A Role for Calcium-Activated Adenylate Cyclase and Protein Kinase A in the Lens Src Family Kinase and Na,K-ATPase Response to Hyposmotic Stress

Mohammad Shahidullah,1,2 Amrital Mandal,1 and Nicholas A. Delamere1,2

1Department of Physiology, University of Arizona, Tucson, Arizona, United States
2Department of Ophthalmology & Vision Science, University of Arizona, Tucson, Arizona, United States

Correspondence: Mohammad Shahidullah, Department of Physiology, University of Arizona, 1501 N Campbell Avenue, Tucson, AZ 85724, USA; shahidiua@email.arizona.edu.

MS and AM contributed equally to the work presented here and should therefore be regarded as equivalent authors.

Submitted: February 1, 2017
Accepted: July 31, 2017

Citation: Shahidullah M, Mandal A, Delamere NA. A role for calcium-activated adenylate cyclase and protein kinase A in the lens Src family kinase and Na,K-ATPase response to hyposmotic stress. Invest Ophthalmol Vis Sci. 2017;58:4447–4456. DOI: 10.1167/iovs.17-21600

PURPOSE. Na,K-ATPase activity in lens epithelium is subject to control by Src family tyrosine kinases (SKFs). Previously we showed hyposmotic solution causes an SKF-dependent increase in Na,K-ATPase activity in the epithelium. Here we explored the role of cAMP in the signaling mechanism responsible for the SKF and Na,K-ATPase response.

METHODS. Intact porcine lenses were exposed to hyposmotic Krebs solution (200 mOsm) then the epithelium was assayed for cAMP, SKF phosphorylation (activation) or Na,K-ATPase activity.

RESULTS. An increase of cAMP was observed in the epithelium of lenses exposed to hyposmotic solution. In lenses exposed to hyposmotic solution SKF phosphorylation in the epithelium approximately doubled as did Na,K-ATPase activity and both responses were prevented by H89, a protein kinase A inhibitor. The magnitude of the SKF response to hyposmotic solution was reduced by a TRPV4 antagonist HC067047 added to prevent TRPV4-mediated calcium entry, and by a cytoplasmic Ca2+ chelator BAPTA-AM. As a direct test of cAMP-dependent SKF activation, intact lenses were exposed to 8-pCPT-cAMP, a cell-permeable cAMP analog. 8-pCPT-cAMP caused robust SKF activation. Using Western blot, two calcium-activated adenyl cyclases, ADCY3 and ADCY8, were detected in lens epithelium.

CONCLUSIONS. Calcium-activated adenyl cyclases are expressed in the lens epithelium and SKF activation is linked to a rise of cAMP that occurs upon hyposmotic challenge. The findings point to cAMP as a link between TRPV4 channel-mediated calcium entry, SKF activation, and a subsequent increase of Na,K-ATPase activity.

Keywords: calcium-activated adenyl cyclase, cAMP, lens, Na,K-ATPase, Src family kinase

Lens ion and water homeostasis is of paramount importance to maintenance of its transparency and hence normal vision. Active ion transport by Na,K-ATPase in the monolayer of lens epithelium plays a critically important role because the mature lens fiber cells, which make up the bulk of the lens, have little or no Na,K-ATPase activity. There is still much to be learned about how the epithelium matches its Na,K-ATPase activity to the needs of the fiber mass. In studies on the signaling mechanisms that modulate Na,K-ATPase activity in the epithelium, we discovered that a Src family tyrosine kinase (SKF)-dependent signaling mechanism is responsible for an increase in Na,K-ATPase activity in the epithelium that occurs when the intact lens is subjected to hyposmotic stress. We found evidence that the SKF phosphorylation and Na,K-ATPase activity responses were dependent on TRPV4 channel activation and hemichannel opening in the epithelium of lenses exposed to hyposmotic solution. In cultured lens epithelium, we showed that TRPV4 activation and opening of connexin hemichannels caused a sustained increase in cytoplasmic calcium concentration. An increase in cytoplasmic calcium concentration is a common and versatile step in many cellular signaling cascades. One of the distinguishing features of calcium signaling is crosstalk with other signaling pathways. For example, increased cytoplasmic calcium can act directly or through Ca2+/calmodulin or Protein Kinase C (PKC) to regulate certain members of adenylate cyclase family, the so-called calcium-sensitive isoforms or Ca2+/calmodulin-sensitive phosphodiesterase PDE1. This has the consequence of changing cytoplasmic cAMP concentrations. Because SKF activation is known in some tissues to be cAMP-dependent, and protein kinase A (PKA)-dependent, we examined the contribution of cAMP/PKA-dependent SKF activation to the signaling response in lens epithelium. The purpose of the present study was to explore cAMP in the context of the signaling mechanism responsible for the activation of SKF and Na,K-ATPase activity in the epithelium of intact porcine lenses subjected to a hyposmotic challenge. We show that the lens epithelium expresses two different calcium-dependent adenyl cyclases and provides several lines of evidence that point to cAMP/PKA-dependent SKF activation.

MATERIALS AND METHODS

Ouabain, HC067047, ODQ, IBMX, H89, alamethicin, Dowex 50W x4-400 mesh cation exchange resin, and dimethylsulfoxide

L

Copyright 2017 The Authors
iovs.arvojournals.org | ISSN: 1552-5783

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

Downloaded From: http://arvojournals.org/ on 01/26/2018
IOVS | September 2017 | Vol. 58 | No. 11 | 4448

Hypotonic SFK Activation in the Lens Involves PKA

M. A. Ghanbarian

DMSO were purchased from Sigma-Aldrich Corp. (St. Louis, MO, USA). BAPTA-AM was purchased from Invitrogen (Carlsbad, CA, USA). Other chemicals including those for preparing the Krebs solution were purchased from Sigma-Aldrich Corp. Rabbit polyclonal antiphospho-Src-family (Tyr 416) kinase antibody and rabbit polyclonal anti-actin antibody were obtained from Cell Signaling Technology (Danvers, MA, USA). Rabbit polyclonal anti-adenylate cyclase 1 (ADCY1), anti-adenylate cyclase 3 (ADCY3), and anti-adenylate cyclase 8 (ADCY8) were purchased from Abcam (Cambridge, MA, USA). Goat antirabbit secondary antibody conjugated with IRDye 680 and goat antimouse secondary antibody conjugated with IR Dye 800 were obtained from LI-COR Biosciences (Lincoln, NE, USA). A biotinylated protein ladder along with antibiotin antibody was obtained from LI-COR Biosciences (Lincoln, NE, USA). A polyclonal antiphospho-Src-family (Tyr 416) kinase antibody and polyclonal antiphospho-ERK antibody were purchased from Cell Signaling Technology (Danvers, MA, USA). Goat anti-actin IgG-biotinylated protein ladder along with antibiotin antibody was purchased from Cell Signaling Technology. Goat antirabbit IgG-HRP-conjugated secondary antibody was purchased from Santa Cruz Biotechnology, Inc. (Fort Worth, TX, USA). Super Signal west Pico Chemiluminescent substrate was obtained from Thermo Scientific (Waltham, MA, USA) and Amersham Hyper Film ECL was purchased from GE Healthcare (Pittsburgh, PA, USA). Adenosine 3'-5'-cyclic phosphosphate, [5',8-3H] (cAMP[5',8-3H]) and a cAMP radioimmunoassay kit (cAMP [125I] RIA Kit) were purchased from Perkin Elmer (Waltham, MA, USA). The Micro Bicinchoninic Acid (BCA) Protein Assay Kit was purchased from Thermo Scientific Pierce.

Krebs Solution Composition

Intact lenses were incubated at 37°C in control (300 mOsm) Krebs solution that contained (in mM) 119 NaCl, 4.7 KCl, 1.2 KH₂PO₄, 25 NaHCO₃, 2.5 CaCl₂, 1 MgCl₂, and 5.5 glucose. Prior to use, the solution was equilibrated with 5% CO₂ for 40 minutes and adjusted to pH 7.4. In specified experiments, lenses were exposed to hyposmotic Krebs solution (200 mOsm) in which the NaCl concentration was reduced to 69 mM.

Intact Lenses

Pig eyes were obtained from the University of Arizona Meat Science Laboratory or from West Valley Processing Meat processors (Buckeye, AZ, USA), or Hatfield Quality Meats (Philadelphia, PA, USA). Human donor eyes were purchased from National Disease Research Interchange (Philadelphia, PA, USA), and the use was approved by the Institutional Review Board of the University of Arizona. The use of porcine tissue was approved by the University of Arizona Institutional Animal Care and Use Committee and conformed to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. The posterior of the eye was dissected open and the zonules were cut, allowing the intact lens to be removed and transferred to Krebs solution. Prior to use, lenses were allowed to equilibrate in Krebs solution for 3 hours at 37°C and 5% CO₂ in a humidified incubator.

Na,K-ATPase Activity

The capsule-epithelium was removed from each lens and homogenized in 350 μL ice-cold double-strength ATPase assay buffer that contained (mM): L-Histidine, 80; NaCl 200; KCl, 10; MgCl₂, 6.0; EGTA, 2.0 (pH 7.4) plus 10 μL/mL Protease Inhibitor Cocktail (Thermo Scientific). The homogenization protocol, which was carried out on ice, was four cycles of 15 seconds at 5-second intervals using a Misonix S3000 sonicator at a 6 W power setting (Misonix, Farmingdale, NY, USA). The homogenate was centrifuged at 13,000g for 30 minutes at 4°C to remove nuclei, mitochondria, and unbroken debris. Then the supernatant was frozen in liquid nitrogen and used at a later date to measure Na,K-ATPase activity. Protein in the supernatant was measured by the BCA assay, using bovine serum albumin as a standard.

Na,K-ATPase activity was measured using a modification of a method described earlier. In brief, 150 μL supernatant was placed in duplicate tubes containing 50 μL double-strength ice-cold Na,K-ATPase buffer. To ensure access of ions and ATP to membrane vesicles, alamethicin (5 μL) was added to give a final approximate concentration of 0.1 mg alamethicin per mg of protein. Either ouabain (10 μL) (final concentration 300 μM) or an equivalent volume of distilled water was added to each tube. Oubain is a potent and selective inhibitor of Na,K-ATPase, and prior studies confirmed 300 μM ouabain is sufficient to cause maximal inhibition of porcine lens epithelium Na,K-ATPase activity. The remainder of the tubes received an additional 145 μL distilled water. The tubes were preincubated at 37°C for 5 minutes then concentrated ATP solution (40 μL) was added to each tube (final ATP concentration of 2 mM), bringing the total volume of the assay mixture to 400 μL and the concentration of the double-strength Na,K-ATPase buffer to single strength. The assay mixture was incubated in the dark at 37°C for 30 minutes with mild shaking. At the end of the incubation period, the ATP hydrolysis reaction was stopped by the addition of 150 μL 15% ice-cold trichloroacetic acid, and the tubes were placed on ice for 30 minutes with occasional mixing by shaking to encourage protein precipitation.

ATP hydrolysis was determined by measuring the amount of inorganic phosphate released in each reaction tube. The tubes were placed in a centrifuge at 3000 rpm for 15 minutes at 4°C then 400 μL supernatant was removed and mixed with 400 μL 4.0% FeSO₄ solution in ammonium molybdate (1.25 g of ammonium molybdate in 100 mL 2.5N sulphuric acid). Standard solutions, which contained NaH₂PO₄ and were equivalent to 0, 10, 62.5, 125, 250, and 500 nmoles of PO₄ 3- were prepared. The mixture was incubated in the dark at 37°C for 30 minutes with mild shaking. At the end of the incubation period, the ATP hydrolysis reaction was stopped by the addition of 150 μL 15% ice-cold trichloroacetic acid, and the tubes were placed on ice for 30 minutes with occasional mixing by shaking to encourage protein precipitation.

ATP hydrolysis was determined by measuring the amount of inorganic phosphate released in each reaction tube. The tubes were placed in a centrifuge at 3000 rpm for 15 minutes at 4°C then 400 μL supernatant was removed and mixed with 400 μL 4.0% FeSO₄ solution in ammonium molybdate (1.25 g of ammonium molybdate in 100 mL 2.5N sulphuric acid). Standard solutions, which contained NaH₂PO₄ and were equivalent to 0, 10, 62.5, 125, 250, and 500 nmoles of PO₄ 3- were prepared. The mixture was incubated in the dark at 37°C for 30 minutes with mild shaking. At the end of the incubation period, the ATP hydrolysis reaction was stopped by the addition of 150 μL 15% ice-cold trichloroacetic acid, and the tubes were placed on ice for 30 minutes with occasional mixing by shaking to encourage protein precipitation.

Western Blot

Infrared Detection System. The capsule-epithelium was isolated from each lens and placed in an Eppendorf tube containing ice-cold lysis buffer that contained (in mM) 50 HEPES, 150 NaCl, 1 EDTA, 10 sodium fluoride, 10 sodium pyrophosphate, 2 sodium orthovanadate, 10% glycerol, 1% Triton X-100, 1% sodium deoxycholate, as well as a protease inhibitor cocktail (Thermo Fisher Scientific) and phosphatase inhibitor cocktails 1 and 2 (EMD Millipore, Billerica, MA, USA) at manufacturer’s recommended concentration (pH of 7.5). Following homogenization for 1 minute (four strokes of 15 seconds at 5-second intervals) using a Misonix S3000 sonicator at 6 W power setting (Misonix), the mixture was centrifuged at 13,000g for 30 minutes at 4°C to remove nuclei, mitochondria, and unbroken debris. The supernatant was frozen in liquid nitrogen and used at a later date when it was thawed and then subjected to Western blot analysis. The protein content in the sample was measured by the BCA assay. For Western blot, proteins were separated by 7.5% SDS-PAGE electrophoresis and transferred to nitrocellulose membrane. The membrane was
kept overnight at 4°C in blocking buffer (AquaBlock/EIA/WB), East Coast Bio, Inc., North Berwick, ME, USA) then incubated overnight at 4°C with mouse monoclonal antiphospho-src-family (Tyr 416) antibody (1:1000) and rabbit polyclonal anti-β-actin antibody (1:5000). After three 5-minute washes with a mixture of Tris-buffered saline and Tween 20 and three times with PBS. Immunoreactive bands were detected and quantified using an Odyssey infrared scanner (LI-COR Biosciences). By using two secondary antibodies that are detectable at different infra-red wavelengths, β-actin could be measured simultaneously with pY416 SFK. pY416 SFK band density was normalized to β-actin band density.

Chemiluminescence Detection System. The procedure was similar to that described above for the Infrared Detection System except that the blocking buffer was replaced with 5% nonfat dry milk in TTBS, and a biotinylated protein ladder and an HRP-conjugated secondary antibody were used. Then, after transfer of proteins, the nitrocellulose membrane was cut into three pieces, one with lanes for the target proteins for primary antibody incubation, another with lanes for target proteins for no primary antibody incubation (non-ive control) and the third with the lane for the biotinylated protein ladder. This separation of lanes was necessary because the antibacterial HRP-linked antibody used to visualize biotinylated protein ladder also interacted with endogenously biotinylated proteins, such as carboxylases, and produced overlapping bands with adenyl cyclases. The primary, secondary and antibacterial antibodies were dissolved in 5% nonfat dry milk in TTBS. One piece of the membrane with the target proteins was incubated with respective primary antibodies, that is, rabbit polyclonal anti-ADCY1 (1:1000), anti-ADCY3 (1:500), or anti-ADCY8 (1:1000) at 4°C for 24 hours. The second piece with the target protein (ive control) and the third piece with the protein ladder were incubated with the blocking buffer at 4°C for 24 hours. The membranes were washed three times (5 minutes each) with TTBS. The membrane pieces with the target protein were then incubated with the secondary antibody solution (goat antirabbit IgG-HRP, 1:10,000), and the piece with the biotinylated protein ladder was incubated with the antibacterial HRP-linked antibody (1:1000), both for 1 hour at room temperature with shaking. The membranes were washed three times (5 minutes each) with TTBS, then excess liquid was removed by absorbent towel and the membranes were placed in clear plastic wrap. Freshly prepared working substrate (Super Signal West Pico Chemiluminescent substrate, Perkin Elmer) following the acetylated cAMP assay procedure recommended by the manufacturer. According to this protocol, each 100 μL aliquot of each reconstituted sample was mixed with 7 mL liquid scintillation fluid in a scintillation vial and counted using a beta counter to calculate recovery percentage. Recovery efficiency was calculated from the total and blank counts. Blank-count tubes contained only the assay buffer, and the total-count tubes contained 4000 cpm of 3H-cAMP. Another 100 μL acetylated cAMP solution from each sample was subjected to radioimmunooassay using a cAMP assay kit (Cat. # NEK035001KT, Perkin Elmer) following the acetylated cAMP assay procedure recommended by the manufacturer. According to this protocol, each 100 μL (out of a total of 400 μL reconstituted cAMP solution) was acetylated with 5.0 μL acetylation reagent and then diluted to 1.0 mL with double distilled water giving an effective dilution of the assayed samples to 40 fold. The CAMP measured in 100 μL was multiplied by 40 to calculate the total CAMP content in each sample. Results were expressed as picomoles of cAMP/mg protein. Protein was measured in the pellet by BCA assay.

Statistical Analysis

Results are expressed as the mean ± SEM of data from a specified number of independent experiments. Statistical comparisons were made by 1-way analysis of variance (ANOVA) followed by the Bonferroni post hoc multiple comparison test. To validate the homogeneity of variance assumption, we performed Levene’s test where possible. A probability (P) value of < 0.05 was considered significant.

RESULTS

Intact lenses were exposed to hypotonic solution (200 mOsm) in the presence of IBMX (500 μM), added to inhibit phosphodiesterase activity. Under these conditions, a transient increase of cAMP was detected in the epithelium (Fig. 1). The cAMP increase was detectable at 2 minutes and peaked at 5...
In separate experiments, intact lenses were exposed to hyposmotic solution (200 mOsm) for 2 minutes and then the epithelium was removed and probed for SFK phosphorylation (activation) or Na,K-ATPase activity. Significant increase in SFK phosphorylation was observed in the epithelium of lenses that had been exposed to hyposmotic solution. Importantly, the hyposmotic solution-induced SFK activation in the epithelium was not observed when the lenses were exposed to hyposmotic solution in the presence of H89 (10 μM), an inhibitor of the cAMP-activated protein kinase, PKA (Fig. 2A). Na,K-ATPase activity was almost doubled in epithelium removed from lenses exposed to hyposmotic solution. In contrast, Na,K-ATPase activity did not increase in the epithelium of lenses exposed to hyposmotic solution in the presence of H89 (Fig. 2B).

To examine calcium-dependence of the responses, intact lenses were exposed to hyposmotic solution in the presence or absence of HC067047 (10 μM) an inhibitor of TRPV4 channel-mediated calcium entry (Fig. 3). Under these conditions SFK phosphorylation was not increased as seen in the case of hyposmotic stress alone. To confirm calcium dependence of SFK activation, a group of lenses was preincubated with a cytosolic calcium chelating agent, BAPTA-AM (10 μM) for 1 hour and then exposed to hyposmotic solution. In contrast, Na,K-ATPase activity did not increase in the epithelium of lenses exposed to hyposmotic solution in the presence of H89 (Fig. 2B).

Earlier we reported that the NO-sGC-cGMP pathway influences SFK activation and Na,K-ATPase activity in the nonpigmented ciliary epithelium. Since an increase in cytoplasmic calcium concentration has the potential to activate nitric oxide synthase (NOS), which would generate nitric oxide that in turn activate soluble guanylate cyclase (sGC) to produce cGMP we tested whether the sGC inhibitor ODQ alters the SFK activation response to hyposmotic solution. ODQ (10 μM) did not alter the magnitude of hyposmotic solution-induced SFK phosphorylation (Fig. 6). Because hyposmotic solution was found to cause cAMP to increase, and because H89 prevented SFK activation, we considered the possibility that SFK activation is cAMP-dependent. To test this notion, intact lenses were exposed to 8pCPT-cAMP, a cell-permeable cAMP analog. 8pCPT-cAMP caused robust and transient SFK activation (Fig. 7). Because the findings are consistent with calcium activation of adenylyl cyclase, Western blot analysis was used to examine expression of the three known calcium-stimulated adenylyl cyclases in the epithelium removed from freshly isolated porcine lenses. Immunoreactive bands were detected for ADCY3 and ADCY8 in both porcine (Fig. 8A) and human (Fig. 8B) lens epithelium. ADCY1 was not detected. To the best of our knowledge, this is the first demonstration of calcium-activated adenylyl cyclases in porcine and human lens epithelium.
DISCUSSION

Previous studies have shown the importance of SFKs in the lens. Zhou and Menko\textsuperscript{19} reported conditions in which simultaneous activation of Src and p38 precedes cataract formation. There have been reports that Src and Fyn influence lens cell proliferation and differentiation\textsuperscript{20,21} and our own laboratory has reported SFK-dependent regulation of lens Na,K-ATPase activity.\textsuperscript{3,22} Here, we present findings that link SFK activation in the porcine lens epithelium to cAMP.

\textbf{FIGURE 2.} The effect of PKA inhibitor H89 (10 \textmu M) on the SFK phosphorylation and Na,K-ATPase activity responses to hyposmotic solution. Intact lenses were exposed to hyposmotic Krebs solution (200 mOsm) for 2 minutes in the presence or absence (control; Con) of H89 (10 \textmu M) added 20 minutes beforehand. Then the epithelium was removed, homogenized, and subjected to Western blot analysis for SFK phosphorylation at Y416 or used to determine Na-K-ATPase activity. \beta actin was probed as a loading control.

\textbf{FIGURE 3.} The effect of TRPV4 antagonist HC067047 (10 \textmu M) on the SFK phosphorylation response to hyposmotic solution (Hypo). Intact lenses were exposed to hyposmotic Krebs solution (200 mOsm) for 2 minutes in the presence or absence (control; Con) of HC067047 (HC) added 20 minutes beforehand. Then the epithelium was removed, homogenized, and subjected to Western blot analysis for SFK phosphorylation at Y416. \beta actin was probed as a loading control. \textit{Upper panel:} Representative Western blot. \textit{Lower panel:} Pooled data (mean ± SEM of results from five independent experiments) showing phospho-SFK (pY416 SFK) band density (relative to control). ** indicates a significant difference from control (P < 0.001). ## indicates a significant difference from group subjected to hyposmotic solution alone (P < 0.01).
after exposure of the intact lens to hyposmotic solution. Under these conditions we observed a significant increase of cAMP in the epithelium and SFK activation was prevented by H89, an inhibitor of PKA. We reasoned that if SFK activation is cAMP-dependent, exposure of the lens to a cell-permeable cAMP analog, 8-pCPT-cAMP, should cause SFK activation and this was the case.

The response of the lens to hyposmotic stress has been studied in some detail and found to be associated with the opening of TRPV4 ion channels, an event that leads to opening of connexin and pannexin hemichannels. These channels and hemichannels provide a means of entry of extracellular calcium to the epithelium, and hyposmotic stress was observed to cause a sustained, but physiologically relevant, increase of cytoplasmic calcium concentration in cultured lens epithelium. Calcium is a ubiquitous and extremely versatile second messenger.

**Figure 4.** The effect of cytoplasmic calcium chelator BAPTA-AM on the SFK phosphorylation and on the Na,K-ATPase activity responses to hyposmotic solution (Hypo). Intact lenses were exposed to hyposmotic Krebs solution (200 mOsm) for 2 minutes in the presence or absence (control; Con) of either BAPTA-AM (10 μM) added 60 minutes beforehand. Then the epithelium was removed, homogenized, and subjected to Western blot analysis for SFK phosphorylation at Y416 (A) or Na,K-ATPase activity measurement (B). β-actin was probed as a loading control for Western blot analysis. The upper panel of (A) shows representative Western blots, and the lower panel shows pooled data (mean ± SEM of results from six independent experiments) on phospho-SFK (pY416 SFK) band density (relative to control). ** and *** indicate a significant difference (P < 0.01 and P < 0.001) from control. ## indicates a significant difference from group subjected to hyposmotic solution alone (P < 0.01).

**Figure 5.** The effect of PP2, a specific SFK inhibitor, on the SFK phosphorylation and Na,K-ATPase activity responses to hyposmotic solution (Hypo). Intact lenses were exposed to hyposmotic Krebs solution (200 mOsm) for 2 minutes in the presence or absence (Control) of 10 μM PP2, added 45 minutes beforehand. Then the epithelium was removed, homogenized, and subjected to Western blot analysis for SFK phosphorylation at Y416. Values are mean ± SEM of results from six independent experiments. ** indicates a significant difference (P < 0.001) from control.
messenger that plays numerous roles in cellular signaling cascades, and crosstalk with other second messenger signaling pathways is common. In some cases, a calcium rise has the ability to change the concentrations of cAMP or cGMP by modulating Ca\(^{2+}\)/calmodulin-sensitive phosphodiesterases. Changes in cGMP concentration can also be the result of calcium-dependent stimulation of NOS-sGC pathways. The NOS-cGMP-sGC pathway did not appear to play a significant role here because ODQ, a highly selective and potent sGC inhibitor, failed to prevent hyposmotic solution-induced SFK activation in the lens epithelium. Instead, the evidence seems to fit with the ability of calcium to regulate certain members of adenylyl cyclase family, the so-called calcium-sensitive isoforms.

Western blot detection data show presence of ADCY3 and ADCY8 in porcine as well as in human lens epithelium. To the best of our knowledge, this is the first demonstration of calcium-activated adenylyl cyclases in lens epithelium. Interestingly, ADCY1 was absent both in the porcine and in the human. This shows strikingly similar expression pattern of calcium-activated adenylyl cyclases in the two species. The implication of this similarity is that results of studies in porcine lenses could be extrapolated to human. In mammals, nine particulate (designated as ADCY1-9) and one soluble adenylyl cyclase isoforms (designated as ADCY10 or sAC) have been reported so far. Five of the particulate ACs are reported to be directly sensitive to calcium, and these Ca\(^{2+}\)-sensitive adenylyl cyclases are considered to be critical integrators of cell signaling. It has been shown that ADCY1, ADCY3, and ADCY8 are stimulated by calcium. In contrast, an increase of cytoplasmic calcium causes inhibition of ADCY5 and ADCY6. In the present investigation, the detection of two Ca\(^{2+}\)-sensitive adenylyl cyclases, ADCY3 and ADCY8, in the lens epithelium is consistent with the notion that calcium entry links to stimulated production of cAMP. It should be made clear that we have no direct evidence to link any particular adenylyl cyclase or combination of adenylyl cyclases to the observed cAMP generation in the lens. It has been suggested that calcium-dependent adenylyl cyclase responses may vary according the source of the calcium rise, perhaps reflecting the transient nature of an increase caused by release from intracellular stores compared to different modes of calcium entry. In an earlier study on lens epithelium, we observed such a pattern of sustained doubling of calcium concentration in response to hyposmotic solution, and it is of particular interest to note that ADCY8 is sensitive to sustained calcium elevation. On this basis, the conditions appear feasible for ADCY8 to contribute to cAMP production in the epithelium of lenses exposed to hyposmotic solution. It is of particular interest to note that ADCY8 is sensitive to sustained calcium elevation. On this basis, the conditions appear feasible for ADCY8 to contribute to cAMP production in the epithelium of lenses exposed to hyposmotic solution. In pancreatic β cells, calcium influx has been shown to activate ADCY8, which in turn regulates insulin release by the combined influence of calcium and cAMP/PKA signaling. This is just one of several instances where increased cytoplasmic calcium concentration stimulates adenylyl cyclase activity and increases cAMP.

FIGURE 6. The effect of sGC inhibitor ODQ (10 μM) on the SFK phosphorylation response to hyposmotic solution (Hypo). Intact lenses were exposed to hyposmotic Krebs solution (200 mOsm) for 2 minutes in the presence or absence (control; Con) of ODQ added 20 minutes beforehand. Then the epithelium was removed, homogenized, and subjected to Western blot analysis for SFK phosphorylation at Y416. β actin was probed as a loading control. Upper panel: Representative Western blot. Lower panel: Pooled data (mean ± SEM of results from six independent experiments) showing phospho-SFK (pY416 SFK) band density. *** indicates a significant difference from control (P < 0.001).

FIGURE 7. The time course of the 8-pCPT-cAMP effect on SFK phosphorylation. Intact lenses were exposed to 10 μM 8-pCPT-cAMP for 0 (control), 2 or 5 or 10 minutes. Then the epithelium was removed, homogenized, and subjected to Western blot analysis for SFK phosphorylation at Y416. β actin was probed as a loading control. Upper panel: Representative Western blot. Lower panel: Pooled data (mean ± SEM of results from three independent experiments) showing phospho-SFK (pY416 SFK) band density (relative to control). ** and *** indicate significant differences from control (P < 0.01 and P < 0.001).
The epithelium of lenses exposed to hyposmotic solution showed a peak cAMP level at 5 minutes followed by a decay at 10 minutes, although the cAMP level at 10 minutes was still significantly higher than that in control lenses. Generally, the cAMP level, and thus the strength of cAMP-mediated signaling, reflects a dynamic balance between the influence of adenylate cyclases and phosphodiesterases (PDEs). In mammalian cells, there are several families of phosphodiesterases. Although it is beyond the scope of this manuscript to identify the enzymes responsible for the phosphodiesterase activity that reduces cAMP levels after the initial rise, we speculate that one or more of the Ca\(^{2+}\)-dependent phosphodiesterases (such as PDE1 isoforms) might contribute to the decrease. Coordinated control of adenylate cyclase and phosphodiesterase activity by Ca\(^{2+}\) is a common occurrence.

To further examine calcium-dependence of the response, lenses were exposed to either HC067047 or BAPTA. The strategy was as follows: HC067047 inhibits the initiating step in the response, TRPV4-mediated calcium entry. BAPTA is a cytoplasmic calcium chelator that suppresses an increase of cytoplasmic calcium even though calcium entry occurs. Importantly, SFK activation was inhibited by BAPTA, HC067047, and a PKA inhibitor H89. Taken together, the findings point to cAMP as a link between TRPV4 channel-mediated calcium entry, activation of calcium-dependent adenyl cyclases, a rise of cAMP and SFK activation. In accordance with this proposed role of calcium-dependent adenyl cyclases, and the dependence of Na,K-ATPase activity on SFK activation, the doubling of Na,K-ATPase activity in the epithelium of lenses exposed to hyposmotic solution was...
Hyposmotic SFK Activation in the Lens Involves PKA

**Figure 9.** Schematic diagram showing steps in the response mechanism that links TRPV4 activation to an increase of Na,K-ATPase activity when the lens is exposed to hyposmotic solution.

Prevented both by H89 and by BAPTA. In an earlier report, phosphorylation of Src has been linked to PKA in the bovine epithelium. As a direct test of cAMP-dependent SFK activation, intact lenses were exposed to 8-pCPT-cAMP, a cell permeable stable analog of cAMP, and SFK phosphorylation was confirmed to occur. In summary, our results point to the following sequence of events in lenses exposed to hyposmotic solution: TRPV4 activation and calcium entry followed by calcium-mediated production of cAMP, PKA-dependent SFK activation, and a subsequent increase of Na,K-ATPase activity (Fig. 9). Regulation of Na,K-ATPase activity in the lens epithelium has significance because the lens is made up almost entirely of differentiated fiber cells that have little or no Na,K-ATPase activity. The fiber cells, however, are well coupled, and as a consequence active transport by Na,K-ATPase in relatively few differentiated fiber cells is able to regulate cytoplasmic sodium and potassium levels in the entire structure. If sodium and potassium levels are not properly controlled, osmotic forces cause the cells to swell and this impairs lens transparency. The findings here are consistent with our earlier proposal that TRPV4 enables the epithelium to sense swelling and adjust Na,K-ATPase activity accordingly. The discovery of SFK-mediated regulation of Na,K-ATPase through the integration of TRPV4-mediated calcium entry and cAMP signaling illustrates a complex regulatory mechanism. The complexity may be greater still because different SFKs may have different effects on Na,K-ATPase activity. Earlier we showed that at least four SFK members (Src, Fyn, Yes, Hck) are expressed in the porcine lens epithelium and that endothelin-1 (ET-1) activated Fyn but inhibited Src and Hck, and had no effect on Yes. In regard to pathology, maintenance of Na,K-ATPase activity is significant in relation to cataract, the most common cause of age-related vision loss. In the human lens, a progressive increase of sodium and water content and a decrease potassium is associated with cortical cataract formation. In other words, cataract is associated with failure of Na,K-ATPase-mediated active transport to keep pace with ion leakage.

**Acknowledgments**

The authors thank the University of Arizona Meat Science Laboratory, West Valley Processing Meat Processors (Buckeye, AZ, USA) and Hatfield Quality Meats (Philadelphia, PA, USA) for the supply of porcine eyes. The authors are thankful to Dhruva Bhattacharya of the Department of Ophthalmology and Vision Science, University of Arizona, for the technical help in developing X-ray film using SRX-101A Medical Film Processor.

Supported by a grant from the National Institutes of Health (EY 006915).

Disclosure: M. Shahidullah, None; A. Mandal, None; N.A. Delamere, None.

**References**


Hyposmotic SFK Activation in the Lens Involves PKA


