Expression and association of TRPC subtypes with Orai1 and STIM1 in human parathyroid

Ming Lu1,3, Robert Bränström1, Erik Berglund1, Anders Höög2, Peyman Björklund4, Gunnar Westin4, Catharina Larsson1, Lars-Ove Farnebo1 and Lars Forsberg1

Departments of 1Molecular Medicine and Surgery and 2Oncology-Pathology, Karolinska Institutet, Karolinska University Hospital L1:03, 171 76 Stockholm, Sweden
3Department of Geriatric Endocrinology, First Affiliated Hospital of Guangxi Medical University, NanNing, People’s Republic of China
4Department of Surgical Sciences, Uppsala University Hospital, Uppsala University, Uppsala, Sweden

(Correspondence should be addressed to R Bränström; Email: robert.bransstrom@ki.se)

Abstract

The mechanism behind Ca2+ entry into the parathyroid cells has been widely debated, and the molecular identities of the responsible ion channels have not been established yet. In this study, we show that the parathyroid cells lack voltage-operated Ca2+ channels. Passive store depletion by thapsigargin, on the other hand, induces a large non-voltage-activated non-selective cation current. The increase in intracellular Ca2+ caused by thapsigargin is attenuated by 2-aminoethoxydiphenyl borate, a blocker of store-operated Ca2+ entry (SOCE). Candidate molecules for non-voltage-operated Ca2+ signaling were investigated. These included members of the transient receptor potential canonical (TRPC) ion channel family, as well as Ca2+ release-activated Ca2+ modulator 1 (Orai1) and stromal interaction molecule 1 (STIM1) that are key proteins in the SOCE pathway. Using RT-PCR screening, quantitative real-time PCR, and western blot, we showed expression of TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 genes and proteins in normal and adenomatous human parathyroid tissues. Furthermore, co-immunoprecipitation experiments demonstrated a ternary complex of TRPC1–Orai1–STIM1, supporting a physical interaction between these molecules in human parathyroid.

Journal of Molecular Endocrinology (2010) 44, 285–294

Introduction

Primary hyperparathyroidism (pHPT) is the second most common endocrine disease in the western populations (Nilsson et al. 2002) after diabetes. The underlying physiological disturbance is the inadequate inhibition of PTH secretion in response to elevated serum calcium. The stimulus–secretion coupling in the parathyroid cells is not completely understood. However, extracellular free calcium (Ca2+) regulates PTH secretion from parathyroid cells by acting on a calcium-sensing receptor (CASR) expressed on the cell surface (Sherwood et al. 1970, Nemeth & Scarpa 1987, Brown et al. 1993, Hofer & Brown 2003). The CASR is a G-protein, phospholipase C (PLC)-linked, membrane-bound receptor, activation of which leads to increased levels of inositol trisphosphate (IP3), and hence to Ca2+ release from intracellular stores (Hofer & Brown 2003). It is generally considered that a high concentration of cytoplasmic free Ca2+ (Ca2+) mediates an inhibition of parathyroid hormone secretion (Shoback et al. 1984). The parathyroid cells are unique in this respect, because in most other endocrine cells, elevated Ca2+ stimulates hormone secretion. Since radioactively labeled Ca2+ enters the parathyroid cells and unselective Ca2+ channel blockers prevent Ca2+ entry (Ridefelt et al. 1992), a transporting mechanism must exist in the plasma membrane. It has been suggested that Ca2+ entry into the parathyroid cells is mediated by L-type voltage-operated Ca2+ channels (VOCCs; Chang et al. 2001). However, the presence of these channels has not been proven (Muff et al. 1998). The aim of this work was to investigate what type of Ca2+ channels can be demonstrated in normal and adenomatous human parathyroid cells. We used electrophysiology and molecular biology techniques to explore the possibility that Ca2+ entry is mediated by VOCCs and/or non-selective cation channels, belonging to the family of transient receptor potential canonical-type (TRPC). In other cell systems, TRPCs have been implicated in store-operated Ca2+ entry (SOCE), and TRPC1 associated with Ca2+ release-activated Ca2+ modulator 1 (Orai1) and stromal interaction molecule 1 (STIM1) were the core components of store-operated Ca2+ channels (SOCs; Ambudkar & Ong 2007, Ambudkar et al. 2007).
Materials and methods

Cells for electrophysiology and Ca$_{2+}$ measurement

Small pieces of human parathyroid tissues (both normal and adenoma) were transported immediately after surgery to the laboratory in sterile tubes, and prepared according to previously published protocol (Välímäki et al. 2003). Parathyroid tissue collection was carried out with approval from the local ethics committee. Pancreatic β-cells were isolated from adult obese mice (ob/ob), and were prepared as described earlier (Bränström et al. 1998).

Electrophysiology

For electrophysiological experiments, cells were seeded into Petri dishes (Nunc, Roskilde, Denmark), and were incubated at 37 °C and 5% CO$_2$ overnight in DMEM/ F-12 + 10% FCS medium. VOCC activity was recorded using the patch-clamp technique (Hamill et al. 1981) with a HEKA EPC-10 patch-clamp amplifier (HEKA Elektronik, Ludwigshafen, Germany). The standard extracellular solution (i.e. bath solution) contained the following (mM): 138 NaCl, 5-6 KCl, 2-6 CaCl$_2$, 1-2 MgCl$_2$, and 5 HEPES–NaOH at a pH of 7.4. For whole-cell recordings of Ca$_{2+}$ currents, the intracellular-like solution (i.e. pipette solution) consisted of the following (mM): 150 N-methyl-d-glucamine (NMG), 110 HCl, 1 MgCl$_2$, 2 CaCl$_2$, 10 EGTA, 3 MgATP, and 5 HEPES–NaOH (pH 7.15). NMG was substituted for K$^+$ in the pipette solution to prevent outward-directed K$^+$ currents. Similarly, SOC currents were recorded using whole-cell configuration. Pipette solution was composed of the following (mM): 145 CsCl, 10 EGTA, 8 NaCl, 10 MgCl$_2$, and 10 HEPES (pH 7.2 with CsOH). Channel current traces were displayed according to the convention that upward deflection denotes outward currents. Pipettes were pulled from borosilicate using a P-2000 laser pipette puller (Sutter Instrument, Novato, CA, USA), and they had a resistance between 2 and 4 MΩ. All the experiments were performed at a room temperature of ~22 °C.

Measurement of Ca$_{2+}$$^+$

Cells were grown on glass cover slides in DMEM/ F-12 + 10% FCS medium overnight until they attached to the slides, and were loaded with 3 μM Fura-2 AM (Invitrogen) at 37°C for 30 min. Experiments were performed using an extracellular solution containing the following (mM): 125 NaCl, 4 KCl, 20 HEPES, 1 MgCl$_2$, 0.8 NaH$_2$PO$_4$, and 5-6 μM glucose. CaCl$_2$ and substances were added as indicated. Slides with cells were kept in a perfusion chamber and exposed to an inverted fluorescence microscope (Axiovert 135 TV, Zeiss, Göttingen, Germany), and the cells were detected by a cooled charge-coupled device camera (CH250/KAF 1400, Photometrics, Tucson, AZ, USA) connected to an imaging system (Inovision, Durham, NC, USA). Fluorescence was provided by a SPEX fluorolog-2 CM1T111 spectrofluorometer (SPEX Industries, Edison, NJ, USA) with excitation wavelength at 340 and 380 nm, and emission monitored at 505 nm. Experiments were performed at ~37 °C. Fluorescence intensity was analyzed using ISEE software for UNIX (Inovision). Thapsigargin, 2-aminoethoxydiphenyl borate (2-APB), and YM-58483 (also known as BTP-2) were all obtained from Sigma.

Tissue samples of pHPT cases and controls

In this study, 20 parathyroid adenomas that were collected from patients treated surgically for pHPT at Karolinska University Hospital, Sweden, and diagnosed histopathologically as chief cell parathyroid adenomas according to the World Health Organization classification were used (DeLellis et al. 2004). The adenomas, the details of which have been published previously (Lu et al. 2008), were employed in RT-PCR, quantitative real-time (qRT)-PCR, western blot, and co-immunoprecipitation (co-IP) experiments. Clinical data for the pHPT patients are age 61.5 ± 14.7 years, serum Ca$_{2+}$ 2.85 ± 0.20 mM (reference 2.20–2.60 mM), PTH level 269 ± 208 ng/l (reference < 65 ng/l), and tumor weight 2.8 ± 2.3 g. For details, see Supplementary Table 2, see section on supplementary data given at the end of this article. Two biopsies from normal parathyroid glands were obtained from patients treated for nodular thyroid lesions when parathyroid glands had to be excised and reimplanted into the sternomastoid muscle for anatomical reasons. Both these patients had normal levels of PTH, serum Ca$_{2+}$, and thyroid hormones preoperatively. They were both verified as histopathologically normal. In addition, anonymous normal uterine tissue was collected by an experienced pathologist, and was used as a positive control for western blot analyses. Standardized sampling procedures, tissue handling, and storage at ~70 °C ensured representative tissue and good quality RNA and protein extracts of all the samples.

Antibodies

The following primary antibodies were used for western blot and immunoprecipitation experiments: rabbit polyclonal anti-TRPC1 and control antigen (Cat. No. ACC-010, Alomone Labs, Jerusalem, Israel); rabbit monoclonal anti-TRPC1 (EP1417Y; Cat. No. 208 ng/l (reference 2.20–2.60 mM), PTH level 269 ± 208 ng/l (reference < 65 ng/l), and tumor weight 2.8 ± 2.3 g. For details, see Supplementary Table 2, see section on supplementary data given at the end of this article. Two biopsies from normal parathyroid glands were obtained from patients treated for nodular thyroid lesions when parathyroid glands had to be excised and reimplanted into the sternomastoid muscle for anatomical reasons. Both these patients had normal levels of PTH, serum Ca$_{2+}$, and thyroid hormones preoperatively. They were both verified as histopathologically normal. In addition, anonymous normal uterine tissue was collected by an experienced pathologist, and was used as a positive control for western blot analyses. Standardized sampling procedures, tissue handling, and storage at ~70 °C ensured representative tissue and good quality RNA and protein extracts of all the samples.
NB110-57630, Novus Biologicals, Littleton, CO, USA); rabbit polyclonal anti-TRPC4 and control antigen (Alomone Labs, Cat. No. ACC-018); rabbit polyclonal anti-TRPC6 and control antigen (Alomone Labs, Cat. No. ACC-017); mouse monoclonal anti-Orai1 (Abcam, Cat. No. ab54076); mouse monoclonal anti-Stim1 (BD Biosciences, Cat. No. G72120-050); and mouse monoclonal anti-β-actin (Cat. No. ab6276, Abcam, Cambridge, UK).

Reverse transcription-PCR

RT-PCR was used to screen for TRPC expression in normal and three pHPT samples. Total RNA was extracted using TRIzol reagent (Invitrogen) and was quantified using a spectrophotometer, and the purity and quality of the RNA were further confirmed by analysis in an Agilent 2100 Bioanalyzer (Agilent Technologies, Santa Clara, CA, USA). Total RNA (3 µg) from each sample was reverse transcribed into 40 µl cDNA applying the SuperScript III First-Strand Synthesis System for RT-PCR (Invitrogen, Cat. No. 18080-051). Two microliters of each cDNA were used for PCR amplification of TRPC1, TRPC3, TRPC4, TRPC5, TRPC6, and TRPC7 transcripts, which was carried out using optimized gene-specific primers (Table 1) and the Platinum Taq DNA polymerase high-fidelity kit (Invitrogen). The program was constituted of i) 94 °C for 2 min and ii) 40–45 cycles of 94 °C for 30 s, 55 °C for 30 s, and 68 °C for 1 min. Human brain cDNA (Invitrogen, Cat. No. B1110033) was used as a positive control since all TRPC genes have been detected previously in human brain tissue (Riccio et al. 2002). The PCR products were subsequently size-verified by agarose gel electrophoresis, observed, and photographed under u.v. light. After purification using the PCR purification kit (Qiagen, Cat. No. Q28104), the products were confirmed by DNA sequencing with the assistance of KISeq, Karolinska Institutet.

Quantitative real-time PCR

Expression of TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 was determined in 2 normal parathyroid and 20 adenoma samples (Supplementary Table 3, see section on supplementary data given at the end of this article). Five micrograms of total RNA from each sample were reverse transcribed into 40 µl cDNA using the methodology described above, which gave a final concentration of 125 ng/µl. Gene expression was quantified using TaqMan Gene Expression Assays (Applied Biosystems) with gene-specific primers and TaqMan probes for TRPC1 (Hs00608195_m1), TRPC4 (Hs00175753_m1), and TRPC6 (Hs00211805_m1) Orai1 (Hs00385627_m1) and STIM1 (Hs00963373_m1) (for details see Supplementary Table 1, see section on supplementary data given at the end of this article), and an ABI real-time PCR 7900HF Fast System (Applied Biosystems). The real-time PCRs were performed in a final volume of 10 µl with 4.5 µl cDNA (~20 ng), 0.5 µl TaqMan Gene Expression Assay (20X), and 5 µl TaqMan Universal PCR Master Mix. The amplification program included i) 95 °C for 10 min and ii) 40 cycles of 95 °C for 15 s and 60 °C for 1 min. For each gene, a standard curve was created by serial dilution (1:10, 1:50, 1:250, 1:1250, and 1:6250) of human brain cDNA (Invitrogen). To normalize the individual mRNA level, the housekeeping gene RPLP0 (Hs99999902_m1) was amplified in parallel as an endogenous control. A no-template sample served as a negative control. Triplicate measurements were performed for all samples, and the experiments were performed on two separate occasions with consistent results.

Western blot

Total proteins were extracted and quantified with a dye-binding assay (Bradford 1976). The yield of the total protein samples was used for western blot and immunoprecipitation experiments. Protein samples

Table 1 Details of primers used for RT-PCR analyses of human TRPC genes

<table>
<thead>
<tr>
<th>Gene</th>
<th>Accession no.</th>
<th>Orientation</th>
<th>Sequence (5’–3’)</th>
<th>Amplicon length (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRPC1</td>
<td>NM_003304</td>
<td>Forward</td>
<td>ACAGCAAAGCAATGATACCT</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse</td>
<td>AAAGTCGCCAAGGCAAGTAAA</td>
<td></td>
</tr>
<tr>
<td>TRPC3</td>
<td>NM_003305</td>
<td>Forward</td>
<td>GGTGTGGAAATGGTGGTACT</td>
<td>722</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse</td>
<td>TGAAAGTTGGAAGTAATGTT</td>
<td></td>
</tr>
<tr>
<td>TRPC4</td>
<td>NM_016179</td>
<td>Forward</td>
<td>GCTGTGAGATTGGTGTTTC</td>
<td>356</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse</td>
<td>CTGCAATGTGTCAGCAATGAT</td>
<td></td>
</tr>
<tr>
<td>TRPC5</td>
<td>NM_012471</td>
<td>Forward</td>
<td>GTGGCCTATTTCGATAGTAA</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse</td>
<td>AGGGTGAGATGAAGGGAAT</td>
<td></td>
</tr>
<tr>
<td>TRPC6</td>
<td>NM_004621</td>
<td>Forward</td>
<td>TCGTTCATGCCCTCCCTTCAGT</td>
<td>454</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse</td>
<td>TGGGATATAATGGTGAGTTCGAG</td>
<td></td>
</tr>
<tr>
<td>TRPC7</td>
<td>NM_020389</td>
<td>Forward</td>
<td>GATCTTTCCTCCAGTCTCC</td>
<td>742</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
were denatured by heating at 95°C for 5 min, electrophoresed in 10% Tricine gels, and transferred onto nitrocellulose membranes. A Ponceau Red stain was used to assess the presence of protein after blotting. After blocking non-specific binding sites with 5% fat-free milk, the membranes were incubated overnight at 4°C with appropriate primary antibodies for rabbit polyclonal anti-TRPC1 (dilution 1:200), anti-TRPC4 (1:200), anti-TRPC6 (1:200), anti-Orai1 (1:100), and anti-STIM1 (1:250), followed by incubation with secondary antibodies (goat anti-mouse IgG-HRP or goat anti-rabbit IgG-HRP) at a dilution of 1:20 000 for 1 h at room temperature. Immunoreactive bands were detected using enhanced chemiluminescence, and were exposed to a hyperfilm. Subsequent incubation with anti-β-actin was used as a control of protein loading and quality. To confirm signal specificity, primary antibodies were pre-incubated with peptide antigen (i.e. blocking peptide) for 1 h at room temperature and for 2 h at 4°C.

Co-immunoprecipitation
Co-IP was used to identify possible associations between TRPC1, Orai1, and/or STIM1 proteins. Precleared protein was obtained by incubating 1 mg parathyroid adenoma protein (patient no. 18, see Supplementary Table 2) with 15 μl protein G-Sepharose bead slurry for 1 h at 4°C to reduce non-specific binding of proteins to the Sepharose beads. After centrifugation, 5 μl of rabbit monoclonal anti-TRPC1 (EP1417Y), anti-Orai1, or anti-STIM1 antibody were added to the supernatant and incubated under rotation for 6 h at 4°C. Subsequently, 50 μl of protein G-Sepharose beads were added, and rotation was continued for 4 h. The beads were washed three times with ice-cold modified RIPA buffer, followed by resuspension of the Sepharose beads in 2× SDS sample buffer. The samples were heated at 95°C for 5 min before electrophoresis and blotted, and signal visualization was done using TRPC1 (rabbit polyclonal), Orai1, or STIM1 primary antibody respectively. As a negative control, protein samples were mock-immunoprecipitated with an irrelevant antibody and treated in the same way as described above. In all the co-IP experiments, the respective antibodies recognized a band of the same and expected size in both the lysate and the immunoprecipitated samples, but not in the mock IP sample.

Statistical analysis
All data are given as mean ± s.d. If not indicated, experiments were repeated at least three times. Statistical significance was analyzed using paired and unpaired t-tests or ANOVA for multiple groups, as appropriate. A P value of <0.05 was considered significant.

Results
Lack of functional VOCCs and demonstration of store-operated cation currents in parathyroid cells
The possible existence of functional VOCCs in parathyroid cells was first addressed by voltage-clamping using the whole-cell configuration. Single parathyroid cells were voltage-clamped at −70 mV, and were subsequently depolarized in steps of 10 to +70 mV. As illustrated in Fig. 1A and B, this did not result in an

Figure 1 Patch-clamp experiments demonstrating the absence of VOCCs in parathyroid cells. Whole-cell Ca²⁺ current (Ica) was not recorded in normal (A) or adenoma (B) parathyroid cells after applying a depolarizing voltage protocol (between −70 and +70 mV in 10-mV increments). Top trace and filled circles show results obtained with a total of 20 mM Ca²⁺ in the extracellular solution, and open circles represent results obtained with 20 mM Ba²⁺. (C) Typical Ca²⁺ current in pancreatic β-cells after applying the same depolarizing voltage protocol.
inward-directed current in normal parathyroid or adenoma cells. Application of the same protocol to pancreatic β-cells, used as a positive control, resulted in inward-directed currents, verifying that our solutions and patch-clamp protocol were suitable for recording of VOCCs (Fig. 1C). These experiments demonstrated that human parathyroid cells do not express a functional VOCC in the plasma membrane. In addition, human parathyroid cells (both normal and adenoma) were voltage-clamped at 0 mV, and every 2 s, a voltage ramp from −80 to +80 mV was applied (rise time 400 ms). In the pipette solution, Cs+ replaced NMG. As shown in Fig. 2A–C, addition of thapsigargin activated a non-selective cation current. The effect of thapsigargin on whole-cell current was rapid and slowly partly reversible (Fig. 2C).

Measurement of Ca2+

Activation of SOCE was assessed by depletion of intracellular Ca2+ store with thapsigargin. In Fig. 3A, Ca2+ was withdrawn from extracellular solution, and the cells were subsequently exposed to 1.5 mM Ca2+, prior to and after the addition of thapsigargin. Addition of thapsigargin, in the absence of Ca2+, caused a small increase in Ca2+ in ~50% of the cells studied. In all the experiments, a larger rise in Ca2+ was seen with 1.5 mM Ca2+ after exposure to thapsigargin. In Fig. 3B, 2-APB caused a transient increase in Ca2+, followed by a lowering of Ca2+. The lower level was kept even when 1.5 mM Ca2+ was added. A sharp elevation of Ca2+ was seen after the removal of 2-APB, suggesting that the effect of 2-APB on Ca2+ entry is reversible. YM-58483, also known as BTP-2, which has been shown to inhibit TRPC3 and 5, but not TRPC1, did not affect the elevation of Ca2+ caused by thapsigargin (Fig. 3C).

Gene expression of TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 in human parathyroid

RT-PCR products of expected lengths corresponding to TRPC1, TRPC4, and TRPC6 were detected in the normal parathyroid and adenoma samples used for screening of TRPC expression (Fig. 4A). No products were obtained for TRPC3, TRPC5, or TRPC7 in any of these samples. In support of the specificity and sensitivity of the assay, all TRPCs were readily amplified from human brain cDNA that was used as a positive control, while no product was detected in the RT-negative control. Furthermore, all PCR products were verified by sequencing, which revealed 100% identity to published human sequences.

Gene expression in parathyroid tissues was further analyzed for TRPC1, TRPC4, and TRPC6 in an extended series of 20 parathyroid adenoma and 2 normal parathyroid samples by TaqMan quantitative real-time PCR (Fig. 4B). Expression of Orai1 and STIM1 was similarly studied. All genes were found expressed in the normal parathyroid and adenomas studied (complete qRT-PCR results may be found in Supplementary Table 3). No statistical comparison was made between normal and adenoma samples since only two normal parathyroids were available for analysis, whereas the expression of TRPC1 was significantly larger than that of TRPC4 and TRPC6. These findings confirm the results obtained from RT-PCR screening, and further demonstrate that TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 are the generally expressed genes in parathyroids.

Protein expression of TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 in human parathyroid tissue

Protein expression of TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 was subsequently determined in parathyroid adenomas. Positive expression of the expected molecular weights was detected in all the 20 samples.
adenomas studied, i.e. 100 kDa for TRPC1, 95 kDa for TRPC4, 110 kDa for TRPC6, 30 kDa for Orai1, and 85 kDa for STIM1 (Fig. 5A–C and Supplementary Figure 1, see section on supplementary data given at the end of this article). The level of expression varied between the individual samples for all proteins. In the control experiments, the primary antibodies were pre-incubated with blocking peptides before incubation with the western blot membranes. In all cases, this resulted in loss of the expected protein product, thus confirming the specificity of the findings. Furthermore, total protein extracts from human uterus, rat brains, or rat pancreas served as a positive control, which revealed a strong signal at the expected molecular weight in all cases.

Demonstration of TRPC1–Orai1–STIM1 ternary complex in human parathyroid

Possible interactions between TRPC1, STIM1, and/or Orai1 were further examined by co-IP experiments. To verify a true association between the proteins, TRPC1, Orai1, or STIM1 antibodies were used as bait in the co-IP, and the same antibodies were then used to detect the proteins in each IP fraction. The IP fractionadenomas studied, i.e. 100 kDa for TRPC1, 95 kDa for TRPC4, 110 kDa for TRPC6, 30 kDa for Orai1, and 85 kDa for STIM1 (Fig. 5A–C and Supplementary Figure 1, see section on supplementary data given at the end of this article). The level of expression varied between the individual samples for all proteins. In the control experiments, the primary antibodies were pre-incubated with blocking peptides before incubation with the western blot membranes. In all cases, this resulted in loss of the expected protein product, thus confirming the specificity of the findings. Furthermore, total protein extracts from human uterus, rat brains, or rat pancreas served as a positive control, which revealed a strong signal at the expected molecular weight in all cases.

Demonstration of TRPC1–Orai1–STIM1 ternary complex in human parathyroid

Possible interactions between TRPC1, STIM1, and/or Orai1 were further examined by co-IP experiments. To verify a true association between the proteins, TRPC1, Orai1, or STIM1 antibodies were used as bait in the co-IP, and the same antibodies were then used to detect the proteins in each IP fraction. The IP fraction

Figure 4 (A) RT-PCR analyses demonstrating mRNA expression of TRPC1, TRPC4, and TRPC6 in human parathyroid. Agarose gel electrophoresis showing amplified products of the expected sizes for TRPC1 (620 bp), TRPC4 (356 bp), and TRPC6 (454 bp) in normal parathyroid (normal), parathyroid adenoma (adenoma), and human brain cDNA used as a positive control (control). (B) qRT-PCR analysis using Taqman showed expression of TRPC1, TRPC4, and TRPC6; Orai1; and STIM1 in both normal (black bar, n=2) and adenomatous (greyed bar, n=20) human parathyroid. The results are presented as mean ± s.d. and normalized to housekeeping gene RPLP0 expression level. ***P<0.001.
revealed a distinct signal at the expected weight from all the three proteins evaluated (Fig. 5D), but not from the mock IP (data not shown). The strongest signals in the IP fraction were revealed using Orai1 antibody as bait. Using STIM1 antibody revealed a clear but rather weaker signal compared with the other antibody that was used. The interaction was demonstrated and verified using any of the corresponding antibodies as bait. The co-IP was repeated twice with identical results. The concordant results from the co-IP experiment show that a TRPC1–Orai1–STIM1 ternary complex does exist in human parathyroid tissues.

Discussion

Intracellular Ca\(^{2+}\) is likely to have a pivotal role in the stimulus-secretion coupling in the parathyroid cells, since alterations in Ca\(^{2+}\) have a major impact on hormone secretion (Shoback et al. 1984, Mihai et al. 2000). Alterations of extracellular Ca\(^{2+}\) levels and addition of Ca\(^{2+}\) channel blockers have indicated that Ca\(^{2+}\) influx is probably an important source for changes in Ca\(^{2+}\). However, many studies have attempted to characterize the mechanism(s) controlling Ca\(^{2+}\) (Wallace et al. 1983, Muff et al. 1998), but the nature of the mechanism transporting Ca\(^{2+}\) into the parathyroid cells is still uncertain. One issue debated during the past two decades has been whether or not the parathyroid cells express a functional VOCC in the plasma membrane (Hove & Sand 1981, Wallace et al. 1983). High potassium, which decreases Ca\(^{2+}\) (Shoback & Brown 1984), stimulated PTH secretion, a finding which does not support the presence of VOCC, even though L-type calcium channel in parathyroid cells has been suggested (Chang et al. 2001, Yokoyama et al. 2009).

In this study, we could not demonstrate any VOCC in parathyroid cells using a protocol that unequivocally demonstrates the presence of VOCC in the pancreatic \(\beta\)-cells. Therefore, non-selective cation channels that mediate SOCE have to be considered, even though the presence or absence of VOCC does not rule out the coexistence of non-selective cation channels.

SOCE is stimulated by depletion of Ca\(^{2+}\) from intracellular calcium stores, and is mediated by activation of specific plasma membrane channels.
termed SOCs. This activation produces a biphasic increase in $\text{Ca}^{2+}$, starting with a rapid $\text{Ca}^{2+}$ release from ER stores, followed by a slower $\text{Ca}^{2+}$ entry from outside the cell. This pattern, typical of PLC-coupled receptors (e.g. CASR), has also been demonstrated in parathyroid cells (Mihai & Farndon 2000). Thapsigargin, a specific inhibitor of $\text{Ca}^{2+}$-ATPase on intracellular stores, has been widely used as a tool to activate SOCE.

Our electrophysiological studies showed a current which increased sixfold in the presence of thapsigargin, indicating the activation of SOCs. Even though thapsigargin irreversibly blocks $\text{Ca}^{2+}$-ATPase activity, whole-cell current decays with time, most likely reflecting channel ‘run-down’. The electrophysiological findings, in combination with recordings of $\text{Ca}^{2+}$ showing a large rise in $\text{Ca}^{2+}$ by 1·5 mM $\text{Ca}^{2+}$ after thapsigargin treatment, are a strong indication for the presence of SOCs in human parathyroid cells.

Interestingly, the characteristics of SOCs in different cell types are quite distinct, suggesting diversity in the channel components (Liu et al. 2004, Beech 2005, Parekh & Putney 2005). The canonical-type family of TRP channels is different from other groups of ion channels in displaying a huge diversity in ion selectivities, modes of activation, and the permeability to cations. All six members of the TRPC-type TRP channel (TRPC1, 3–7) have been proposed to be involved in $\text{Ca}^{2+}$ release from ER stores, followed by a slower $\text{Ca}^{2+}$ entry further supports the existence of SOCs in human parathyroid.

In summary, our study provides evidence for a close association between TRPC1, Orai1, and STIM1, which was demonstrated for the first time in human parathyroid.

**Supplementary data**

This is linked to the online version of the paper at [http://dx.doi.org/10.1677/JME-09-0138](http://dx.doi.org/10.1677/JME-09-0138).
Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Funding

This work was supported by grants from the Swedish Research Council, the Novo Nordisk Foundation, Funds of the Karolinska Institute, the Tore Nilsson Foundation, the Turing Foundation, the Jeansson Foundations, the Åke Wiberg Foundation, the Göran Gustafsson Foundation for Research in Natural Sciences and Medicine, Magn. Bergvall Foundations, the Stockholm County Council, the Swedish Cancer Foundation, and the Knut and Alice Wallenberg Foundation.

References


Liu X, Groschner K & Ambudkar IS 2004 Is distinct Ca(2+)-permeable cation currents are activated by internal Ca(2+) store depletion in RBL-2H3 cells and human salivary gland cells, HSG and HSY. Journal of Membrane Biology 200 93–104.


Received in final form 11 February 2010
Accepted 26 February 2010
Made available online as an Accepted Preprint 1 March 2010