-BSA and analysed with a flow cytometer at an excitation and an emission wavelength that are specified according to the fluorochrome used.

**Pitfalls**

This is a very specific monoclonal antibody, and optimal conditions must be determined individually for each application, however, it is also an expensive method.

**Glutathione (GSH) Abundance**

**Flow cytometry**

RBCs have a large amount of glutathione (GSH) that buffer the damaging effects of oxidative stress, which is well known to deplete GSH and changes it into its disulfide form GSSG. Flow cytometry is a defined technique to determine the level of GSH on RBCs. GSH is known to be reduced in eryptosis therefore reduced glutathione (GSH) abundance can be determined by utilizing 5-chloromethylfluorescein diacetate (5-CMFDA). After incubation, 100 \(\mu\)l suspension of RBCs should be centrifuged at 1600 rpm for 3 min at 22 °C, followed by discarding of the supernatant and staining of the cells with 5-CMFDA (in PBS containing...
5-CMFDA at a final concentration of 1 μM. RBCs should then be incubated at 37 °C for 45 min in the dark, and washed in PBS, followed by re-suspending the 5-CMFDA-loaded RBCs in 200 μL PBS, and measuring the 5-CMFDA-dependent fluorescence intensity at an excitation and an emission wavelength, specified in the manufacturer’s instructions using a flow cytometer.

Another method used to determine reduced GSH is with mercury orange. Cells should be incubated for 30 min in PBS, containing 40 μM mercury orange. After incubation of the RBCs, they should be washed only once, and re-suspended in 200 μL PBS. The fluorescence intensity can be measured with flow cytometry according to the excitation and emission wavelength specified by the manufacturer.

**Confocal microscopy.**

An alternative method to mercury orange has been suggested, where RBCs are incubated with pre-warmed to 37°C with 10 μM 5-chloromethylfluorescein diacetate (CMFDA) and left for 30 min at 37°C. Cells should then be washed with PBS and fixed with 3.7% paraformaldehyde. Membrane-containing cells should then be removed, followed by mounting on a glass slide, and viewed with any typical confocal microscope [269].

**Pitfalls**

- The Mercury orange method requires thorough washing; therefore cell loss is an important factor to take in consideration when preparing RBCs with this method.
- Mercury orange has also been found to be less consistent and has higher background staining.

**Colorimetric measurement of glutathione (GSH)**

The Glutathione Assay (colorimetric) Kit provides a useful, colorimetric method for analysing either total glutathione or the reduced form glutathione alone using a microtiter plate reader. 5,5'-Dithiobis(2-nitrobenzoic acid) DTNB and glutathione (GSH) react to produce 2-nitro-5-thiobenzoic acid which has a yellow colour that can be determined by measuring the absorbance at 412 nm using a micro-plate reader.

RBC Sample Preparation according to the above-mentioned kit: Citrated blood should be centrifuged at 1000 x g for 10 min at 4°C, followed by suspending of the supernatant. The RBCs should then be lysed with a 4x volume of Glutathione Buffer and kept on ice for 10 min. Following this, 1x volume of a 5% SSA should be added, followed by mixing and centrifuged at 8000 x g for 10 minutes. Supernatant should then be transferred to a new tube and use to measure glutathione with a micro-plate reader [214].

**Measurement of membrane lipid hydroperoxides**

The purpose of measuring lipid hydroperoxides is to determine the oxidative degradation of lipids in the cell membrane. RBC ghosts should be prepared by washing 3x for 30 min, washing-centrifugation cycles (20000 g, 4°C), with excess hypotonic PBS, and finally suspended in 1 ml PBS. Conjugate diene (CD) lipid hydroperoxides should be extracted from 500 μl of the suspension using 3 ml of a CHCl₃:CH₂OH (2:1) mixture. The organic solvent should be evaporated using nitrogen stream, followed by re-suspending in cyclohexane, and quantify spectrophotometrically at 234 nm [214].

**Measurement of APL-translocase (APLT) activity**

The inhibition of APLT keeps PS at the outer side of the membrane after externalization [214]. This assay confirms eryptosis by looking at the APLT activity. RBC suspensions (0.5 ml) should be incubated at 37°C with 0.5 mM NBD-PS fluorescent probe, from a 1mmol.L⁻¹ stock solution in HEPES-buffer. After 60 min, 5 μl of the sample should be added to 250 μl HEPES buffer containing 0.1 mM EGTA and 1% bovine serum albumin that will extract the NBD-PS probe from the outer plasma-membrane. Cytofluorimetric measurements of residual fluorescence of the sample will then reveal the amount of NBD-PS localized on the inner leaflet in the plasmamembrane as a result of the APLT activity [214].
Pitfalls
- Extreme care should be taken not to haemolyse the RBCs. The cells should be fixed for only 10-15 min at room temperature.
- Exposure of 0.01% Triton-X 100 for 5 min has been found to work specifically well for RBCs.

Confocal microscopy
This method could not be validated for confocal microscopy.

Ultrastructural analysis to study eryptosis
Scanning electron microscopy (SEM) is a useful and specialized method to study physical structural changes associated with eryptosis, used in our laboratory. In the biochemical analysis methods, discussed above, are primarily used as indicator of eryptosis, however, ultrastructural analysis visually confirms these changes, by showing membrane blebbing, microparticle shedding, cell shrinkage, membrane fragility and RBC agglutination. We previously showed these ultrastructural changes in various diseases associated with RBC eryptosis. SEM can be used to study single RBCs or by adding thrombin to whole blood, to create an extensive fibrin network where RBCs are then trapped [12, 264, 270-276] In healthy blood the RBCs keep their shape and do not fold around the fibrin fibres. However, during systemic inflammation and under conditions associated with the development of eryptosis, the RBCs lose their typical shape and fold around the fibres, showing fragility of the membrane and membrane blebbing. To prepare SEM samples either 10 µl of whole blood is placed on a glass cover slip or 10 µl whole blood together with 5 µl thrombin is added to create an extensive fibrin network with trapped RBCs. A thin smear is created on the glass cover slip, and washed in PBS to remove excess proteins. The samples are then fixed in 4% formaldehyde followed by post-fixation of osmium tetroxide and standard SEM preparation methods. Samples are mounted and coated with carbon and viewed at 1 kV under a scanning electron microscope. Figure 3 shows examples of damaged RBCs showing various degrees of eryptosis, prepared for SEM analysis.

Pitfalls
The whole blood smear, with or without addition of thrombin should not be too thick, and when thrombin is added, the time between the mixing of the whole blood and the thrombin

Fig. 3. RBCs showing various stages of eryptosis. Scale bar: 1 µm.
should not be too long, otherwise a coagulated layer of plasma will form and this will cover the actual clot. We determined that when thrombin is added to whole blood, PBS should be added about 30 seconds after the smear is made, to prevent the clot washing off, but also to prevent the coagulated layer on top of the clot. For whole blood smears without thrombin, the smear should be left for at least 60 seconds, before adding PBS. This is particularly helpful for healthy blood, as it washed off easier than RBCs from inflammatory conditions, due to increased agglutination of the RBCs and increased plasma proteins spontaneously associated with the RBCs. The smear should also be done gently using a bent pipette tip, and without introducing too much force onto the sample, otherwise the RBCs will be damaged.

**Conclusion**

When reviewing the literature, most of the papers used Annexin-V binding to identify eryptosis using the PS flip, together with selected other conformational methods. We therefore suggest that this is probably the one method that most clearly confirms eryptosis. The method can be used as a flow cytometry as well as confocal microscopy method, and is easy and versatile for even a novice. Throughout the literature, if the PS flip was shown with Annexin-V binding, all the other methods confirmed eryptosis as well, suggesting that PS is a robust and singularly proven and confirming method of the presence of eryptosis. Together with an ultrastructural method like SEM, Annexin-V binding showing the presence of PS in the outer leaflet of an absolute confirmation of eryptosis.

RBC biophysical and shape changes may be particularly helpful in haematological changes associated with inflammatory conditions and determining the impact of medication after diagnosis. RBC healthiness can be used and is therefore extremely valuable as an indicator of inflammatory status, disease progression and/or treatment monitoring, as the biophysical and biochemical changes to RBCs are a significant accompaniment to a variety of (inflammatory) diseases, as shown in this paper. Ultrastructure and latest state-of-the-art fluorescent marker methods (e.g. confocal microscopy and flow cytometry), that represents both biochemical and biophysical clinically relevant readouts, and together cytokine profiles usually measured during inflammation, should be combined with targeted RBC membrane immunofluorescent biomarkers. We still know very little about the effects of inflammation, upregulated cytokine effects, as well as drug interactions with RBCs at the level of membrane receptor and single molecule interactions. The RBC membrane and its role in disease might provide researchers with an excellent model, particularly because it is a relatively non-invasive method to track the healthiness of an individual.

As the NIH is now driving the global process where precision medicine and individualized medicine is advised to form an integral part in the diagnosis and treatment of patients [277], eryptosis, single molecule as well as receptor interactions using both biophysical and biochemical analysis may give ultimately give practitioners an easy method to track inflammation and disease patterns before and after treatment, in a truly individualized, patient orientated precision medicine approach, where one-medication-regime-fits-all is no longer appropriate.

**Ethical Considerations**

Ethical clearance was obtained from the University of Pretoria Human Ethics Committee for the use of blood from patients with inflammatory conditions and healthy volunteers. All participants filled in informed consent forms.

**Acknowledgements**

Funding: National Research Foundation (NRF) and Medical Research Council (MRC) of South Africa: E Pretorius.
Disclosure Statement

There are no conflicts of interest to declare by any of the authors. EP: study leader, paper concept and writing of paper; JB and JdP: preparation of samples and methods descriptions. All authors approved of the submitted paper.

References

Archararit N, Sirireung S: Normalized coagulation markers and anticoagulation proteins in children with ... from normal individuals and sickle cell patients. Cell Calcium 2012;51:51-56.

Pretorius et al.: Eryptosis Review

DOI: 10.1159/000447895
Published online: October 24, 2016
© 2016 The Author(s). Published by S. Karger AG, Basel
www.karger.com/cpb


26 Weiss E, Cytlak UM, Rees DC, Osei A, Gibson JS: Deoxygenation-induced and Ca(2+) dependent phosphatidylserine externalisation in red blood cells from normal individuals and sickle cell patients. Cell Calcium 2012;51:51-56.


Pretorius et al.: Eryptosis Review

DOI: 10.1159/000447895
Published online: October 24, 2016
© 2016 The Author(s). Published by S. Karger AG, Basel
www.karger.com/cpb


170 Sopani M, Foller M, Lang F: Gold stimulates Ca2+ entry into and subsequent suicidal death of erythrocytes. Toxicology 2008;244:271-279.


