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Version: Version of Record

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1016/j.ceca.2018.04.005

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Deleterious effects of calcium indicators within cells; an inconvenient truth

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ARTICLE INFO

Keywords:
Calcium Indicator GECI BAPTA ATPase Signaling

ABSTRACT

The study of cellular Ca2+ signalling is indebted to Roger Tsien for the invention of fluorescent indicators that can be readily loaded into living cells and provide the means to measure cellular Ca2+ changes over long periods of time with sub-second resolution and microscopic precision. However, a recent study [1] reminds us that as useful as these tools are they need to be employed with caution as there can be off-target effects. This article summarises these recent findings within the wider context of confounding issues that can be encountered when using chemical and genetically-encoded Ca2+ indicators, and briefly discusses some approaches that may mitigate against misleading outcomes.

Tsien and colleagues invented numerous fluorescent indicators that are used to monitor cellular Ca2+ [2,3]. The fluorescent indicators vary in properties such as affinity, excitation and emission wavelengths, cellular location, and whether they have single wavelength maxima for excitation/emission, or can be used in a ratiometric manner [4]. These chemical Ca2+- indicators (as they are sometimes called; hereafter referred to as ‘Ca2+- indicators’) are based on BAPTA, an aminopolycarboxylic acid (Fig. 1). Being charged molecules, Ca2+- indicators are hydrophilic and therefore cell impermeant. Tsien showed that esterification of the carboxyl groups conferred lipophilicity, allowing the Ca2+- indicators to cross cell membranes [5]. Once inside cells, the esters are hydrolysed, and the free acid, Ca2+-binding molecule is released. Depending on the loading conditions used, the intracellular accumulation of Ca2+- indicators can plausibly span from micromolar to millimolar concentrations. Where loading of esterified Ca2+- indicators is sub-optimal, the free acid forms can be introduced into cells using techniques such as microinjection or via patch pipettes.

The ease with which Ca2+- indicators can be loaded and monitored has led to their use in thousands of studies that have characterised the spatial and temporal properties of Ca2+ signals in various cell types. Chemical Ca2+- indicators are ideal in many ways; they have rapid Ca2+-binding kinetics, are brightly fluorescent, and are functional within cells for long periods of time [6]. Moreover, the output from these Ca2+- indicators can usually be readily calibrated into Ca2+ concentration [7]. BAPTA is commonly used to test, or negate, the involvement of Ca2+ in cellular processes, and is often loaded to large excess to provide stringent buffering of Ca2+ concentration. While Ca2+ indicators and BAPTA are critical tools for dissecting cellular responses, relatively few studies have included controls for their potential off-target effects.

A recent study from Maiken Nedergaard’s lab [1] highlighted an interaction of Ca2+- indicators and BAPTA with the Na+/K+-ATPase, a ubiquitous cellular enzyme, with consequent deleterious effects on metabolism, signalling and cell survival. Specifically, Smith et al. [1] observed that commonly used Ca2+- indicators (Fluo-4, Rhod-2 and Fura-2), as well BAPTA, inhibited the Na+/K+-ATPase in several primary cell types independent of Ca2+ binding. They found that the Ca2+- indicators and BAPTA altered K+ homeostasis and caused ATP release within the cortex of living animals, as well as reducing spontaneous Ca2+ signals within primary astrocytes. An additional effect of Fluo-4, Fura-2 and BAPTA was to decrease the cellular uptake of glucose. Given the critical role of the Na+/K+-ATPase in establishing Na+ and K+ gradients (which are critical for the membrane potential, secondary active transport, ionic transport and cell volume regulation), it is not surprising that inhibition of this enzyme would influence many downstream processes. For example, the Na+/K+-ATPase is the primary mechanism for extracellular K+ buffering in the brain; the archetypal function of astrocytes, and critical for overall regulation of the excitability of the central nervous system [8]. Moreover, the Na+/K+-ATPase can function within cellular microdomains that include other transporters and signalling moieties including Src kinase, phospholipase C-γ and inositol 1,4,5-trisphosphate (IP3) receptors [9]. Long-term inhibition of the Na+/K+-ATPase leads to altered gene transcription [10] and prevents autophagic cell death (autosis) [11]. Rhod-2...

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https://doi.org/10.1016/j.ceca.2018.04.005
Received 4 March 2018; Received in revised form 3 April 2018; Accepted 11 April 2018
Available online 15 April 2018
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appeared to have a further negative effect on mitochondrial ATP production since it stimulated glucose uptake and glycolysis to compensate for reduced respiration. Although some labs use Rhod-2 to monitor cytosolic Ca\(^{2+}\), due to its delocalised positive charge Rhod-2 accumulates within the mitochondrial matrix and has been used extensively to monitor mitochondrial Ca\(^{2+}\) sequestration [12]. Further work is needed to establish how Rhod-2 alters mitochondrial function, but other rhodamine-based compounds have been shown to affect the electron transfer and the F\(_{1}\)F\(_{0}\)-ATPase [13], and the adenine nucleotide translocase [14].

A number of studies have noted that Ca\(^{2+}\) indicators and BAPTA have Ca\(^{2+}\)-independent off-target actions and may not be freely diffusible within cells (Fig. 2 and Table 1) [15]. Although more work is needed to understand how these compounds affect cellular targets, a direct interaction is plausible since they are known to bind to cellular proteins [16,17]. In fact, it has been estimated that the majority of Fura-2 molecules within a cell may be bound by cytosolic proteins, even if the Ca\(^{2+}\) indicator is injected as the free acid [17]. Within muscle cells, typically > 80% of Ca\(^{2+}\) indicator molecules are bound to cellular components [18], leading to changes in the indicator’s fluorescence properties [19,20]. Non-specific binding of Fura-2 to proteins is enhanced in environments with an acidic pH [21].

Smith et al. [1] observed that the inhibition of Na\(^+\)/K\(^+\)-ATPase by Ca\(^{2+}\) indicators and BAPTA was retained in cell membrane
preparations that had been incubated in a lysis buffer for several hours. Under such conditions any freely diffusible molecules would have been lost from the cells. Whilst these data suggest a long-lasting interaction, it is unclear whether the Na+/K+-ATPase is directly targeted by Ca2+ indicators, or if their effects are mediated by accessory factors. Ouabain, a naturally occurring inhibitor of the Na+/K+-ATPase, binds to the enzyme at an extracellular site with nanomolar affinity [22], although other binding sites have been proposed [23]. It remains to be shown if, and where, BAPTA and Ca2+ indicators bind to the Na+/K+-ATPase. Because BAPTA and Ca2+ indicators inhibit the Na+/K+-ATPase when loaded into cells it is likely that they access the enzyme from its cytosolic aspect. Given the resemblance of the Na+/K+-ATPase to the sarco/endoplasmic reticulum Ca2+-ATPase (SERCA), responsible for Ca2+ uptake into organelles, it is possible that other P-type ATPases may be affected by Ca2+ indicators and BAPTA [22,24].

There is insufficient evidence to draw robust conclusions relating to the structure-activity profile of either BAPTA or chemical Ca2+ indicators. The required libraries of structurally diverse analogues have not been systematically tested against these recently identified targets, and it is therefore difficult to make assumptions as to the parts of the molecular framework responsible for their interactions with proteins. The structure of BAPTA (the parent compound) is shown in Fig. 1 as the free acid, the AM ester form and, in a complex with Ca2+. BAPTA can be a planar molecule, but it can also rotate around the ether bonds that connect the aromatic groups, or altering the position of the benzene rings changed their polarity. The required libraries of structurally diverse analogues have not been systematically tested against these recently identified targets, and it is unclear whether the Na+/K+-ATPase is directly targeted by Ca2+ indicators and/or if their effects are mediated by accessory factors. Ouabain, a naturally occurring inhibitor of the Na+/K+-ATPase, binds to the enzyme at an extracellular site with nanomolar affinity [22], although other binding sites have been proposed [23]. It remains to be shown if, and where, BAPTA and Ca2+ indicators bind to the Na+/K+-ATPase. Because BAPTA and Ca2+ indicators inhibit the Na+/K+-ATPase when loaded into cells it is likely that they access the enzyme from its cytosolic aspect. Given the resemblance of the Na+/K+-ATPase to the sarco/endoplasmic reticulum Ca2+-ATPase (SERCA), responsible for Ca2+ uptake into organelles, it is possible that other P-type ATPases may be affected by Ca2+ indicators and BAPTA [22,24].

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Table 1

<table>
<thead>
<tr>
<th>Reagent</th>
<th>Cell type</th>
<th>Working concentration</th>
<th>Effect</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAPTA-AM</td>
<td>Rat parotid cells</td>
<td>100 μM</td>
<td>Reduced cellular ATP levels</td>
<td>[26]</td>
</tr>
<tr>
<td>BAPTA-AM</td>
<td>3T3-L1 adipocytes</td>
<td>50 μM</td>
<td>Reduced insulin-stimulated translocation of GLUT4</td>
<td>[27]</td>
</tr>
<tr>
<td>BAPTA-AM</td>
<td>A6 (Xenopus), RAT2 cells</td>
<td>50 μM</td>
<td>Cytoskeletal disassembly</td>
<td>[28]</td>
</tr>
<tr>
<td>BAPTA</td>
<td>Murine brown adipocytes</td>
<td>1–2 mM</td>
<td>Changes in mitochondrial morphology and distribution</td>
<td></td>
</tr>
<tr>
<td>BAPTA-AM</td>
<td>3T3-L1 adipocytes</td>
<td>12.5–50 μM</td>
<td>Decrease tubulin polymerisation</td>
<td>[30]</td>
</tr>
<tr>
<td>BAPTA and di-bromo BAPTA</td>
<td>Drosophila photoreceptors</td>
<td>~1–10 Mm (IC50 for BAPTA)</td>
<td>Inhibition of phospholipase C</td>
<td>[31]</td>
</tr>
<tr>
<td>BAPTA-AM, di-fluoro BAPTA-AM, and di-bromo BAPTA-AM</td>
<td>Endothelial cells</td>
<td>0.5–50 μM</td>
<td>Enhanced prostacyclin release. Concentration- and time-dependent effect of BAPTA; both activation and inhibition were observed.</td>
<td></td>
</tr>
<tr>
<td>BAPTA-AM</td>
<td>HEK293 cells</td>
<td>0.1–50 μM (IC50 ~ 1 μM)</td>
<td>Inhibition of heterologously-expressed K+ channels</td>
<td></td>
</tr>
<tr>
<td>BAPTA-AM</td>
<td>Liver macrophages</td>
<td>10 μM</td>
<td>Enhanced prostacyclin release. Concentration- and time-dependent effect of BAPTA; both activation and inhibition were observed.</td>
<td></td>
</tr>
<tr>
<td>BAPTA</td>
<td>Hepatocytes</td>
<td>1 μM–10 mM (Kd ~ 1.8 mM)</td>
<td>Inhibition of insitol 1,4,5-trisphosphate-induced Ca2+ release</td>
<td></td>
</tr>
</tbody>
</table>

A critical question concerning the continued use of chemical Ca2+ indicators is whether it is possible to overcome or control for, their effects on Na+/K+-ATPase inhibition. One of the products resulting from the intracellular hydrolysis of esterified Ca2+ indicators is formaldehyde, which is widely used as a tissue fixating agent. However, Smith et al. [1] found that the free acid forms of Ca2+ indicators and BAPTA could inhibit the Na+/K+-ATPase, suggesting that products released via ester hydrolysis were not causative. These observations indicate that introduction of Ca2+ indicators and BAPTA via microinjection or patch pipettes cannot solve the issue.

An alternative to the use of chemical Ca2+ indicators is genetically-encoded Ca2+ indicators (GECIs), which are generally based on the fusion of Ca2+-binding proteins with fluorescent proteins [42]. In their study, Smith et al. [1] demonstrated that the GECI GCaMP3 did not cause inhibition of the Na+/K+-ATPase, or alter the frequency of astrocytic Ca2+ signals. However, whilst GECIs have great utility, particularly for long-term recordings [43], they may not perform as well as chemical Ca2+ indicators in terms of their Ca2+-binding kinetics or sensitivity [44], and might be unsuitable in situations where cells (e.g. cardiomyocytes) could functionally change during the time needed for the GECI expression. As with chemical Ca2+ indicators, the use of GECIs relies on an adequate expression level, correct localization and the absence of deleterious cellular effects. However, it was found that following viral transduction, the expression level of GCaMP3 was not stable and increased over time, reaching an expression level above the optimum signal-to-noise ratio after 7 weeks [45]. Moreover, following long-term expression, GCaMP3 protein was not only found in the cytoplasm (its intended compartment), but additionally non-functional, N-terminally cleaved GCaMP3 accumulated in the nuclei of neurons [46,47], and atypical responses were observed [46]. The presence of non-functional GECI molecules resulted in an under-estimation of the observed Ca2+ responses.

Similar to chemical Ca2+ indicators, a substantial portion of GECIs can be bound to cellular targets (around 50% in neurons) [47], which could lead to altered properties such as a change of Ca2+ sensitivity. Furthermore, long-term expression of GECIs may result in prolonged Ca2+ buffering, thereby impacting on Ca2+-regulated processes including transcriptional regulation via NFAT and CREB. Since the expression of several Ca2+-transport systems is controlled through these Ca2+-dependent transcription factors (e.g. insitol 1,4,5-trisphosphate receptors and the mitochondrial uniporter via NFAT2 and CREB, respectively [48,49]), GECIs might adversely affect the expression of Ca2+ channels and transporters. Moreover, GECIs (specifically...
Table 2

Assessing, and controlling for, Ca\(^{2+}\)-independent cellular actions Ca\(^{2+}\) indicators and BAPTA, and other experimental issues arising from fluorescence imaging. Abbreviations: GECI; genetically-encoded Ca\(^{2+}\) indicator, IP\(_3\); inositol 1,4,5-trisphophate, 2-APB; 2-aminoethoxy diphenyl borate, U73122; 1-[(17β)-3-Methoxyestra-1,3,5(10)-trien-17-ylamino]hexyl]-1H-pyrole-2,5-dione.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Utility</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of ouabain</td>
<td>Given that the Na(^+)/K(^+)-ATPase has been shown to be affected by Ca(^{2+}) indicators and BAPTA, ouabain could be used as a control. If ouabain replicates experimental outcomes observed using Ca(^{2+}) indicators and BAPTA, then the Na(^+)/K(^+)-ATPase may be involved.</td>
<td>It would be difficult to know exactly how much ouabain would be needed to replicate putative Na(^+)/K(^+)-ATPase inhibition.</td>
</tr>
<tr>
<td>Use of low affinity BAPTA analogues</td>
<td>Low affinity BAPTA analogues can be loaded using the same conditions as for BAPTA. Due to their lesser affinity for Ca(^{2+}), the analogues should not replicate the effect of BAPTA if a particular cellular process is Ca(^{2+}) dependent.</td>
<td>This is potentially the simplest control to perform. However, since the low affinity BAPTA analogues may not buffer Ca(^{2+}) to the same extent as BAPTA, it would be necessary to show that they have loaded into the cells by measuring increased absorption at ∼260 nm.</td>
</tr>
<tr>
<td>Non-Ca(^{2+})-buffering AM ester compounds</td>
<td>To assess the potential effects of de-esterification of Ca(^{2+}) indicators and BAPTA within cells, it could be helpful to use non-Ca(^{2+})-buffering, cell-permeable esters as a reference. For example, BCECF-AM, a cell-permeable pH indicator, could be used as a reference.</td>
<td>One potential caveat in the use of BAPTA analogues is whether they have the same off-target effects. There is evidence that they share the same off-target actions on the Na(^+)/K(^+)-ATPase [1], phospholipase C [31] and prostacyclin release [32].</td>
</tr>
<tr>
<td>Use of pharmacological reagents to verify the involvement of Ca(^{2+})</td>
<td>An adjunct to the use of BAPTA to investigate the role of Ca(^{2+}) signals in a cellular response could be pharmacological reagents that target specific Ca(^{2+}) transport processes. For example, U73122, 2-APB and xestospongin B could be used to implicate IP(_3) signaling and/or Ca(^{2+}) influx [53-55], or mitoxantrone may be used to examine the role of the mitochondrial Ca(^{2+}) uniporter [56].</td>
<td>Whilst this is an easy control to perform, it might be difficult to match the intracellular concentrations of Ca(^{2+}) indicators and BAPTA with a reference indicator such as BCECF. In addition, reference indicators may have their own off-target effects.</td>
</tr>
<tr>
<td>Use of chelators to rule out effects of heavy metals</td>
<td>Chemical Ca(^{2+}) indicators all show varying degrees of affinity for heavy metal ions like Mn(^{2+}) and Zn(^{2+}) [59]. If changes in the concentration of heavy metal ion concentrations occur, these might be interpreted as changes in the Ca(^{2+}) concentration without appropriate controls.</td>
<td>Some pharmacological tools have genetic correlates that can be used in parallel. For example, xestospongin B and 2-APB can be used in conjunction with the IP(_3) 5'-phosphatase, or a high-affinity IP(_3) sponge, to inhibit IP(_3)-mediated Ca(^{2+}) signals [57,58].</td>
</tr>
<tr>
<td>Effects of pH and experimental reagents on Ca(^{2+}) indicators and their calibration</td>
<td>The spectral characteristics and affinities of many chemical Ca(^{2+}) indicators (and GECIs) is pH dependent. The affinity for Ca(^{2+}) is usually not affected within the physiological cytosolic pH range, but can be reduced at acidic pH [65]. The fluorescence of Ca(^{2+}) indicators may be affected by experimental reagents such as caffeine [66] and resveratrol [67].</td>
<td>Pharmacological tools are sometimes ideal for acute experiments, and when the effective concentrations of the reagents are known. However, it can be difficult to definitively say that there are no off-target effects of a particular reagent, even when used at a low concentration.</td>
</tr>
<tr>
<td>Expression of GECIs and Ca(^{2+})-binding proteins</td>
<td>GECIs and Ca(^{2+})-binding proteins can be used for the same purposes as chemical Ca(^{2+}) indicators and BAPTA providing that they can be expressed within the cells of interest.</td>
<td>Some potential caveats in the use of BAPTA analogues is whether they have the same off-target effects. There is evidence that they share the same off-target actions on the Na(^+)/K(^+)-ATPase [1], phospholipase C [31] and prostacyclin release [32].</td>
</tr>
<tr>
<td>Mitigating potential pitfalls of chemical Ca(^{2+}) indicators</td>
<td>There are a number of issues that can arise when performing fluorescence experiments: chelation of heavy metals, indicator bleaching, production of reactive oxygen species (ROS), compartmentalisation/extrusion of fluorescent reporters, and varying affinities of reporters for Ca(^{2+}) in different cellular environments [73]. An issue that is not widely considered is the induction of autophagy when using simple extracellular solutions that do not have growth factors or amino acids. Autophagy can induce a change in Ca(^{2+}) transport systems [75].</td>
<td>The impact of bleaching and ROS may be minimised by using short excitation exposure times and low incident light energy, or supplementation with ROS scavengers.</td>
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</table>
GCaMPs) change the apparent sensitivity of cells to IP3 [44]. Most transgenic GECI mice do not show an obviously altered phenotype [47], but profound effects of GECI expression have been observed, e.g. cardiac hypertrophy in a mouse expressing GCaMP2 [50]. It is plausible that mild phenotypic changes, which go undetected, could nevertheless affect the experimental results obtained with specific cell types. For example, a detailed study of transgenic mice expressing the troponin C-based GECI TN-XXL revealed changes in behavioural parameters, cardiac function and gene expression, despite the absence of a strong whole animal phenotype [51].

It is hard to say how much the effects of Ca2+ indicators and BAPTA on the Na+/K+-ATPase, as reported by Smith et al. [1], impinge on the results of published studies. However, it is a reminder that the loading of Ca2+ indicators is best kept minimal and should be controlled for. Whilst substantial loading of Ca2+ indicators may improve signal to noise in fluorescence recordings, it can actually lead to diminished Ca2+ signals due to buffering. Smith et al. [1] observed that the inhibition of the Na+/K+-ATPase was proportional to the concentration of Ca2+ indicator loaded. With modest concentrations of Ca2+-indicator loading, there was no significant effect on the Na+/K+-ATPase activity. It is possible that empirically establishing minimal Ca2+-indicator-loading conditions may avoid deleterious effects of the Na+/K+-ATPase and other yet unknown cellular targets. Some years ago, Erwin Neher pointed out that both very high and very low concentrations of a Ca2+ indicator, such as Fura-2, can be useful but for different experimental purposes, and that intermediate concentrations should be avoided as they will not give accurate results. Generally, to measure changes in the cytosolic free Ca2+ concentration, a minimal indicator concentration should be used to circumvent extra Ca2+ buffering, whilst for measuring Ca2+ flux a sufficient amount of Ca2+ indicator must be present to overcome the endogenous Ca2+ buffers in the cell [52].

In experiments where BAPTA is used to implicate the involvement of Ca2+ in a cellular process, it could be important to perform additional controls using low affinity versions of BAPTA such as dibromo-bapta and difluoro-BAPTA (Kd values 1.6 and 65 μM, respectively, compared to a Kd of 160 nM for BAPTA) (Fig. 1). These low affinity Ca2+ chelators should not phenocopy the effect of BAPTA if the cellular response involves Ca2+. Moreover, it would be ideal if the Ca2+ buffering of BAPTA was tested after it has been loaded into cells. The buffering of cytosolic Ca2+ is generally assumed after BAPTA-AM loading, and is not routinely demonstrated in studies that use BAPTA as a means of blocking cellular Ca2+ signalling. The effectiveness of BAPTA could be easily tested by stimulating GECI-expressing or Ca2+ indicator-loaded cells with a Ca2+-releasing agonist (e.g. ATP). If this is not suitable, the loading of BAPTA into cells could be verified by measuring absorbance of the compound at ~260 nm. Some of the approaches that may be taken to mitigate off-target effects of Ca2+ indicators and BAPTA, and ancillary experimental issues, are described in Table 2.

The study by Smith et al. [1] is a timely reminder that we need to be cautious in our use of chemical Ca2+ indicators and BAPTA. Evidence has been presented over many years that these compounds may have deleterious off-target actions (Table 1). However, there are a range of strategies that can be adopted to counteract potential confounding effects (Table 2). Chemical Ca2+ indicators and BAPTA remain ideal tools for certain situations, but additional control experiments may be both necessary and prudent.

Acknowledgements

Work in the authors’ laboratories has been supported by grants provided by The Open University, and the Research Council – KU Leuven and the Research Foundation – Flanders (FWO).

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[22] C. Toyoshima, R. Kanai, F. Cornelius, First crystal structures of Na + + K+-ATPase: The induction of autophagy can be tested using a number of markers, and can be avoided by including growth factors and amino acids in the extracellular medium. Complete phenol red-free culture medium can be used for imaging providing that it is supplemented with a pH buffer that can work outside a CO2-gassed incubator. However, long term (> 7b) presence of HEPES in the medium has been shown to induce autophagy [77].