Regulation of Calcium Channels and Exocytosis in Mouse Adrenal Chromaffin Cells by Prostaglandin EP3 Receptors

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ABSTRACT

Prostaglandin (PG) E2 controls numerous physiological functions through a family of cognate G protein-coupled receptors (EP1–EP4). Targeting specific EP receptors might be therapeutically useful and reduce side effects associated with nonsteroidal anti-inflammatory drugs and selective cyclooxygenase-2 inhibitors that block prostanoid synthesis. Systemic immune challenge and inflammatory cytokines have been shown to increase expression of the synthetic enzymes for PGE2 in the adrenal gland. Catecholamines and other hormones, released from adrenal chromaffin cells in response to Ca\(^{2+}\) influx through voltage-gated Ca\(^{2+}\) channels, play central roles in homeostatic function and the coordinated stress response. However, long-term elevation of circulating catecholamines contributes to the pathogenesis of hypertension and heart failure. Here, we investigated the EP receptor(s) and cellular mechanisms by which PGE2 might modulate chromaffin cell function. PGE2 did not alter resting intracellular [Ca\(^{2+}\)] or the peak amplitude of nicotinic acetylcholine receptor currents, but it did inhibit Ca\(_{\text{v}2}\) voltage-gated Ca\(^{2+}\) channel currents (I\(_{\text{Ca}}\)). This inhibition was voltage-dependent and mediated by pertussis toxin-sensitive G proteins, consistent with a direct G\(\beta\gamma\) subunit-mediated mechanism common to other G\(\alpha_i\)-coupled receptors. mRNA for all four EP receptors was detected, but using selective pharmacological tools and EP receptor knockout mice, we demonstrated that EP3 receptors mediate the inhibition of I\(_{\text{Ca}}\). Finally, changes in membrane capacitance showed that Ca\(^{2+}\)-dependent exocytosis was reduced in parallel with I\(_{\text{Ca}}\). To our knowledge, this is the first study of EP receptor signaling in mouse chromaffin cells and identifies a molecular mechanism for paracrine regulation of neuroendocrine function by PGE2.

Introduction

Catecholamines and other hormones released from adrenal chromaffin cells help maintain normal homeostatic function and play central roles in the coordinated response to acute stressors, for example, during “fight-or-flight” sympathetic activation. Elevation of circulating catecholamines is closely correlated with hypertension and is a hallmark of chronic heart failure. Indeed, specifically targeting the adrenal gland to inhibit catecholamine outflow in vivo improved cardiac function in rat models of heart failure, suggesting adrenal hormone release as a potential therapeutic target (Lymeropoulos et al., 2008). In situ, acetylcholine (ACh) released from splanchnic nerve fibers activates nicotinic ACh receptors on the chromaffin cell, causing membrane depolarization, opening of voltage-gated calcium channels, and influx of calcium that subsequently triggers exocytosis (Boarder et al., 1987). Thus, as with neurons and other excitable cells, voltage-gated calcium channels play pivotal roles in chromaffin cell function. The cells also express a variety of G protein-coupled receptors (GPCRs) that orchestrate complex regulation of stimulus-secretion coupling. For example, chromaffin cells express autoreceptors for ATP (P2Y receptors), catecholamines (\(\alpha\)-adrenergic), and enkephalin (\(\mu\)-opioid receptors) that couple to G\(\alpha_i\)-type G proteins and mediate autocrine/paracrine inhibition of catecholamine release through inhibition of voltage-gated calcium channels (Albillos et al., 1996; Currie and Fox, 1996; Harkins and Fox, 2000; Powell et al., 2000; Ulate et al., 2000) and other downstream targets (Chen et al., 2005; Yoon et al., 2008).

In this study, we investigated the effects of prostaglandin (PG) E\(_2\) on chromaffin cells. PGE\(_2\) is produced in a variety of cell types through metabolism of arachidonic acid by cyclooxygen-
a (COX-1 or COX-2) and prostaglandin E syntheses. It acts in an autocrine/paracrine manner, primarily through binding to a family of cognate GPCRs (EP1–EP4 receptors) (Breyer et al., 2001) to control a variety physiological functions, including protection of the gastric mucosa, renal function, inflammation, pain, blood pressure, and secretion of hormones and neurotransmitters. Nonsteroidal anti-inflammatory drugs such as aspirin and selective COX-2 inhibitors reduce the production of PGE$_2$ but also disrupt synthesis of other prostanooids and can cause serious side effects. One strategy to reduce these unwanted side effects is to identify specific cellular functions of EP receptors and develop EP receptor subtype-selective drugs. For example, characterization of EP receptor signaling in smooth muscle suggests that EP1 receptors could be targeted for anti-hypertensive treatment, and an EP3 receptor antagonist (2E)-3-[l-(2,4-dichlorophenyl)methyl]-5-fluoro-3-methyl-1H-indol-7-yl]-N-[(4,5-dichloro-2-thienyl)sulfonfyl]-2-propenamide (DG-041) is under investigation for treatment of atherothrombosis (Guan et al., 2007; Heptinstall et al., 2008).

EP1 and EP3 receptors are expressed in the adrenal medulla (Breyer et al., 1993; Namba et al., 1993; Shibuya et al., 1999; Engström et al., 2008) along with the synthetic enzymes for PGE$_2$ (Ichitani et al., 2001; Engström et al., 2008). Moreover, systemic immune challenge or circulating cytokines rapidly recruit dendritic cells and macrophages to the adrenal gland and increase the expression of COX-2 and PGE synthase and presumably local PGE$_2$ production (Engström et al., 2008). Thus, the components are in place for local modulation of chromaffin cells by PGE$_2$, but previous studies present confusing and contradictory findings: PGE$_2$ has been reported to increase (Marley et al., 1988; Yamada et al., 1988; Yokohama et al., 1988; Karaplis et al., 1989) or decrease (Karaplis et al., 1989) adrenal catecholamine release, elevate intracellular calcium levels (Mochizuki-Oda et al., 1991; Shibuya et al., 1999), or inhibit voltage-gated calcium channels (Currie et al., 2000). In sympathetic neurons, which are closely related to chromaffin cells, PGE$_2$ can modulate nicotinic ACh receptors (Tan et al., 1998; Du and Role, 2001) and voltage-gated calcium channels (Ikeda, 1992). Thus, PGE$_2$ may alter calcium signaling and exocytosis in chromaffin cells by multiple pathways and potentially through multiple EP receptors.

The goal of this study was to define the receptors and mechanisms by which PGE$_2$ modulates calcium signaling in adrenal chromaffin cells using a combination of pharmacological tools and EP receptor knockout mice. We show that PGE$_2$ did not alter the peak amplitude of nicotinic ACh receptor currents or resting intracellular [Ca$^{2+}$] but potently inhibited Ca$_{\text{a,2}}$ voltage-gated calcium current channels (I$_{\text{Ca,2}}$) (EC$_{50}$ = 5.5 nM). Although mRNA for all four EP receptor subtypes is expressed in the mouse adrenal gland, our data unequivocally show that EP3 receptors mediate this inhibition of I$_{\text{Ca,2}}$. PGE$_2$ also decreased the change in membrane capacitance in response to membrane depolarization/calcium entry, suggesting that the number of secretory vesicles undergoing exocytosis was reduced. To our knowledge, this is the first study of EP receptor signaling in mouse chromaffin cells and identifies a cellular/molecular mechanism for paracrine regulation of neuroendocrine function by PGE$_2$.

### Materials and Methods

#### Cell Preparation and Culture.

Male mice (6–12 weeks old), wild-type, EP3 receptor knockout (Y. Zhang, C. E. Swan, K. I. Boyd, A. Bian, A. Shintani, D. Lee, D. W. Threadgill, R. C. Harris, R. Zent, and R. M. Breyer, manuscript in preparation), or EP1 receptor knockouts (Guan et al., 2007), all on C57BL/6 background, were euthanized using carbon dioxide followed by cervical dislocation. Adrenal glands were quickly harvested and placed in ice-cold magnesium-free Locke’s solution containing 153 mM NaCl, 6 mM KCl, 2 mM Na$_2$HPO$_4$$\cdot$ 7H$_2$O, 1 mM NaH$_2$PO$_4$$\cdot$ H$_2$O, 10 mM glucose, and 10 mM HEPES. The glands were trimmed of fat, and the cortex was dissected from the medulla. The medullae were incubated for 15 min at 37°C in a papain digestion solution (2.5 mg/ml papain; Gentantis, San Diego, CA) followed by another 10-min incubation at 37°C in collagenase P (3 U/ml; Roche Diagnostics, Indianapolis, IN). Tissues were washed twice with Locke’s and transferred to growth medium consisting of Dulbecco’s modified Eagle’s medium/F-12/ GlutaMAX (Invitrogen, Carlsbad, CA) supplemented with HyClone-defined fetal bovine serum (10%) (Thermo Fisher Scientific, Waltham, MA) and penicillin (100 U/ml)/streptomycin (100 µg/ml) (Sigma-Aldrich, St. Louis, MO). Tissues were then triturated with a 2 ml of fire-polished glass pipette coated in growth medium and allowed to settle. The cell containing supernatant was removed and plated on glass coverslips thinly coated in growth factor-reduced Matrigel (BD Biosciences Discovery Labware, Bedford, MA). Cells were allowed to settle and adhere to the coverslips for 2 h before 2 ml of growth medium was added to the coverslips. Cells were maintained at 37°C in a humidified, 5% CO$_2$ atmosphere and used 1 to 3 days after isolation. Each cell preparation was from a single mouse. All experimental studies were approved by the Institutional Animal Care and Use Committee of Vanderbilt University Medical Center.

#### Electrophysiology.

Electrodes were pulled from borosilicate glass capillary tubes (World Precision Instruments, Sarasota, FL), coated with dental wax (Electron Microscopy Sciences, Hatfield, PA) and fire-polished to a final resistance of 1.8 to 3 MΩ when filled with a CsCl-based internal solution. Cells were voltage-clamped in the whole-cell configuration using an Axopatch 200B amplifier, Digidata1400A interface, and pClamp10 software (Molecular Devices, Sunnyvale, CA). Analogue data were filtered at 2 kHz and digitized at 20 µs per point (50 kHz). Data were analyzed using pClamp10, OriginPro software (OriginLab Corp, Northampton MA), and Prism version 5 (GraphPad Software Inc., San Diego, CA). For perforated whole-cell recording configuration, the pipette tip was filled with amphotericin-free solution and then backfilled with solution that contained −0.5 mg/ml amphotericin B (Calbiochem, San Diego, CA). After forming a cell-attached seal, series resistance was monitored to assess the progress of perforation. Typically, series resistance <10 to 15 MΩ was achieved within 5 to 15 min, and cells that did not show good perforation within this time frame were discarded. I$_{\text{Ca,2}}$ was activated by brief 20-100-ms step depolarizations to a predetermined peak (10–30 mV) from a holding potential of −80 mV. Data were subjected to linear capacitance and leak subtraction using standard pulse/number (P/N) protocols. When determining the inhibition of I$_{\text{Ca,2}}$, produced by PGE$_2$ (100 nM), cells in which the current amplitude decreased <10% were designated as “nonresponders” and are reported as such under Results. Only “responders” (i.e., >10% current decrease) were included when calculating the mean percentage of inhibition. The presence of both responders and nonresponders was consistently observed in multiple cell preparations, but we did not investigate any other possible differences between the two sets of cells in this study. To calculate an EC$_{50}$ for inhibition of I$_{\text{Ca,2}}$ by PGE$_2$, data were fit with a Boltzmann function of the form $Y = Y_{\text{max}}/(1 + 10^{(\log EC_{50} - X)/\gamma})$, where $Y$ is the percentage of inhibition of $Y_{\text{max}},$ and $X$ is the concentration of PGE$_2$. The Hill slope was assumed to be 1, and the curve fit with the least-squares method in Prism 5 software. Goodness of fit was indicated by R$^2 = 0.97.$
Nicotinic ACh receptor currents were activated by bath perfusion for 45 s with 30 to 100 μM carbachol. This enabled multiple reproducible responses to be obtained from the same cell. The delay in current activation (Fig. 3A) was due to the “dead space” in the perfusion system. The amplitude of the sustained inward current activated by carbachol was determined by calculating the mean current amplitude over a 5-s period starting 30 s after carbachol application. The mean current amplitude over this 5-s period was determined for each cell, and then data were pooled. The current amplitude was also calculated (mean over a 5-s period) at the end of the drug application to determine the extent to which the response declined.

Changes in membrane capacitance (ΔCm) were monitored in the perforated whole-cell recording configuration using a HEKA EPC10 amplifier in combination with PatchMaster data acquisition software (HEKA, Lambrecht/Pfalz, Germany). The software lock-in module was used to implement the “sine + d.c.” approach for estimating Cm. A sine wave (1-kHz, 20-mV peak to peak) was imposed on the holding potential of −80 mV, and the assumed reversal potential was set to 0 mV. The software simultaneously calculated membrane conductance (Gs), and any cells that showed simultaneous changes in Cm and Gs were discarded. Cells were stimulated by two-step depolarizations (to +10 mV, 100-ms duration) separated by 100 ms. The stimulus was repeated every 3 min. Membrane capacitance was averaged over a 50-ms period before the stimulus (baseline) and again 50 ms after the end of the stimulus to calculate ΔCm. After two control responses, cells were exposed to 100 nM PGE2 during the third response. The second control response was typically of equal or greater magnitude than the first, and if this was not the case, the cell was discarded because of concern about “run-down.” For data analysis, cells were divided into those that responded to PGE2 with decrease in ICa amplitude (group 1) and those in which ICa was not inhibited (group 2) (see Results for more discussion). Data are reported as mean ± S.E.M., and statistical significance was determined using paired or independent Student’s t test as appropriate.

[Ca2+]i, Measurements. Free cytosolic Ca2+ concentration ([Ca2+]i) was measured in cells loaded with the fluorescent Ca2+ indicator Fura-2 (Invitrogen, Carlsbad, CA). Cells were washed twice with HEPES-buffered Hank’s balanced salt solution and incubated for 30 to 45 min with 3 μM Fura-2 acetoxymethyl ester at 37°C. Cells were then washed in Fura-free solution for 30 to 60 min before recording. For recording, the coverslip with the cells attached was transferred to a recording chamber and mounted on the stage of a Nikon TE2000 fluorescence microscope (Nikon, Tokyo, Japan). The recording chamber had a volume of 300 to 400 μl and was continually perfused with fresh solution from gravity-fed reservoirs at a flow rate of 4 ml/min. An InCyt IM2 fluorescence imaging system (Intracellular Imaging Inc., Cincinnati, OH) was used to monitor [Ca2+]i. Cells were alternately excited at wavelengths of 340 and 380 nm and emission at 510 nm detected using a PixelFly digital camera as detailed previously (Dzhura et al., 2006). Ratios were collected every 2 s throughout the experiment and converted to [Ca2+]i, using an in vitro calibration curve, generated by adding 15.8 μM Fura-2 pentapotassium salt to solutions from a calibration kit containing 1 mM MgCl2 and known concentrations of Ca2+ (0–1350 nM) (Invitrogen). One or two cells in the field of view were selected in each experiment and after a 2-min baseline were exposed to 1 μM PGE2 for 3 min and subsequently to a 50 mM KCl-containing solution (by replacing an equimolar amount of NaCl in our standard extracellular solution; see below). This was done as a positive control for the assay to ensure the cells were loaded with Fura-2 and responded to calcium elevations. It also served as a means to identify any nonexcitable (i.e., nonchromaffin) cells because these typically fail to respond to KCl. Cells that had an unstable baseline or failed to respond robustly to KCl (>300 nM elevation) were excluded from analysis. Data analysis was performed using OriginPro software (OriginLab Corp).

RT-PCR. Total RNA was prepared from mouse adrenal and kidney tissue using QIAGEN RNeasy Mini Kit (QIAGEN, Valencia, CA). cDNA was synthesized from total RNA with ABI High-Capacity Reverse Transcriptase kit (Applied Biosystems, Foster City, CA) and amplified using specific primers: EP1, 5′-TTAACTGAGCCTAGGGATG-3′ (sense primer, nucleotides 311–331), 5′-CGCTGAGCTTGGACAGCACTA-3′ (antisense primer, nucleotides 956–976); EP3, 5′-CCTGGAGCATGTGGCTTT-TAATG-3′ (sense primer, nucleotides 1404–1423), 5′-GGTGCGCTTGA-TATGACAAA-3′ (antisense primer, nucleotides 1397–1379); EP3, 5′-TGGTGGCTTCCATGGGCCCA-3′ (antisense primer, nucleotides 1572–1592); EP4, 5′-GGTGCTTCTTCTACATGCG-CACCTTCTC-3′ (sense primer, nucleotides 1092–1075; TGCCACTA-ACCTATCCAAAACAG-3 (antisense primer, nucleotides 1572–1586); and GAPDH, 5′-GGCATTGCTCTCAATGACAA-3′ (antisense primer, nucleotides 1122–1141).

Drugs and Solutions. Cells were perfused at a rate of 4–5 ml/min with external solution consisting of 136 mM NaCl, 2 mM CaCl2, 1 mM MgCl2, 6 mM glucose, 10 mM HEPES, and 10 mM CaCl2, 2H2O, pH 7.3, with osmolarity of ~305. All drugs were diluted (≈1000×) and perfused in this extracellular solution unless otherwise noted. For whole-cell recordings, electrodes were filled with internal solution containing 110 mM CsCl, 10 mM EGTA, 20 mM HEPES, 4 mM MgCl2, 0.35 mM GTP, 4 mM ATP, and 14 mM creatine phosphate, pH 7.3, with osmolarity of ~305. The free calcium concentration in this solution is estimated to be very low (<1 nM) (http://maximelander.stanford.edu). For perforated whole-cell recording, electrode tips were filled with internal solution containing 145 mM cesium glutamate, 10 mM HEPES, 10 mM NaCl, and 1 mM tetrabutylammonium chloride, pH 7.3, with osmolarity of 529, and backfilled with internal solution containing amphotericin B (Calbiochem) at a final concentration of 0.53 mM, prepared from a 100× stock solution in dimethyl sulfoxide every 2 h. PGE2 (Cayman Chemical Company, Ann Arbor, MI) and Suprolstrole (Sigma-Aldrich) were prepared as 10 mM stock solutions in ethanol and dimethyl sulfoxide, respectively, and frozen until the day of use. DG-041 was synthesized from total RNA with ABI High-Capacity Reverse Transcriptase Core. Pertussis toxin (Calbiochem) was prepared as a 100× stock solution in dimethyl sulfoxide every 2 h. PGE2 (Cayman Chemical Company, Ann Arbor, MI) and Suprolstrole (Sigma-Aldrich) were prepared as 10 mM stock solutions in ethanol and dimethyl sulfoxide, respectively, and frozen until the day of use. DG-041 was synthesized in the Vanderbilt Institute of Chemical Biology Chemical Synthesis Core. Pertussis toxin (Calbiochem) was prepared as a 100 μg/μl stock in water and applied 24 h before experiment in cell culture medium at 300 μg/ml. Carbachol (Calbiochem) and tetrodotoxin (Alomone Labs, Jerusalem, Israel) were prepared in sterile water at 100 and 1 mM stocks, respectively, and diluted on the day of use. Nitrendipine (ICN Biomedicals Inc., Aurora, OH) was prepared as a 10 mM stock solution in ethanol and diluted to 10 μM in external solution. Stock solutions of s-conotoxin GIV (100 μM) (Alomone Labs) and s-agatoxin IVA (10 μM) (Bachem Biosciences, King of Prussia, PA) were prepared in standard extracellular solution and diluted to final working concentrations of 1.5 μM and 400 nM, respectively, on the day of use.

Results

PGE2 Inhibits ICa in Mouse Adrenal Chromaffin Cells. Given the pivotal roles of voltage-gated calcium channels in stimulus-secretion coupling and many other cellular functions, we initially tested whether PGE2 inhibited the calcium channel currents (ICa) in mouse chromaffin cells. The cells were voltage-clamped at −80 mV and stimulated with a 20-ms step depolarization to evoke ICa every 10 s (Fig. 1A). Application of 100 nM PGE2 produced a significant and reversible inhibition of peak ICa amplitude (Fig. 1A) in approximately 76% of cells tested under similar experimental conditions (conventional whole-cell recording, n = 37 of 49 cells, n = 9 mice). The inhibition of ICa was concentration dependent (Fig. 1B) and the data fit well with a Boltzmann func-
tion that yielded a maximal inhibition of 40% and an EC$_{50}$ of 5.5 nM consistent with the low nanomolar affinities reported for PGE$_2$ binding to EP receptors (Breyer et al., 2001).

The Inhibition of I$_{Ca}$ by PGE$_2$ Is Voltage-Dependent and Mediated by Pertussis Toxin-Sensitive G Proteins. GPCRs inhibit I$_{Ca}$ by several different mechanisms, but perhaps the most widespread and best understood pathway is mediated by direct binding of G protein $\beta$y subunits to P/Q-type (Ca$_{V2.1}$) and N-type (Ca$_{V2.2}$) channels (Currie, 2010a). Although there are exceptions, in most cases, this pathway involves GPCRs that couple to pertussis toxin-sensitive G$_{i/o}$-type G proteins. We and others have shown previously that P2Y purinergic receptors and $\mu$-opioid receptors use this pathway to produce autocrine/paracrine inhibition of I$_{Ca}$ in chromaffin cells (Albillos et al., 1996; Currie and Fox, 1996; Powell et al., 2000). To determine whether PGE$_2$ acts through a G$_{i/o}$-coupled GPCR, we incubated isolated mouse chromaffin cells with pertussis toxin (300 ng/ml) for ~24 h before whole-cell recording. Control cells were from the same cell preparations and were recorded on the same days as the pertussis toxin-treated cells. As shown in Fig. 2A, the inhibition of I$_{Ca}$ produced by PGE$_2$ was virtually abolished in pertussis toxin-treated cells (2 ± 2.6%, n = 6, compared with 31 ± 7.1%, n = 7, in control cells; p < 0.002). As a positive control, we also used the P2Y receptor agonist ATP (100 $\mu$M), because this is known to inhibit I$_{Ca}$ via pertussis toxin-sensitive G proteins in chromaffin cells (Currie and Fox, 1996). The inhibition produced by ATP was also significantly reduced (29 ± 8.5%, n = 7 in control cells compared with 7 ± 5.4%, n = 6, in pertussis toxin-treated cells; p < 0.05). These data confirmed that PGE$_2$ acts though a G$_{i/o}$-coupled GPCR to inhibit I$_{Ca}$.

A defining biophysical signature of direct G$\beta$y-mediated inhibition of N- and P/Q-type channels is reversal by a strongly depolarizing voltage step. This reversal is believed to reflect transient dissociation of G$\beta$y from the channel at the depolarized membrane potential (Currie, 2010a). Therefore, we used a prepulse facilitation protocol to determine whether PGE$_2$ used
this mechanism to inhibit $I_{Ca}$ in mouse chromaffin cells. Figure 2B illustrates a representative voltage command (top) and current trace (bottom). The cell was stimulated by two identical test pulses (P1 and P2), the second of which was preceded by a 50-ms step to +120 mV. PGE$_2$ significantly reduced the amplitude of $I_{Ca}$ during both P1 and P2 (Fig. 2C), but the prepulse (immediately preceding P2) significantly reduced this inhibition from 43 ± 6% during P1 to 13 ± 3% during P2 ($n = 6; p < 0.001$) (Fig. 2D). Thus, the inhibition of $I_{Ca}$ produced by PGE$_2$ was largely voltage-dependent, although there was also a voltage-independent component to the inhibition (the residual inhibition seen during P2) consistent with what has been reported previously for P2X and opioid receptors.

Voltage-dependent inhibition of $I_{Ca}$ by other GPCRs preferentially targets the Ca$_{v}$2 family of calcium channels, in particular P/Q-type (Ca$_{v}$2.1) and N-type (Ca$_{v}$2.2) channels (Currie, 2010a). Mouse chromaffin cells are known to express Ca$_{v}$2 channels (P/Q-, N-, and R-type channels) and members of the Ca$_{v}$1 family (L-type channels) (García et al., 2006). Consistent with previous reports, we found that nitrendipine, a dihydropyridine antagonist of L-type channels, blocked 41 ± 5% ($n = 7$) of the whole-cell current. We did not systematically dissect the channel types comprising the non-L-type current, but previous reports indicate the majority is carried by N- and P/Q-type channels, with 10 to 20% accounted for by R-type and perhaps T-type channels (García et al., 2006). After block of N-type (Ca$_{v}$2.1) channels by preincubation with ω-conotoxin GVIA (1.5 μM) and ω-agatoxin IVA (400 nM), respectively, the inhibition by PGE$_2$ was dramatically reduced (7 ± 1%, $n = 6; p < 0.05$) confirming that N- and P/Q-type channels are the main target for this pathway.

**Short-Term Application of PGE$_2$ Did Not Alter Peak Nicotinic Acetylcholine Receptor Currents.** In situ, chromaffin cells are directly innervated by cholinergic splanchnic nerve fibers. Activation of nicotinic acetylcholine receptors (nAChRs) on the chromaffin cells causes membrane depolarization, activation of voltage-gated calcium channels, and influx of calcium that triggers exocytosis. It has been reported that PGE$_2$ modulates nicotinic acetylcholine receptors (nAChRs) on the chromaffin cells causes membrane depolarization, activation of voltage-gated calcium channels, and influx of calcium that triggers exocytosis. It has been reported that PGE$_2$ modulates nicotinic acetylcholine receptors on sympathetic neurons (Tan et al., 1998; Du and Role, 2001), although we are not aware of any similar studies in chromaffin cells. However, it has been shown that inhibition of nAChRs in chromaffin cells can reduce cytosolic calcium elevations and catecholamine release elicited by cholinergic stimuli (Dzhura et al., 2006). Thus, PGE$_2$ could indirectly alter calcium channels and calcium signaling in chromaffin cells by modulating nAChR.

To test this possibility, cells were voltage-clamped at a holding potential of −80 mV in the perforated whole-cell recording configuration, and the bath was continuously perfused with fresh extracellular recording solution. Nicotinic ACh receptor currents were evoked by application of 100 μM carbachol for 45 s (Fig. 3A). Under these conditions, the inward current was primarily due to the relatively nondenaturing nACh receptors found in chromaffin cells. After washout of carbachol, the cells were allowed to recover for 6 min before exposure to 100 nM PGE$_2$ and a second application of 100 μM carbachol (in the continued presence of PGE$_2$) (Fig. 3A). Short-term application of PGE$_2$ had no effect on the mean peak inward current evoked by carbachol (351 ± 65 pA in the presence of PGE$_2$ compared with 352 ± 63 pA before application of PGE$_2$; $n = 8$) (Fig. 3B). The inward current response did decay slightly during continued application of carbachol (9 ± 2% in control conditions), and this was significantly increased in the presence of PGE$_2$ (21 ± 3%; $p < 0.01$).

**Short-Term Application of PGE$_2$ Did Not Elevate Basal Intracellular Calcium Concentration.** Previous reports indicated that relatively high concentrations of PGE$_2$ ranging from 200 nM to 1 μM can directly elevate intracellular calcium concentration ([Ca$^{2+}$]$_i$) either by activating a Ca$^{2+}$ influx pathway or by releasing Ca$^{2+}$ from intracellular stores (Mochizuki-Oda et al., 1991; Shibuya et al., 1999). However, in the experiments investigating the effects of PGE$_2$ on nAChR currents, PGE$_2$ did not alter the holding current of chromaffin cells voltage-clamped at −80 mV (Fig. 3A), suggesting that PGE$_2$ did not activate an inward calcium current. We also used Fura-2 imaging to determine whether PGE$_2$ could elevate resting [Ca$^{2+}$]$_i$ in individual mouse chromaffin cells. Our data showed that a short-term (3-min) application of 1 μM PGE$_2$ had no effect on [Ca$^{2+}$]$_i$ during P1 (82 ± 15 nM before and 85 ± 16 nM during application of PGE$_2$; $n = 9$ cells from seven independent experiments) (Fig. 3C).

**mRNA for All Four EP Receptor Subtypes Was Detected in Mouse Adrenal Tissue.** The data presented above demonstrate that PGE$_2$ acts through a G$_{i/o}$-coupled GPCR to inhibit $I_{Ca}$ in mouse chromaffin cells. Of the four known receptors for PGE$_2$, termed EP1 to EP4, only EP3 typically couples to G$_{i/o}$-type G proteins, although it has been reported that EP1 receptors might also couple to G$_{i/o}$ at least in some cell types (Ji et al., 2010). Both EP3 and EP1 receptors have been reported previously in the adrenal medulla (Breyer et al., 1993; Namba et al., 1993; Engström et al., 2008).

![Fig. 3. PGE$_2$ does not alter peak nicotinic acetylcholine receptor currents or resting [Ca$^{2+}$]$_i$ in mouse chromaffin cells. A, representative recording of nAChR currents evoked by two applications of carbachol (100 μM) in the absence (left) or presence (right) of 100 nM PGE$_2$. B, bar chart showing that PGE$_2$ had no effect on the mean amplitude of the nAChR currents evoked by carbachol (8 cells). C, ratiometric imaging of Fura-2-loaded chromaffin cells. Inset, a representative recording from a single cell plotting [Ca$^{2+}$]$_i$ against time (sampling rate, 0.5 Hz). The cell was exposed to 1 μM PGE$_2$ for 3 min and then to 50 mM KCl to depolarize the membrane and elicit Ca$^{2+}$ entry through voltage-gated Ca$^{2+}$ channels (positive control). The main chart shows mean [Ca$^{2+}$]$_i$, before (control), during (PGE$_2$), and after washout (wash) of 1 μM PGE$_2$ and the response to 50 mM KCl (9 cells from seven independent experiments).](molpharm.aspetjournals.org)
To determine which EP receptors were expressed in the mouse adrenal gland we used RT-PCR. The adrenal gland was isolated as described under Materials and Methods, and kidney tissue, which expresses all four EP receptor subtypes, was isolated in parallel as a positive control. The adrenal cortex was dissected from the gland leaving the adrenal medulla for RNA isolation; however, small traces of cortex were probably present. Three known splice variants of the EP3 receptor are found in mice: EP3α, EP3β, and EP3γ (Irie et al., 1993; Breyer et al., 2001). The C-terminal tails of these splice variants are different, and the variants can exhibit different downstream signaling pathways and agonist-dependent desensitization in heterologous expression systems. We detected mRNA for all three EP3 receptor splice variants in the mouse adrenal tissue (Fig. 4A). We also detected mRNA for the EP1, EP2, and EP4 receptors (Fig. 4B). GAPDH was used as an internal standard and amplified in all tissues (data not shown).

**Pharmacological Evidence that EP3 Receptors Mediate the Inhibition of ICa by PGE2.** We showed that the inhibition of ICa was abolished in pertussis toxin-treated cells (Fig. 2A), so is mediated by Gi/o-coupled GPCRs. Although we diated the Inhibition of ICa by PGE2. We showed that the inhibition of ICa was abolished in pertussis toxin-treated cells (Fig. 2A), so is mediated by Gi/o-coupled GPCRs. Although we detected mRNA for all four EP receptor subtypes in the mouse adrenal gland (Fig. 4), generally, only EP3 receptors couple to Gs (Breyer et al., 2001). Therefore, we used EP receptor subtype-selective agonists and antagonists to investigate the involvement of EP3 receptors. First, we used the selective EP1/EP3 receptor agonist sulprostone (Fig. 5, A and B). In these experiments, we used perforated whole-cell recordings to maintain endogenous calcium buffering of the chromaffin cells. The inhibition produced by 100 nM PGE2 (43 ± 6%, n = 15) was similar to that in conventional whole-cell recording. Sulprostone (100 nM) significantly reduced the amplitude of ICa in six of seven cells by 41 ± 9% (n = 6), and this was not significantly different from the inhibition produced by 100 nM PGE2 under the same recording conditions (p = 0.89).

It has been reported that DG-041 is a selective, noncompetitive antagonist of EP3 receptors (Heptinstall et al., 2008). Cells were stimulated every 10 s with a 20-ms step depolarization to evoke ICa. DG-041 (30 nM) was applied to the cells for ~2 min before the application of PGE2 (100 nM). DG-041 alone had little effect on ICa but completely blocked the inhibition produced by PGE2 (2.0 ± 2.2%, n = 9; Fig. 5, C and D). Subsequent applications of PGE2 after several minutes of washout of DG-041 also produced no inhibitory effect, suggesting that DG-041 is functionally irreversible over the time course of our experiments. As a control, we used ATP (100 nM) to activate P2Y receptors in the presence of DG-041. ATP inhibited ICa by 26 ± 4.7% (n = 4) (Fig. 5D), similar to the inhibition produced by ATP in the absence of DG-041 (29 ± 8.5%; Fig. 2B). This suggests that DG-041 selectively blocked PGE2, and the downstream signaling pathways responsible for voltage-dependent inhibition of ICa were intact.

**The Inhibition of ICa Produced by PGE2 Was Abolished in Cells Isolated from EP3 Receptor Knockout Mice.** The pharmacological data presented above strongly implicated EP3 receptors in the inhibition of ICa by PGE2. However, it was still possible that other receptors could play a role. For example, DG-041 is reported to be a selective noncompetitive antagonist of EP3 receptors but off-target effects of the compound have not been widely studied. Therefore, to unequivocally identify the receptor subtype involved, we isolated chromaffin cells from EP3 receptor knockout mice [EP3(-/-) mice]. As shown in Fig. 6, the inhibition of ICa by PGE2 was abolished in cells isolated from EP3(-/-) mice. In the same cells, 100 µM ATP significantly reduced the amplitude of ICa by 33 ± 7% (n = 6, p < 0.05), indicating

![Fig. 4. EP receptor mRNA expressed in mouse adrenal tissue. A, RT-PCR was used to detect expression of the EP3 receptor in mouse adrenal tissue (left) and kidney tissue (right) that was isolated in parallel as a positive control. Top, primers common to all splice variants of the EP3 receptor were used. Bottom, primers selective for the splice variants were used. The forward primers for EP3α and EP3β are identical so the fragments run in the same lane (middle); the top band corresponds with the expected amplicon size of EP3α and the bottom band EP3β. B, in addition to EP3, EP1 (top), EP2 (middle), and EP4 (bottom) mRNA were amplified. All samples from A and B expressed the internal standard GAPDH (data not shown). Data shown are representative of three replicate experiments on tissue from three different mice.](image-url)
that the effect of the knockout was selective for PGE$_2$ and did not perturb G protein-mediated inhibition of I$_{\text{Ca}}$ by other receptors. Likewise, in perforated whole-cell recording, PGE$_2$ did not inhibit I$_{\text{Ca}}$ in cells isolated from EP3(-/-/-) mice (1 ± 4% inhibition; n = 6).

As a complementary approach, we tested the ability of sulprostone (an EP1/EP3 selective agonist) to inhibit I$_{\text{Ca}}$ in cells isolated from EP1 receptor knockout mice. Under these conditions, any effect of sulprostone can be attributed to EP3 receptor signaling because the EP1 receptors are absent. Sulprostone inhibited I$_{\text{Ca}}$ in these EP1(-/-/-) chromaffin cells by 47 ± 12% (n = 4), an effect that was not significantly different from that seen in chromaffin cells from wild-type mice (41 ± 9%; n = 6). Taken together, our data using pharmacological approaches and knockout mice demonstrate the inhibition of I$_{\text{Ca}}$ by PGE$_2$ is mediated solely by EP3 receptors.

**Effects of PGE$_2$ on Ca$^{2+}$-Dependent Exocytosis.** Ca$^{2+}$ influx through voltage-gated calcium channels is the primary trigger for fusion of large dense-core vesicles with the plasma membrane (i.e., Ca$^{2+}$-dependent exocytosis). Inhibition of I$_{\text{Ca}}$ is believed to an important mechanism that controls neurosecretion, and a number of GPCRs inhibit I$_{\text{Ca}}$ and exocytosis in parallel in adrenal chromaffin cells (García et al., 2006; Currie, 2010b). Membrane capacitance precisely reflects the surface area of a cell and transiently increases when secretory vesicles fuse with the plasma membrane. The magnitude of this increase (∆Cm) reflects the number of vesicles that has undergone exocytosis. We used perforated whole-cell recordings to measure I$_{\text{Ca}}$ and ∆Cm evoked by two 100-ms steps from −80 to +10 mV (Fig. 7A) in chromaffin cells isolated from wild-type mice. As already noted, cells could be separated into two groups based on the response of I$_{\text{Ca}}$ to the application of PGE$_2$. In this particular series of experiments, PGE$_2$ (100 nM) inhibited the peak amplitude of I$_{\text{Ca}}$ in 7 of 12 cells (group 1) by 41 ± 10% (n = 7; p < 0.005) but had no effect in the remaining 5 cells (group 2) (3 ± 4% decrease; n = 5; p = 0.41) (Fig. 7B). Application of 100 nM PGE$_2$ significantly reduced ∆Cm in group 1 (those cells in which I$_{\text{Ca}}$ was abolished by PGE$_2$). The inhibition of I$_{\text{Ca}}$ by PGE$_2$ was abolished in cells isolated from EP3 receptor knockout mice (Fig. 6). As already noted, EP3 receptors. Under these conditions, any effect of sulprostone can be attributed to EP3 receptor signaling because the EP1 receptors are absent. Sulprostone inhibited I$_{\text{Ca}}$ in these EP1(-/-/-) chromaffin cells by 47 ± 12% (n = 4), an effect that was not significantly different from that seen in chromaffin cells from wild-type mice (41 ± 9%; n = 6). Taken together, our data using pharmacological approaches and knockout mice demonstrate the inhibition of I$_{\text{Ca}}$ by PGE$_2$ is mediated solely by EP3 receptors.

**Materials and Methods**
Perforated whole-cell recording was used to measure I$_{\text{Ca}}$ and Cm in chromaffin cells isolated from wild-type mice. A, voltage command (top), I$_{\text{Ca}}$ (middle), and membrane capacitance (bottom) recorded from a representative cell. Two superimposed recordings are shown in the absence (control) and presence of 100 nM PGE$_2$. The stimulus (top) consisted of two step-depolarizations (100-ms duration) from −80 to +10 mV. A 1-kHz sine wave was superimposed on the holding potential to calculate membrane capacitance (see Materials and Methods for details) and this was interrupted during the step-depolarizations as indicated. B, peak amplitude of I$_{\text{Ca}}$ in the presence of PGE$_2$ was normalized to control I$_{\text{Ca}}$ amplitude in the same cell (control, control). Cells were separated into two groups based on the response of I$_{\text{Ca}}$ to application of PGE$_2$: group 1 (n = 7 of 12 cells), in which PGE$_2$ significantly reduced the amplitude of I$_{\text{Ca}}$, and group 2 (n = 5 of 12 cells), in which PGE$_2$ did not inhibit I$_{\text{Ca}}$ (p > 0.05 comparing group 1 and group 2 in the presence of PGE$_2$). C, the change in membrane capacitance (∆Cm) in response to stimulation in the presence of PGE$_2$ was normalized to ∆Cm in control conditions in the same cell. D, (group 1) data from cells in which I$_{\text{Ca}}$ was inhibited (7 of 12 cells), and the E (group 2) show data from cells in which I$_{\text{Ca}}$ was not inhibited. ∆Cm was reduced in both groups but the inhibition was significantly greater in group 1 compared with group 2 (p < 0.05) (i.e., in those cells in which I$_{\text{Ca}}$ was also reduced).
inhibited) from 153 ± 40 fF to 68 ± 16 fF (n = 7, p < 0.03). ∆Cm was also significantly smaller during application of PGE₂ in group 2, even though I_{Ca} was not reduced in these cells (Fig. 7C). This might reflect other pathways activated by PGE₂ to control exocytosis independent of I_{Ca} and/or time-dependent rundown of the exocytotic response, but these possibilities will require further investigation. It is noteworthy that the inhibition of ∆Cm was significantly greater in group 1 cells (in which I_{Ca} was also reduced) compared with group 2 cells (49 ± 7%, n = 7 compared with 24 ± 4%, n = 5; p < 0.02) (Fig. 7C), consistent with the idea that inhibition of Ca²⁺ entry by PGE₂ leads to a parallel inhibition exocytosis as reported for other G_{i/o}-coupled GPCRs (Harkins and Fox, 2000; Powell et al., 2000; Ulate et al., 2000).

Discussion

Previous work has suggested that PGE₂ might modulate adrenal chromaffin cells, although the effects and EP receptors involved remained unclear. The synthetic enzymses for PGE₂ are present in the adrenal medulla, and cholinergic stimulation leads to release of prostaglandins from the intact adrenal gland (Ramwell et al., 1966). Furthermore, an in vivo analysis showed that systemic immune challenge or circulating cytokines rapidly recruited dendritic cells and macrophages to the adrenal gland and increased the expression of COX-2 and PGE synthase (Engström et al., 2008). Thus, periods of inflammation or stress might boost the production of PGE₂ within the adrenal gland. We reported previously that PGE₂ inhibited I_{Ca} in bovine chromaffin cells, although the receptor(s) and detailed mechanisms were not determined (Currie et al., 2000). In contrast, others reported that PGE₂ stimulated calcium influx (Mochizuki-Oda et al., 1991) or released calcium from a ryanodine-sensitive intracellular store, an effect attributed to EP1 receptors (Shibuya et al., 1999). It has also been reported that PGE₂ inhibited nicotinic ACh receptors in sympathetic neurons (Tan et al., 1998). To our knowledge, this has not been tested in chromaffin cells, but if it were to occur, it could reduce cholinergic excitation/membrane depolarization and thereby opening of voltage-gated calcium channels.

In the current article, we report that PGE₂ inhibited I_{Ca, h} in mouse chromaffin cells through pertussis toxin-sensitive G proteins. The inhibition was voltage-dependent (reversed by strong membrane depolarization) and preferentially targeted Ca²⁺-sensitive calcium channels (N- and P/Q-type channels). Thus, PGE₂ mimicked agonists of other G_{i/o}-coupled GPCRs, including P2Y receptors that inhibit I_{Ca} in chromaffin cells (Albillos et al., 1996; Currie and Fox, 1996; Powell et al., 2000). The inhibition by PGE₂ bore all of the hallmarks of that mediated by Gβγ subunit binding to the calcium channels (Currie, 2010a). To unequivocally identify the EP receptor subtype(s) involved, we used cells isolated from knockout mice that lack either the EP3 or EP1 receptors. To complement this genetic approach, we used selective pharmacological tools, including a recently described EP3 receptor antagonist, DG-041 (Heptinstall et al., 2008). Because this compound was not readily available, it was made in the Vanderbilt Institute for Chemical Biology Chemical Synthesis Core. Our data provide conclusive evidence that EP3 receptors mediated the inhibition of I_{Ca} by PGE₂ in chromaffin cells.

It should be noted that PGE₂ inhibited I_{Ca, h} in approximately three quarters of cells tested, presumably reflecting the expression of the EP3 receptor in this subpopulation of cells. In the rodent adrenal medulla 70 to 80% of chromaffin cells express phenylethanolamine N-methyltransferase, the enzyme that converts norepinephrine to epinephrine, so are termed “adrenergic” (Verhofstad et al., 1985). The remainder lack phenylethanolamine N-methyltransferase and are termed “noradrenergic.” There is evidence for differential expression of GPCRs in adrenergic versus noradrenergic cells (Renshaw et al., 2000), so it is interesting to speculate that EP3 receptor expression might be limited to the adrenergic cells and preferentially modulate epinephrine release. Further work is required to determine whether this is the case. It is also noteworthy that the EP3 receptor undergoes alternative splicing, leading to sequence diversity in the cytoplasmic C terminus (Breyer et al., 2001). In recombinant systems, all of the splice variants couple to G_{i/o}-type G proteins but can also couple differentially to other effectors, including G_{s} and G_{q/11}-RhoA. Because extracellular ligand binding is not altered, pharmacological distinction of the EP3 splice variants is not possible. Four alternatively spliced variants of the EP3 receptor have been identified in a bovine chromaffin cell line library (Namba et al., 1993), and we detected mRNA for all three murine splice variants (EP3α, EP3β, and EP3γ) in the adrenal gland using RT-PCR (Fig. 4). However, a more detailed molecular analysis will be required to determine which splice variants are expressed in chromaffin cells and if additional non-G_{i/o}-coupled signaling pathways are recruited.

In contrast to some previous reports (Mochizuki-Oda et al., 1991; Shibuya et al., 1999), we found no evidence that PGE₂ can directly elevate [Ca²⁺]i (Fig. 3C). PGE₂ had no effect on the holding current needed to voltage-clamp cells at −80 mV (i.e., did not open/close any channels) (Fig. 3A) and had no effect on resting [Ca²⁺]i in Fura-2-loaded cells (Fig. 3C). It is possible that there are species differences in the expression of the EP receptor subtype(s) because none of the previous studies used mice. We also found that PGE₂ had no effect on the peak amplitude of whole-cell nicotinic ACh receptor currents evoked by bath application of carbachol for 45 s (Fig. 3, A and B). However, we did note that there was a modest increase in current decay during the sustained application of carbachol in the presence of PGE₂ (21 ± 3%; p < 0.01 compared with 9 ± 2%). Although “nondesensitizing α3β4*-containing channels predominate in chromaffin cells, several other nicotinic receptor subunits are expressed in a species-dependent manner, including the rapidly desensitizing α7 subunit (López et al., 1998; Sala et al., 2008). In chick sympathetic neurons, PGE₂ inhibited the whole-cell nicotinic current, but closer analysis revealed opposing effects on different channel subtypes. In particular, the dominant 36-pS channel was inhibited, but a 23-pS channel probably mediated by α7 containing receptors was potentiated by PGE₂ (Du and Role, 2001). Further studies using fast, brief agonist applications are needed to fully address the effects of PGE₂ on nicotinic receptors, but our data do suggest that the predominant nondesensitizing nAChR current (α3β4* receptors) is probably not a major target for PGE₂ modulation of chromaffin cell function.

Previous studies investigating the effects of PGE₂ on catecholamine secretion have all used large populations of cul-
tured chromaffin cells or intact adrenal gland preparations and present somewhat inconclusive findings. In some cases, PGE₂ inhibited release (Karaplis et al., 1989), whereas others report that PGE₂ potentiated release (Marley et al., 1988; Yamada et al., 1988; Yokohama et al., 1988). As discussed above, high concentrations of PGE₂ used in some of these studies raise the possibility of non-EP receptor involvement. Our data demonstrate for the first time that EP3 receptors use the same mechanism as P2Y, α2-adrenergic, and μ-opioid receptors to inhibit voltage-gated calcium channels in chromaffin cells. Typically, such inhibition of Iₘₜₜ by GPCRs is paralleled by an inhibition of Ca²⁺-dependent exocytosis, the mechanism that underlies vesicular catecholamine release (Harkins and Fox, 2000; Powell et al., 2000; Ulate et al., 2000). Exocytosis can be monitored in individual cells by tracking changes in membrane capacitance (ΔCm) that precisely reflect the surface area of a cell. The magnitude of ΔCm reflects the number of vesicles that have undergone exocytosis. As reported previously for other GPCRs, the application of PGE₂ led to a robust inhibition of ΔCm (49 ± 7%) that paralleled inhibition of Iₘₜₜ (41 ± 10%) (Fig. 7). There was also a modest decrease in ΔCm (24 ± 4%) in cells that showed no inhibition of Iₘₜₜ. This might reflect a time-dependent rundown of the exocytotic response or the possibility that other mechanisms are recruited to control secretion. Gβγ-mediated inhibition of catecholamine release independent from Iₘₜₜ modulation has been reported for other Gₛₒₜ-coupled receptors (Chen et al., 2005; Yoon et al., 2008). We also detected mRNA for EP1, 2, and 4 receptors in the mouse adrenal gland, in addition to all three splice variants of the EP3 receptor (Fig. 4). Further detailed investigations will be required to determine whether these receptors are expressed in chromaffin cells and what functional affect they might have. However, our data clearly show that the inhibition of ΔCm was significantly greater when Iₘₜₜ was also reduced (49 ± 7%, n = 7 compared with 24 ± 4%, n = 5; p < 0.02) (Fig. 7C), supporting the idea that inhibition of Ca²⁺ entry by PGE₂ leads to a parallel inhibition exocytosis as reported for other Gₛₒₜ-coupled GPCRs (Harkins and Fox, 2000; Powell et al., 2000; Ulate et al., 2000).

To summarize, there is growing interest in developing subtype-selective EP receptor drugs as therapeutic agents for a variety of disorders, so identifying the physiological roles distinct receptors play will be important for interpreting and predicting the affect of these drugs. We have used a powerful combination of pharmacology and cells isolated from receptor knockout mice to demonstrate that prostaglandin EP3 receptors inhibit Iₘₜₜ in adrenal chromaffin cells and that this results in a parallel inhibition of Ca²⁺-dependent exocytosis. To our knowledge, this is the first study of EP receptor signaling in mouse chromaffin cells and identifies a cellular/molecular mechanism for paracrine regulation of neuroendocrine function by PGE₂.

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Authorship Contributions
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Conducted experiments: Jewell.

Contributed new reagents or analytic tools: Breyer.
Performed data analysis: Jewell and Currie.
Wrote or contributed to the writing of the manuscript: Jewell, Breyer, and Currie.

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References


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