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RESEARCH PAPER

Novel vasocontractile role of the $P2Y_{14}$ receptor: characterization of its signalling in porcine isolated pancreatic arteries

M Alsaqati, M L Latif, S L F Chan and V Ralevic

Life Sciences, University of Nottingham, Nottingham, UK

Correspondence
Dr Vera Ralevic, School of Life Sciences, University of Nottingham, Nottingham NG7 2UH, UK. E-mail: vera.ralevic@nottingham.ac.uk

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BACKGROUND AND PURPOSE

The $P2Y_{14}$ receptor is the newest member of the P2Y receptor family; it is $G_{i/o}$ protein-coupled and is activated by UDP and selectively by UDP-glucose and MRS2690 (2-thiouridine-5′-diphosphoglucose) (7–10-fold more potent than UDP-glucose). This study investigated whether $P2Y_{14}$ receptors were functionally expressed in porcine isolated pancreatic arteries.

EXPERIMENTAL APPROACH

Pancreatic arteries were prepared for isometric tension recording and UDP-glucose, UDP and MRS2690 were applied cumulatively after preconstriction with U46619, a TxA_2 mimetic. Levels of phosphorylated myosin light chain 2 (MLC2) were assessed with Western blotting. cAMP concentrations were assessed using a competitive enzyme immunoassay kit.

KEY RESULTS

Concentration-dependent contractions with a rank order of potency of MRS2690 (10-fold) > UDP-glucose ≥ UDP were recorded. These contractions were reduced by PPTN {4-[4-(piperidin-4-yl)phenyl]-7-[4-(trifluoromethyl)phenyl]-2-naphthoic acid}, a selective antagonist of $P2Y_{14}$ receptors, which did not affect responses to UTP. Contraction to UDP-glucose was not affected by MRS2578, a $P2Y_6$ receptor selective antagonist. Raising cAMP levels and forskolin, in the presence of U46619, enhanced contractions to UDP-glucose. In addition, UDP-glucose and MRS2690 inhibited forskolin-stimulated cAMP levels. Removal of the endothelium and inhibition of endothelium-derived contractile agents (TxA_2, $PGF_{2\alpha}$ and endothelin-1) inhibited contractions to UDP glucose. Y-27632, nifedipine and thapsigargin also reduced contractions to the agonists. UDP-glucose and MRS2690 increased MLC2 phosphorylation, which was blocked by PPTN.

CONCLUSIONS AND IMPLICATIONS

$P2Y_{14}$ receptors play a novel vasocontractile role in porcine pancreatic arteries, mediating contraction via cAMP-dependent mechanisms, elevation of intracellular Ca^{2+} levels, activation of RhoA/ROCK signalling and MLC2, along with release of TxA_2, $PGF_{2\alpha}$ and endothelin-1.

Abbreviations

IP_3, inositol 1,4,5-triphosphate; MLC2, myosin light chain 2; NDGA, nordihydroguiaretic acid; PPADS, pyridoxalphosphate-6-azophenyl-2′,4′-disulfonic acid); PPTN, 4-(4-(Piperidin-4-yl)phenyl)-7-(4-(trifluoromethyl)phenyl)-2-naphthoic acid; RhoA, ras homolog gene family member A; ROCK, Rho-associated protein kinase; SNP, sodium nitroprusside; UDP-glucose, uridine diphosphate glucose

Introduction

P2Y receptors are members of the superfamily of GPCRs; they are responsive to purine and pyrimidine nucleotides and nucleotide sugars [ADP, ATP, uridine-5′-triphosphate (UTP), uridine diphosphate (UDP) and UDP-glucose]. Eight mammalian subtypes of P2Y receptors have been identified: $P2Y_1$, $P2Y_2$, $P2Y_4$, $P2Y_6$, $P2Y_{11}$, $P2Y_{12}$, $P2Y_{13}$ and $P2Y_{14}$ receptors

(Abbracchio *et al.*, 2006; receptor nomenclature follows Alexander *et al.*, 2013). The $P2Y_{14}$ receptor was the most recently identified (Chambers *et al.*, 2000). In contrast to other P2Y receptors, $P2Y_{14}$ receptors are activated by nucleotide sugars such as UDP-glucose, in addition to UDP-galactose and UDP-glucuronic acid that are less potent than UDP-glucose (Abbracchio *et al.*, 2003; Fricks *et al.*, 2008; Harden *et al.*, 2010). They are also activated by UDP and MRS2690 (2-thiouridine-5′-diphosphoglucose), which is more selective at $P2Y_{14}$ receptors and 7–10-fold more potent than UDP-glucose (Carter *et al.*, 2009; Jacobson *et al.*, 2009; Gao *et al.*, 2010). The $P2Y_{14}$ receptor is involved in G_i-protein-mediated signalling, leading to the inhibition of AC activity and, accordingly, is sensitive to *Pertussis* toxin (PTX) (Jacobson *et al.*, 2009). G_i-protein-derived $G_{\beta\gamma}$ dimers can initiate PLC_β signalling pathways, which leads to the stimulation of DAG and inositol 1,4,5-triphosphate (IP_3) and subsequent activation of RhoA/ROCK (Rho-associated protein kinase) signalling, PKC and myosin light chain (MLC) kinase, besides elevation of the intracellular calcium level (Amano *et al.*, 1996; Hartshorne and Gorecka, 2011; Sesma *et al.*, 2012).

Pyridoxalphosphate-6-azophenyl-2′,4′-disulfonic acid (PPADS) and suramin are non-selective antagonists at most of the P2Y receptors, but some P2Y receptors are insensitive to these antagonists (Chootip *et al.*, 2005). There is currently no report of antagonist sensitivity of $P2Y_{14}$ receptors for suramin and PPADS. Recently, a novel antagonist at $P2Y_{14}$ receptors was identified; this antagonist, 4-[4-(piperidin-4-yl)phenyl]-7-[4-(trifluoromethyl)phenyl]-2-naphthoic acid (PPTN) (Barrett *et al.*, 2013), was characterized in HEK cells through its ability to inhibit UDP-glucose-stimulated Ca^{2+} mobilization (Robichaud *et al.*, 2011). In addition, it showed good affinity for the $P2Y_{14}$ receptor (K_i = 1.9 nM in a chimpanzee $P2Y_{14}$ binding assay) (Robichaud *et al.*, 2011). When it was studied in human C6 glioma cells, PPTN showed selectivity for $P2Y_{14}$ receptors with a K_B of 434 pM, with no agonist or antagonist affinity at $P2Y_1$, $P2Y_2$, $P2Y_4$, $P2Y_6$, $P2Y_{11}$, $P2Y_{12}$ or $P2Y_{13}$ receptors (Barrett *et al.*, 2013).

$P2Y_{14}$ receptor mRNA and protein have a varied expression in the body; they have been found in the spleen, placenta, lung, heart, adipose tissue, gastrointestinal smooth muscle, endothelial cells and immune cells (Chambers *et al.*, 2000; Scrivens and Dickenson, 2005; Umapathy *et al.*, 2010). Relatively little is known, however, about the functional expression of the $P2Y_{14}$ receptor. The best characterized role is in regulation of the immune system, as a number of studies have described an involvement of $P2Y_{14}$ receptors in modulation of the function of human neutrophils and T-lymphocytes, and in secretion of the pro-inflammatory cytokine IL-8 in airway epithelial cells (Scrivens and Dickenson, 2005; 2006; Jacobson *et al.*, 2009). UDP-glucose can be released in a constitutive manner and during shear stress, to act as an extracellular signalling molecule (Lazarowski *et al.*, 2003); its release from multiple cell types suggests potentially broad role(s) of the $P2Y_{14}$ receptor.

Although the exact mechanisms remain to be established, an increase in pancreatic endocrine cell activity during hormone secretion corresponds to an increase in blood flow, to meet metabolic demand. Thus, alterations in blood flow can influence pancreatic function. The role of exogenous purine and pyrimidine di- and triphosphate nucleotides in controlling the functions of endocrine and exocrine components of the pancreas are well described (Novak, 2008; Burnstock and Novak, 2012). Within the pancreatic vasculature, P2X receptors were suggested to mediate vasoconstriction, and P2Y receptors vasodilatation, in response to ATP (Hillaire-Buys *et al.*, 1991). P2X1, $P2Y_2$, $P2Y_4$ and $P2Y_6$ receptors, with different sensitivities to ATP, UDP and UTP, mediate vasoconstriction in a number of blood vessels (Ralevic and Burnstock, 1998), and there is some evidence for a vasocontractile function of the $P2Y_{12}$ receptor (Wihlborg *et al.*, 2004; Högberg *et al.*, 2010). In the current study, we describe the pharmacological characterization of $P2Y_{14}$ receptor-mediated contractile responses of porcine isolated pancreatic artery preparations. A preliminary account of some of these data has previously been presented to the British Pharmacological Society (Alsaqati *et al.*, 2010).

Methods

Tissue preparation

Pancreases from pigs (either sex, age less than 6 months, weighing ~50 kg) were obtained on ice from a local abattoir (G Wood & Sons Ltd, Mansfield, UK). A crude dissection was conducted to isolate the pancreatic arteries (greater pancreatic artery), which were located in the body of the pancreas. The vessels were dissected out and placed in Krebs–Henseleit buffer containing 2% (w/v) Ficoll (type 70) and refrigerated overnight at 4°C. The next day, fine dissection was performed, and the arteries were cut into rings of 0.5 cm in length and suspended in Krebs–Henseleit buffer (gassed, 95% O_2, 5% CO_2).

The endothelium of some arteries was removed by gently rubbing their innermost surface with forceps before attaching them to the set-up (Rayment *et al.*, 2007a). Successful removal of endothelium was tested using substance P (10 nM). Endothelium-denuded arteries relaxed in response to substance P to less than 10% of the U46619 (11α,9α-epoxymethano-PGH_2)-induced contraction, while in endothelium-intact arteries, the relaxation to substance P was 36 ± 8% (n = 7).

Responses in the porcine isolated pancreatic artery

Arterial rings were mounted onto wires in tissue baths (20 mL) containing warm (37°C), oxygenated Krebs–Henseleit solution and were connected via isometric force transducers (ADInstruments, Sydney, Australia) to a PC running the computer program LabChart (ADInstruments). Rings were put under tension (15 g) and allowed to equilibrate for 60 min before assessing viability with two challenges of 75 mM KCl. The tissues were then allowed to equilibrate for 60 min, after which U46619 (10–100 nM), a TxA_2 mimetic, was used to contract the tissues to between 40 and 80% of the second KCl response. This ensured that if there was a vasodilator component to the response, for example, due to activation of multiple P2 receptor subtypes, this could be detected. Once an appropriate level of U46619 response had been achieved, cumulative addition of UDP-glucose, UDP or MRS2690 was applied. Antagonists or inhibi-

tors were applied 10 min prior to the addition of U46619, allowing incubation with the tissues for a minimum of 30 min before the application of agonists. Desensitization of the contraction to UDP-glucose was generated by exposing the arteries to UDP or UDP-glucose, 10 min before the addition of U46619. An exception to preconstriction with U46619 were experiments with L-655,240 {1-[(4-chlorophenyl)methyl]-5-fluoro-α,α,3-trimethyl-1*H*-indole-2-propanoic acid}, in which arteries were preconstricted with endothelin-1. In experiments using DMSO as the solvent (see Materials), DMSO was added to the arteries (vehicle control).

Effect of forskolin on subsequent UDP-glucose or UTP responses

Tissues were exposed to U46619 (10–100 nM) and relaxed with forskolin (1 μM), involving elevation of cAMP, back to the baseline; cumulative concentration–response curves were then constructed for UDP-glucose (1 μM–1 mM) or UTP (10 μM–1 mM). Responses to UDP-glucose or UTP obtained under these conditions were compared with control responses in which drugs were added at basal tone without exposing to either U46619 or forskolin. The tissue was allowed to recover for 20 min before a concentration–response curve to UDP-glucose or UTP was constructed.

Western blotting

Segments of porcine pancreatic arteries were set up in the organ baths under a tension of 15 g and then left for approximately 60 min to reach a new baseline of resting tension. Tissues were incubated with 100 μM UDP-glucose for 30, 60, 120, 180, 240 and 300 s. In addition, in other experiments, the tissues were incubated with UDP-glucose (100 μM) or MRS2690 (10 μM) for 30 s in the presence or absence of PPTN. Segments were quickly removed from the organ baths and immediately frozen on dry ice. Control tissues were not exposed to any compound (basal conditions). Segments were then homogenized in lysis buffer [20 mM Tris, 1 mM EGTA, 0.1% (v/v) Triton X-100, 1 mM NaF, 10 mM β-glycerophosphate, pH 7.6], containing protease inhibitor cocktail tablets, EDTA free. Samples with solubilization buffer 6 × SB [24% (w/v) SDS, 30% (v/v) glycerol, 5% (v/v) β-mercaptoethanol, 2.5% (v/v) bromophenol blue, 1.5 M Tris–HCl, pH 6.8] were heated at 95°C for 5 min. Subsequently, electrophoresis was carried out on 4–20% Tri-Glycine (PAGE) Gold Precast Gels (Bio-Rad, Hercules, CA, USA), 15 μg protein per lane. Samples were transferred to nitrocellulose membranes. Next, blots were incubated in blocking solution [5% (w/v) powdered milk in Tris-buffered saline containing 0.1% (v/v) Tween 20; Fisher Scientific UK Ltd., Loughborough, UK] for 60 min at room temperature. Blots were incubated overnight at 4°C with primary antibody against phosphorylated myosin light chain kinase 2 (pMLC2, 1:500) or total (MLC2, 1:1000) diluted in blocking solution. After washing in Tris-buffered saline containing 0.1% (v/v) Tween 20, the blots were incubated with an appropriate IRDye®-conjugated secondary antibody (Li-Cor Biosciences, Biotechnology, Lincoln, NE, USA). Proteins were visualized using the Li-Cor/Odyssey infrared imaging system. Bands were analysed by densitometry using the Odyssey application software and expressed as phosphorylated MLC2 normalized to total MLC2.

cAMP measurement in porcine pancreatic arteries

Pancreatic artery rings were stimulated with 75 mM KCl followed by U46619 (10 nM) and forskolin (1 μM), and then the arteries were challenged for 3 min with UDP-glucose (1 mM), MRS2690 (10 μM), UTP (1 mM) or distilled water (control group). Pancreatic artery rings were collected and immediately frozen on dry ice and then stored in vials at –80°C until their study. The tissues were homogenized in 5% (w/v) trichloroacetic acid (TCA) in water with a borosilicate glass homogenizer and then centrifuged for 10 min at 1500× *g*. TCA was extracted from the supernatant samples using water-saturated ether and evaporated for 5 min to remove the residual ether from the aqueous fractions. Samples were diluted (1:2) in ether-extracted 5% (w/v) TCA. cAMP concentration was measured using a competitive enzyme immunoassay (EIA) kit (Cayman Chemical Co., Ann Arbor, MI, USA). The working range of the cAMP assay was 0.1–1000 pmol·mL^{-1}. cAMP concentration was expressed as a percentage of forskolin-induced [cAMP] elevation.

Data analysis

Data were expressed as log concentration–response plots. The contraction to all agonists was expressed in g, and measured from the stabilized U46619 response. Values for all figures refer to mean ± SEM with 95% confidence. Results were compared by two-way ANOVA or Student's unpaired *t*-test (Prism; GraphPad, San Diego, CA, USA). Differences were considered to be significant when the *P*-value was <0.05. *n* expresses the number of animals.

Materials

Krebs–Henseleit buffer was of the following composition (mM): NaCl 118, KCl 4.8, $CaCl_2{\cdot}H_2O$ 1.3, $NaHCO_3$ 25.0, KH_2PO_4 1.2, $MgSO_4{\cdot}1.2$ and glucose 11.1. Suramin, nordihydroguaiaretic acid (NDGA), nifedipine, thapsigargin, UTP, U46619, sodium nitroprusside (SNP), zafirlukast, BQ788 (*N-cis*-2,6-dimethylpiperidinocarbonyl-L-gmethylleucyl-D-1-methoxycarboyl-D-norleucine), UDP-glucose and UDP were purchased from Sigma (Poole, Dorset, UK), while DUP 697, MRS2578 {*N*,*N*″-1,4-butanediyl *bis*[*N*′-(3-isothiocynatophenyl)] thiourea}, PPADS and substance P, MRS2690, L-655,240, endothelin-1, BQ123 [*cyc*(DTrp-DAsp-Pro-D-Val-Leu)], Y-27632 {*trans*-4-[(1R)-1-aminoethyl]-N-4-pyridinyl-cyclohexane carboxamide} and forskolin were from Tocris Biosciences Ltd. (Bristol, UK). PPTN, a selective high-affinity antagonist of $P2Y_{14}$ receptor, was a gift from Merck Frosst Centre for Therapeutic Research. Primary antibodies for Western blotting were purchased from Cell Signaling Technology (Danvers, MA, USA) for phosphorylated MLC2 antibody (Cat No. 3674S) and total MLC2 antibody (Cat No. 3672). cAMP EIA kit (Cat No. 581001) was purchased from Cayman Chemical Company. U46619 was dissolved in ethanol at 10 mM stock concentration. DUP 697, PPTN, BQ788, MRS2578, L-655,240, nifedipine, thapsigargin, zafirlukast and forskolin were dissolved in DMSO. All other drugs were dissolved in distilled water.

Results

Effect of UDP-glucose, UDP and MRS2690 in porcine isolated pancreatic arteries

To investigate the possible functional expression of $P2Y_{14}$ receptors and their role in porcine pancreatic arteries, agonists for this receptor were applied as cumulative concentrations. MRS2690, a selective $P2Y_{14}$ receptor agonist (0.1–30 μM), UDP-glucose (1 μM–1 mM) and UDP (1 μM–1 mM) were added after preconstriction with U46619. All of the agonists induced a concentration-dependent contraction with a rank order of potency of MRS2690 > UDP-glucose ≥ UDP. MRS2690 was significantly more potent, by approximately 10-fold, than UDP-glucose ($P < 0.01$, two-way ANOVA; Figure 1A), while UDP-glucose and UDP responses were equipotent (Figure 1A). In other experiments, pre-exposure of the arteries to both UDP-glucose and UDP ($P2Y_{14}$ receptor agonists) separately induced significant attenuation of the contraction to UDP-glucose; for instance, the response to 100 μM UDP-glucose was decreased by 55 ± 7% in the presence of 100 μM UDP-glucose and by 53 ± 7% in the presence of 100 μM UDP ($P < 0.001$, n = 10–13; Figure 1B).

Effect of PPADS and suramin on responses to UDP-glucose, UDP and MRS2690 in porcine isolated pancreatic arteries

Responses to UDP-glucose, UDP and MRS2690 were characterized using the non-selective P2 receptor antagonists PPADS (10 μM) and suramin (100 μM) (Rayment *et al.*, 2007b). Both PPADS and suramin significantly enhanced the contractions evoked by UDP-glucose and UDP (Figure 2A,B). The contraction to 100 μM UDP-glucose was enhanced by 121 ± 38% ($P < 0.001$, n = 7) and 100 ± 23% ($P < 0.001$, n = 8) in the presence of PPADS and suramin respectively (Figure 2A). The contraction to 1 mM UDP was enhanced by 180 ± 46% ($P < 0.001$, n = 8) and 154 ± 30% ($P < 0.001$, n = 8) in the presence of PPADS and suramin respectively (Figure 2B). Suramin and PPADS failed to alter the contraction to MRS2690 (Figure 2C). In contrast, suramin and PPADS blocked the contraction to UTP, a $P2Y_2$ and $P2Y_4$ receptor agonist (von Kügelgen, 2006; M. Alsaqati, unpubl. obs.). UDP is a ligand at $P2Y_6$ receptors as well as $P2Y_{14}$ receptors. Therefore, the effect of UDP was examined in the presence of MRS2578 (10 μM), a $P2Y_6$ receptor selective antagonist (Mamedova *et al.*, 2004). The contraction evoked by UDP was unaffected at lower concentrations but was augmented at higher concentrations of UDP (Supporting Information), while MRS2578 did not alter the responses to UDP-glucose or MRS2690 (Supporting Information).

Effect of PPTN, a selective high-affinity antagonist of $P2Y_{14}$ receptor, on responses to UDP-glucose and MRS2690 in porcine isolated pancreatic arteries

The responses to UDP-glucose and MRS2690 were examined in the presence of PPTN (1 μM), a selective high-affinity antagonist of $P2Y_{14}$ receptors (Robichaud *et al.*, 2011; Barrett *et al.*, 2013). This compound significantly reduced the contraction evoked by UDP-glucose at basal tone (Supporting Information) and that by UDP-glucose and MRS2690 at raised tone (Figure 3A,B). PPTN inhibited the contraction to 100 μM UDP-glucose and 10 μM MRS2690 by 55 ± 10% ($P < 0.05$, n = 7) and 46 ± 9% ($P < 0.01$, n = 9) respectively (Figure 3A,B). The contraction to UTP was not altered in the presence of PPTN (Figure 3C). Typical traces, showing the effect of MRS2690 in the absence and presence of PPTN, are shown in Figure 3D.

Effect of endothelium removal on responses to UDP-glucose, UDP and MRS2690 in porcine isolated pancreatic arteries

The responses of UDP-glucose, UDP and MRS2690 were studied after the endothelium had been removed. The contractions induced by UDP-glucose, UDP and MRS2690 were significantly attenuated in the endothelium-denuded arteries (Figure 4). Removal of endothelium reduced the contractions

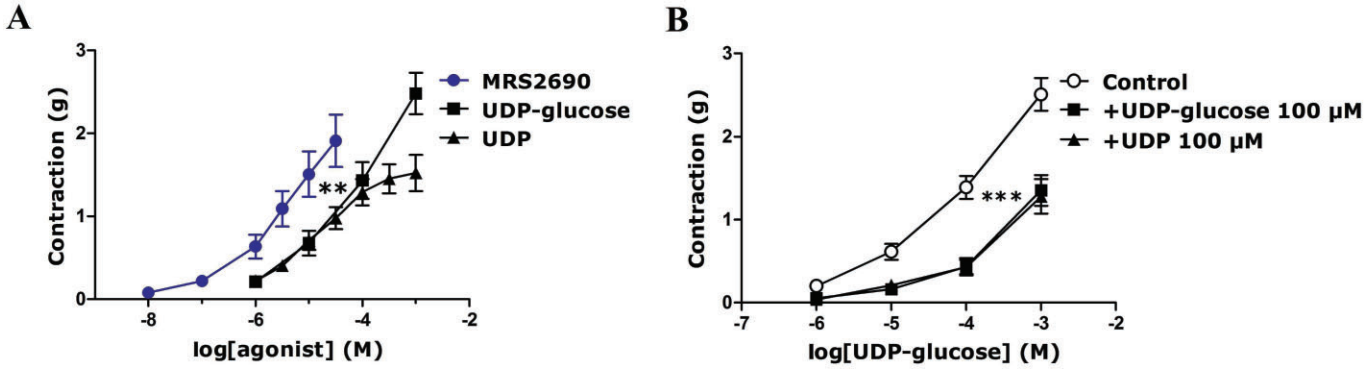

Figure 1

(A) Concentration-dependent contractions evoked by UDP-glucose, UDP and MRS2690 in U46619-preconstricted porcine pancreatic arteries (**$P < 0.01$, two-way ANOVA, MRS2690 response vs. UDP-glucose and UDP responses, F = 13.74, 16.03; n = 9–12). (B) Attenuation of UDP-glucose-induced contraction (the control) in the presence of UDP-glucose (100 μM) and UDP (100 μM) (added 10 min prior to U46619 addition). Both UDP-glucose and UDP significantly attenuated the contraction evoked by UDP-glucose (***$P < 0.001$, two-way ANOVA, UDP-glucose contraction in the absence or presence of UDP-glucose or UDP, F = 63.11, 56.48; n = 10–13). Data are presented as mean ± SEM.

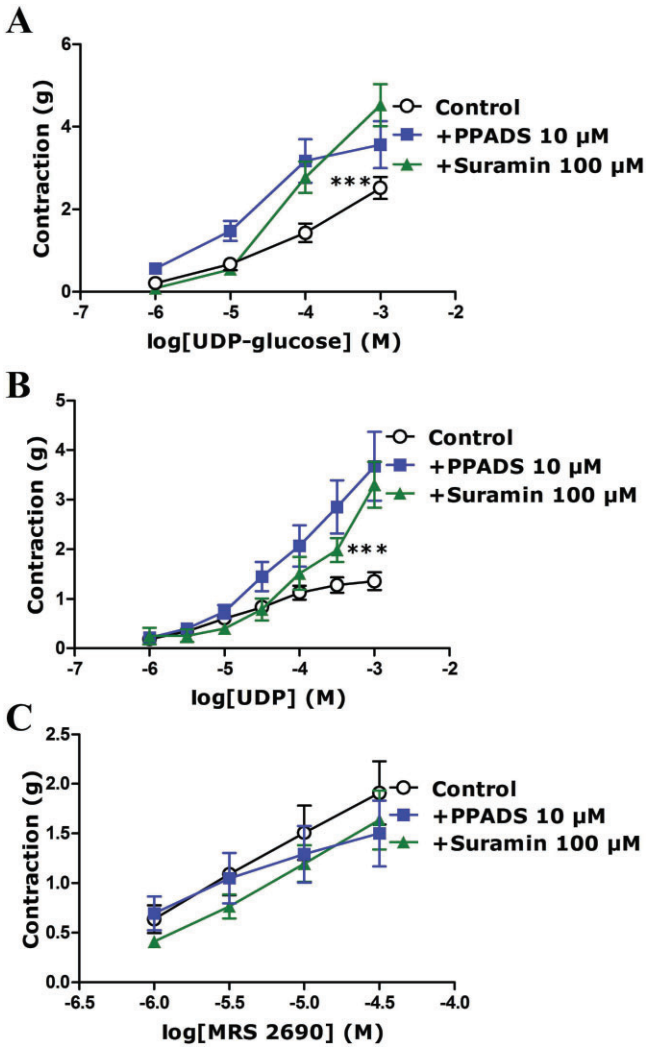

Figure 2

Effect of PPADS (10 μM) and suramin (100 μM) on responses to (A) UDP-glucose, (B) UDP and (C) MRS2690 in U46619-preconstricted porcine pancreatic arteries. (A) Suramin and PPADS enhanced the effects of UDP-glucose (***P < 0.001, two-way ANOVA, UDP-glucose with suramin or PPADS vs. UDP-glucose alone, F = 19.85, 23.07; n = 6–10). (B) Suramin and PPADS enhanced the effects of UDP (***P < 0.001, two-way ANOVA, UDP with suramin or PPADS vs. UDP alone, F = 16.83, 45.24; n = 8–16). (C) Suramin and PPADS had no effect on the contraction to MRS2690 (n = 5–9). Data are presented as mean ± SEM.

to 1 mM UDP-glucose by 50 ± 7% (P < 0.001, n = 12), that to 1 mM UDP by 61 ± 11% (P < 0.001, n = 15) and that to 30 μM MRS2690 by 41 ± 5% (P < 0.01, n = 5) (Figure 4).

Effect of DUP 697 on responses to UDP-glucose, UDP and MRS2690 in porcine isolated pancreatic arteries

Because the contractions to P2Y$_{14}$ receptor agonists were mainly endothelium dependent, these were studied in the presence of DUP 697, a COX-2 inhibitor, as COX-2 facilitates the release of agents that are responsible for endothelium-dependent contraction. DUP 697 (3 μM) diminished the responses to UDP-glucose, UDP and MRS2690 to a similar extent as removal of the endothelium (Figure 5), while DUP 697 did not alter the contraction to U46619 (the preconstriction agent) or the contraction to ATP (data not shown). DUP 697 reduced the contraction to 1 mM UDP-glucose by 34 ± 10% (P < 0.01, n = 11), that to 1 mM UDP by 38 ± 7.5% (P < 0.001, n = 15) and that to 30 μM MRS2690 by 22.5 ± 13% (P < 0.01, n = 4) (Figure 5).

The role of endothelium-derived contracting factors in the response to UDP-glucose in porcine isolated pancreatic arteries

The following experiments were carried out using mainly UDP-glucose or UDP due to the cost considerations involved with use of MRS2690. The possible involvement of TxA$_2$, LTs, endothelin-1 and PGF$_{2\alpha}$, which can be released from endothelial cells (Mombouli and Vanhoutte, 1993; Kurahashi *et al.*, 2003; Wong *et al.*, 2009), in endothelially mediated contraction to UDP-glucose was investigated. The contraction to UDP-glucose was not altered in the presence of NDGA (10 μM), a lipoxygenase inhibitor (Figure 6A), or zafirlukast (10 μM), an LT receptor inhibitor (Figure 6B). The contraction to UDP-glucose was reduced in the presence of BQ123 (1 μM), a selective ET$_A$ receptor antagonist; the response to 100 μM UDP-glucose was attenuated by 10 ± 3% (P < 0.05, n = 14) in the presence of BQ123 (Figure 6C), which was only effective in arteries with intact endothelium (Supporting Information). The contraction to UDP-glucose was unaltered in the presence of BQ788 (1 μM), a selective ET$_B$ receptor antagonist (Supporting Information). In addition, UDP-glucose induced-contraction was reduced in the presence of L-655,240 (1 μM), a selective TxA$_2$/PG endoperoxide receptor antagonist. The response to 100 μM UDP-glucose was inhibited by 38 ± 5% (P < 0.001, n = 9) in the presence of L-655,240 (Figure 6D). These data indicate that UDP-glucose-mediated contraction occurs mainly via thromboxane and PGs, with a lesser involvement of endothelin-1.

Effect of inhibition of calcium release and calcium entry on the response to UDP-glucose and UDP in porcine isolated pancreatic arteries

Binding of agonist to the recombinant P2Y$_{14}$ receptor leads to increase Ca^{2+} flux in some cells (Skelton *et al.*, 2003; Gao *et al.*, 2010). To test this in porcine pancreatic arteries, responses to UDP-glucose and UDP were examined in the presence and absence of nifedipine (1 μM), an L-type voltage-gated calcium channel blocker, and thapsigargin (100 nM), a potent inhibitor of sarco-endoplasmic reticulum Ca^{2+}-ATPases, which leads to depletion of intracellular calcium. Both of these inhibitors reduced the contraction evoked by 100 μM UDP-glucose, by 39 ± 5% (P < 0.001, n = 15) in the presence of nifedipine and by 25 ± 8% (P < 0.05, n = 12–15) in the presence of thapsigargin (Figure 7A,B). Responses to 100 μM UDP were inhibited by 53 ± 2% (P < 0.001, n = 9) in the presence of nifedipine and by 36 ± 6% (P < 0.001, n = 9) in the presence of thapsigargin (data not shown). Typical traces showing the effect of UDP-glucose in the absence and presence of nifedipine are shown in Figure 7C.

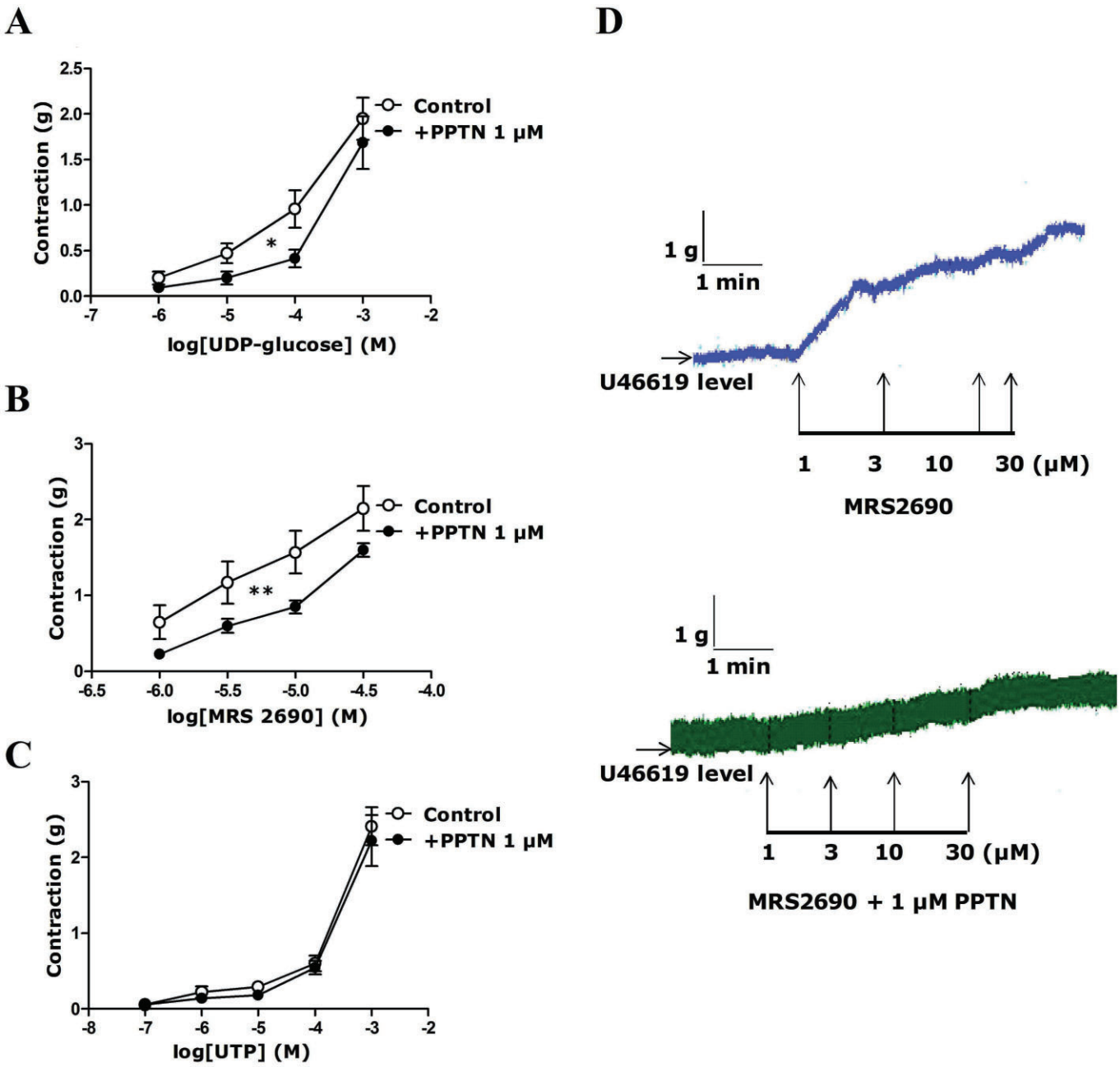

Figure 3

Effect of PPTN (1 µM), a $P2Y_{14}$ receptor antagonist, on responses to (A) UDP-glucose, (B) MRS2690 and (C) UTP in U46619-preconstricted porcine pancreatic arteries. (A) PPTN inhibited the effect of UDP-glucose (*$P < 0.05$, two-way ANOVA, $F = 6.56$; $n = 7$). (B) PPTN inhibited the effect of MRS2690 (**$P < 0.01$, two-way ANOVA, $F = 12.85$; $n = 9$). (C) PPTN had no effect on the response to UTP ($n = 8$–10). Data are presented as mean ± SEM. (D) Typical traces showing the effect of MRS2690 in the absence and presence of PPTN.

Effect of inhibition of the Rho-kinase pathway on the responses to UDP-glucose, UDP and MRS2690 in porcine isolated pancreatic arteries

Activation of $P2Y_{14}$ receptors may cause stimulation of RhoA/ROCK signalling (Sesma *et al*, 2012). To test the possible involvement of this pathway, experiments were conducted to study the contractions to UDP-glucose, UDP and MRS2690 in the presence of Y-27632 (5 µM), a selective inhibitor of the Rho-associated protein kinase, p160ROCK. Y-27632 significantly inhibited the contraction evoked by UDP (Figure 8A), MRS2690 (Figure 8B) and UDP-glucose (data not shown). For instance, the response to 300 µM UDP was reduced by 50 ± 4% ($P < 0.001$, $n = 15$; Figure 8A), that to 30 µM MRS2690 by 50 ± 15% ($P < 0.001$, $n = 9$; Figure 8B) and that to 1 mM UDP-glucose by 52 ± 8% ($P < 0.001$, $n = 9$, data not shown). The response to UDP-glucose was associated with an increase in the level of MLC2 phosphorylation, after 30–60 s of treat-

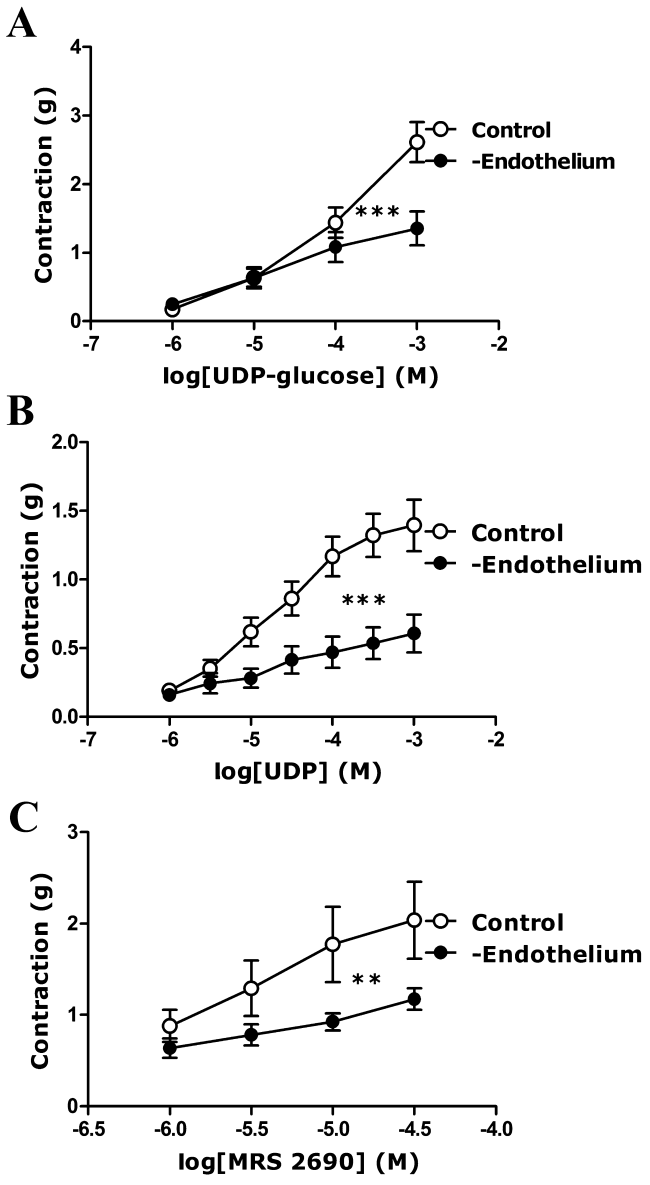

Figure 4

Effect of removal of the endothelium on responses to (A) UDP-glucose, (B) UDP and (C) MRS2690 in U46619-preconstricted porcine pancreatic arteries. The removal of endothelium reduced the contractions evoked by (A) UDP-glucose, (B) UDP and (C) MRS2690 (**$P < 0.01$, ***$P < 0.001$, two-way ANOVA, $F = 8.15$, 51.24, 9.48; $n = 4$–15). Data are presented as mean ± SEM.

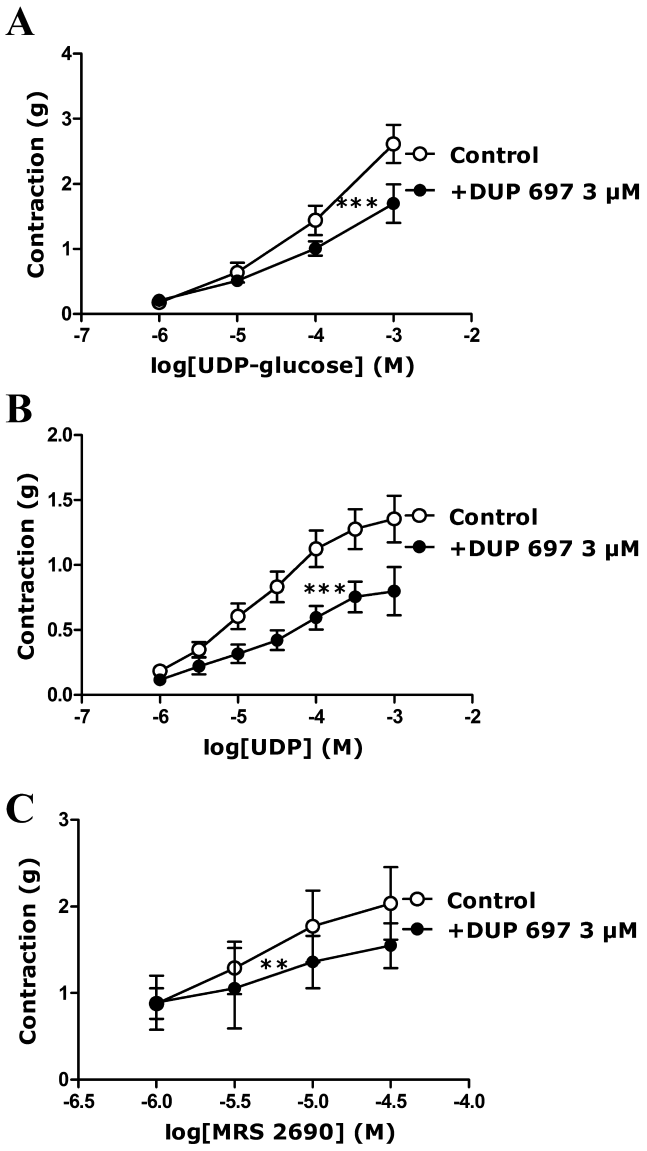

Figure 5

Effect of DUP 697 (3 μM) on responses to (A) UDP-glucose, (B) UDP, (C) MRS2690 in U46619-preconstricted porcine pancreatic arteries. DUP 697 inhibited the contractions evoked by (A) UDP-glucose, (B) UDP and (C) MRS2690 (** $P < 0.01$, *** $P < 0.001$, two-way ANOVA, $F = 7.85$, 35.31, 4.95; $n = 4$–15). Data are presented as mean ± SEM.

ment with 100 μM UDP-glucose, and returned to the basal level of phosphorylated MLC2 from 120 to 300 s (Figure 8C), which suggested an involvement of MLC2 activation in the response to UDP-glucose $P2Y_{14}$ receptor signalling pathway. The ability of UDP-glucose (100 μM) or MRS2690 (10 μM) to elevate the MLC2 phosphorylation (after 30 s of treatment) was abolished in the presence of PPTN (1 μM), which shows that the ability of UDP-glucose or MRS2690 to elevate MLC2 phosphorylation in porcine pancreatic arteries is mediated by $P2Y_{14}$ receptors (Figure 9).

Effect of pre-constriction with U46619, and relaxation with forskolin, on the response to UDP-glucose in porcine isolated pancreatic arteries

Agonist-promoted activation of G_i and subsequent inhibition of AC is one of the signalling responses of $P2Y_{14}$ receptors. Therefore, the response to UDP-glucose was tested after exposure to U46619 and subsequent relaxation by forskolin (back to the baseline), involving elevation of intracellular cAMP. UDP-glucose induced a greater contraction compared with the control, in which UDP-glucose was applied at basal tone without the tissues being exposed to U46619 or forskolin

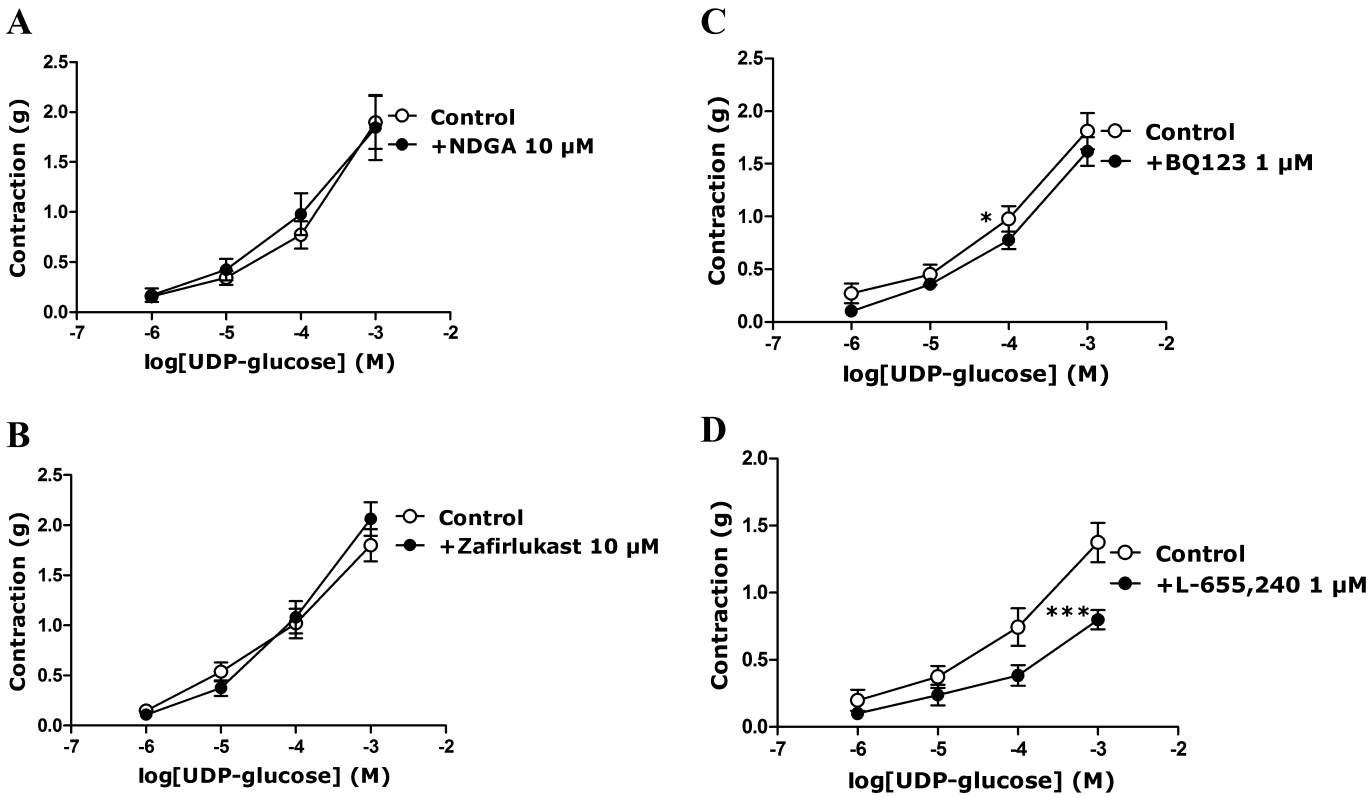

Figure 6

The contraction evoked by UDP-glucose in the presence of (A) NDGA (10 μM), (B) zafirlukast (10 μM), (C) BQ123 (1 μM) in U46619-preconstricted porcine pancreatic arteries, and (D) L-655,240 (1 μM) in endothelin-1-preconstricted porcine pancreatic arteries. (A, B) NDGA and zafirlukast did not alter the response to UDP-glucose (n = 7–10). (C, D) BQ-123 and L-655,240 inhibited the response evoked by UDP-glucose (*P < 0.05, ***P < 0.001, two-way ANOVA, F = 4.97, 19.03; n = 9–14). Data are presented as mean ± SEM.

(Figure 10). The contraction to 100 μM UDP-glucose was enhanced by 930 ± 108% (P < 0.001, n = 11) after the exposure to U46619 and forskolin (Figure 10A). In contrast, when responses to UTP, an agonist at $P2Y_2$ and $P2Y_4$ receptors (G_q-protein coupled receptors), were investigated in vessels exposed to U46619 and forskolin, there was no change in the contractions (Figure 10B). In addition, the response to UDP-glucose was not altered after contraction with U46619 and relaxation with SNP (100 μM), which elevates intracellular cGMP (Roberts *et al.*, 1999). Typical traces showing the effect of UDP-glucose on basal tone and after the tissues had been contracted by U46619 and then relaxed with forskolin are shown in Figure 10C.

Effect of UDP-glucose and MRS2690 on the cAMP level in porcine isolated pancreatic arteries

On the basis that cAMP is involved in the contraction to $P2Y_{14}$ receptor agonists, we measured the cellular levels of this second messenger in pancreatic artery rings. We investigated the effects of UDP-glucose, MRS2690 and UTP (as a negative control, as it is coupled to G_q protein) on cAMP levels in the presence of U46619 + forskolin (to mimic the raised tone condition of the pharmacology experiments). UDP-glucose (1 mM) and MRS2690 (10 μM) induced a significant decrease in the cAMP level relative to the control (U46619 + forskolin only, expressed as 100%) (*P < 0.05, n = 4), while UTP had no significant effect on cAMP levels (Figure 11).

Discussion

The current study presents evidence for the functional expression of contractile $P2Y_{14}$ receptors, sensitive to the endogenous nucleotides UDP-glucose and UDP in porcine pancreatic arteries. Evidence from the contractile studies and the cAMP immunoassay is consistent with the ability of this receptor to inhibit AC, while immunoblotting indicates the downstream involvement of MLC2. The contractile response was mediated largely by the endothelium with an involvement of endothelin, TxA_2 and $PGF_{2\alpha}$.

Contractile studies showed that contractions to UDP-glucose and UDP were almost equipotent, whereas MRS2690, a selective $P2Y_{14}$ receptor agonist, was approximately 10-fold more potent than UDP-glucose at the $P2Y_{14}$ receptor (Figure 1A). This is consistent with previous reports, which suggest a 7–10-fold greater potency of MRS2690 over UDP-glucose (Jacobson *et al.*, 2009; Gao *et al.*, 2010). In the present study, MRS2690 activity was observed at ≤10 μM; at 10 μM, MRS2690 is inactive at $P2Y_2$ receptors (Ko *et al.*, 2009).

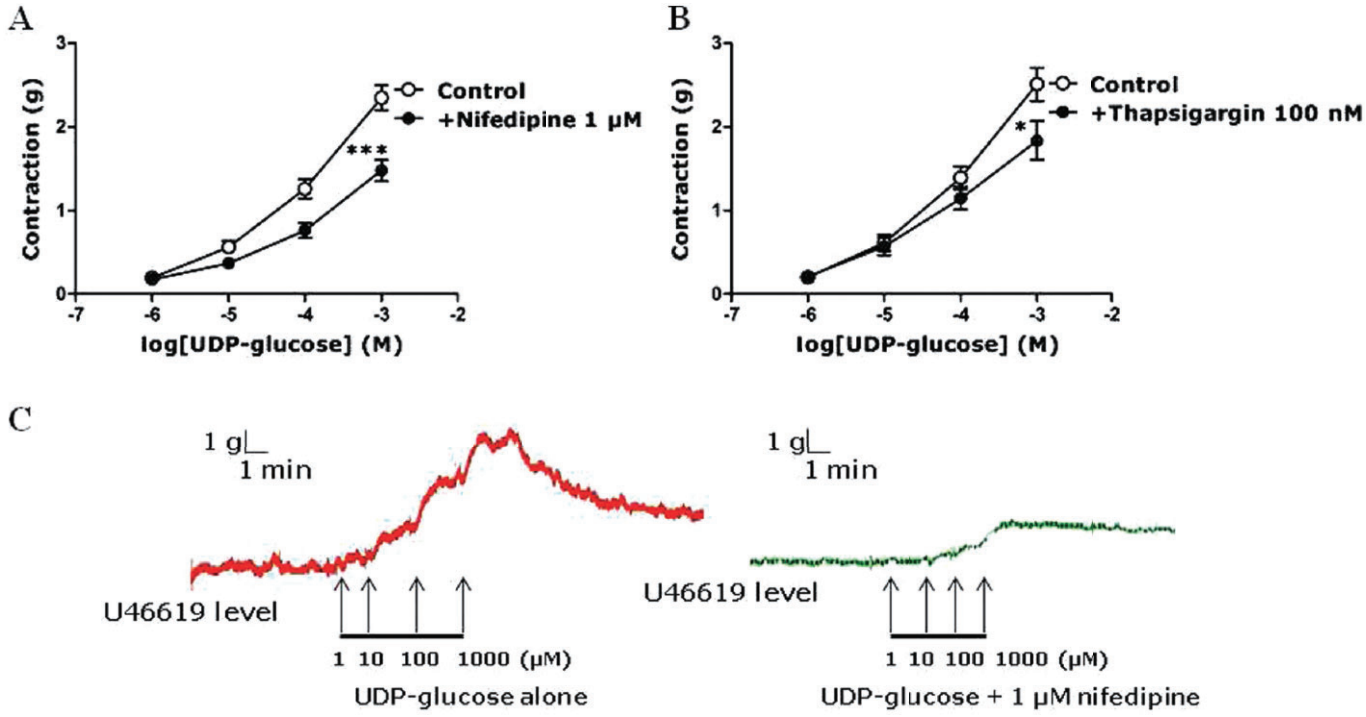

Figure 7

Effect of (A) nifedipine (1 μM) and (B) thapsigargin (100 nM) on the response to UDP-glucose in U46619-preconstricted porcine pancreatic arteries. Both inhibitors, nifedipine and thapsigargin, inhibited the contraction evoked by UDP-glucose (*$P < 0.05$, ***$P < 0.001$, two-way ANOVA, $F = 32.5, 5.84$; $n = 12–15$). Data are presented as mean ± SEM. (C) Typical traces showing the responses of UDP-glucose in the absence and presence of nifedipine.

PPTN is a non-nucleotide, high-affinity competitive antagonist at $P2Y_{14}$ receptors. It was assessed in HEK cells using a calcium mobilization assay and it inhibited UDP-glucose-mediated signalling, and showed no effect on other P2Y receptors at concentrations up to 10 μM (Robichaud *et al.*, 2011; Barrett *et al.*, 2013). The responses to the $P2Y_{14}$ receptor agonists were examined in the presence of this antagonist. PPTN (1 μM) blocked the contractions induced by UDP-glucose and MRS2690, which confirms the involvement of $P2Y_{14}$ receptors in our arteries (Figure 3A,B).

The responses to the $P2Y_{14}$ receptor agonists were examined in the presence of the non-selective P2 receptor antagonists, suramin and PPADS. The non-selective antagonists induced a small increase in the contractions to UDP and UDP-glucose (Figure 2A,B). However, they failed to change the response to MRS2690 (Figure 2C). The lack of effect of suramin and PPADS appears to rule out an involvement of $P2Y_2$ and/or $P2Y_4$ receptors as we have shown that they blocked the responses to UTP in porcine pancreatic arteries (M. Alsaqati, unpubl. obs.) and other tissues (Rayment *et al.*, 2007b). It is unclear why these antagonists enhanced the effects of $P2Y_{14}$ receptor agonists. However, it is clear that suramin and PPADS had different effects on responses to UTP from those on responses to MRS2690 and UDP-glucose, indicating actions at different receptors.

Contractile responses to UDP-glucose, UDP and MRS2690 were significantly inhibited after the endothelium was removed (Figure 4), which indicated that the main expression of $P2Y_{14}$ receptors may be on the endothelial layer of porcine pancreatic arteries. Similarly, the $P2Y_{14}$ receptor is expressed in endothelial cells of porcine coronary artery, human lung microvascular endothelial cells and pulmonary artery vasa vasorum endothelial cells (Umapathy *et al.*, 2010; Abbas *et al.*, 2011; Lyubchenko *et al.*, 2011). $P2Y_{14}$ receptor expression was barely detectable in mouse thoracic aorta (Kauffenstein *et al.*, 2010); in contrast, rat aortic smooth muscle cells show robust expression of the receptor, as observed in freshly isolated and cultured cells (Govindan *et al.*, 2010).

To investigate the mechanism underlying the contraction mediated by $P2Y_{14}$ receptors in pancreatic arteries, responses to UDP-glucose, UDP and MRS2690 were examined in the presence of DUP 697. As seen in Figure 5, the endothelium-dependent contractions were attenuated in the presence of the selective COX-2 inhibitor. Endothelial cells can release contractile factors (EDCFs), which may include TxA_2, $PGF_{2\alpha}$, LTs and endothelin-1. TxA_2 and $PGF_{2\alpha}$ are released from the endothelium as products of COX-2 (Mombouli and Vanhoutte, 1993; Wong *et al.*, 2009). To characterize EDCFs involved in the contraction to UDP-glucose, experiments were conducted to study the responses to UDP-glucose in the presence of zafirlukast, BQ123, BQ788 and L-655,240. Only BQ123 and L-655,240 were able to inhibit the contraction evoked by UDP-glucose, which indicated an involvement of TxA_2, PGs and endothelin-1 (Figure 6). These agents, after being released from the

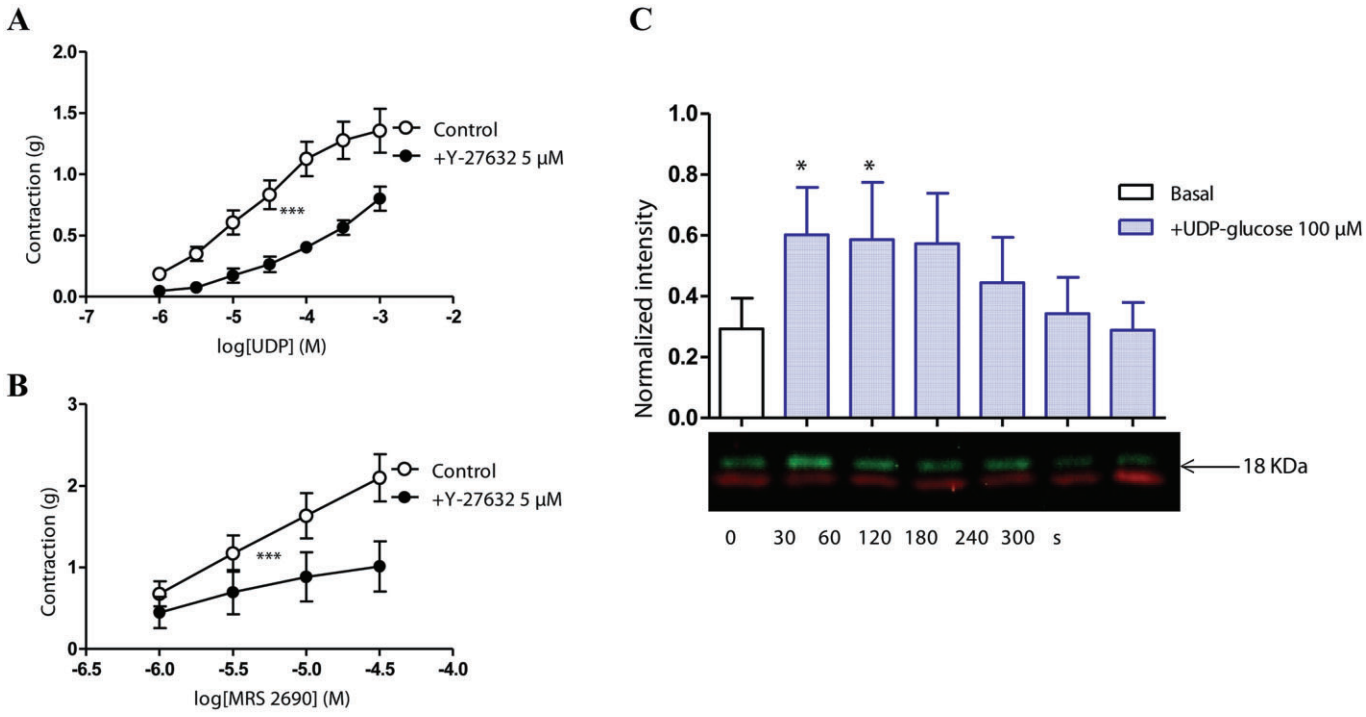

Figure 8

Effect of Y-27632 (5 µM), a selective inhibitor of the Rho-associated protein kinase, on responses to (A) UDP and (B) MRS2690 in U46619-preconstricted porcine pancreatic arteries. Y-27632 reduced the contraction to (A) UDP and (B) MRS2690 (***$P < 0.001$, two-way ANOVA, $F = 53.07$, 10.32; $n = 9$–15). Data are presented as mean ± SEM. (C) MLC2 phosphorylation induced by 100 µM UDP-glucose in porcine pancreatic arteries. A time course (above) and a representative blot (below) of phospho- (green) and total- (red) MLC2 (*$P < 0.05$, one-way ANOVA, $n = 4$).

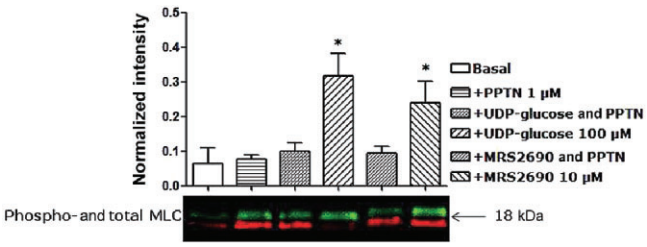

Figure 9

PPTN, a selective high-affinity antagonist of $P2Y_{14}$ receptor, abolished the ability of UDP-glucose and MRS2690 to elevate the level of MLC phosphorylation (*$P < 0.05$, Student's unpaired t-test, $n = 3$). Data are presented as mean ± SEM. Representative immunoblots of phospho- (green) and total- (red) MLC2 from three separate experiments in the absence or presence of PPTN.

endothelium, may act on their receptors on vascular smooth muscle cells (Wong *et al.*, 2009).

The involvement of extracellular calcium influx and calcium released from sarcoplasmic reticulum (SR) as a part of the response to $P2Y_{14}$ receptor activation has been reported (Verin *et al.*, 2011). In addition, calcium-induced release of calcium from SR and influx of external Ca^{2+} in excitation-contraction in response to some activated receptors have been also reported (Fabiato, 1983; Li *et al.*, 2003). In porcine pancreatic arteries, contractions to UDP-glucose (Figure 7A,B) and UDP (data not shown) were significantly decreased in the presence of nifedipine or thapsigargin, which identified an involvement of elevated intracellular calcium level. Collectively, our results suggest that when UDP-glucose, UDP and MRS2690 act at the $P2Y_{14}$ receptors, which are expressed mainly on the endothelium, the intracellular Ca^{2+} levels may be elevated; this may then lead to the release of endothelin-1 and activation of PLA_2, which liberates arachidonic acid, which is then converted by the activity of COX-2 to produce TxA_2 and PGs, which bind to receptors on vascular smooth muscle cells to induce contraction.

A number of studies have considered the signalling mechanism underlying the functional response of $P2Y_{14}$ receptors (Harden *et al.*, 2010; Sesma *et al.*, 2012). Recent reports claimed that UDP-glucose promotes concentration-dependent activation of RhoA in isolated human neutrophils (Sesma *et al.*, 2012). This was tested in porcine pancreatic arteries when responses were investigated in the presence of Y-27632; this compound inhibited the contraction evoked by UDP-glucose, UDP and MRS2690 (Figure 8A,B), which showed an involvement of RhoA in the response to $P2Y_{14}$ receptor agonists. Activation of RhoA leads to phosphorylation of MLC and subsequently contraction of arteries in a calcium-independent manner (Amano *et al.*, 1996; Hartshorne and Gorecka, 2011). Accordingly, when UDP-glucose or MRS2690 were incubated with the tissues, the level of phosphorylated MLC2 was elevated, but this elevation was abolished in the presence of PPTN, confirming that it

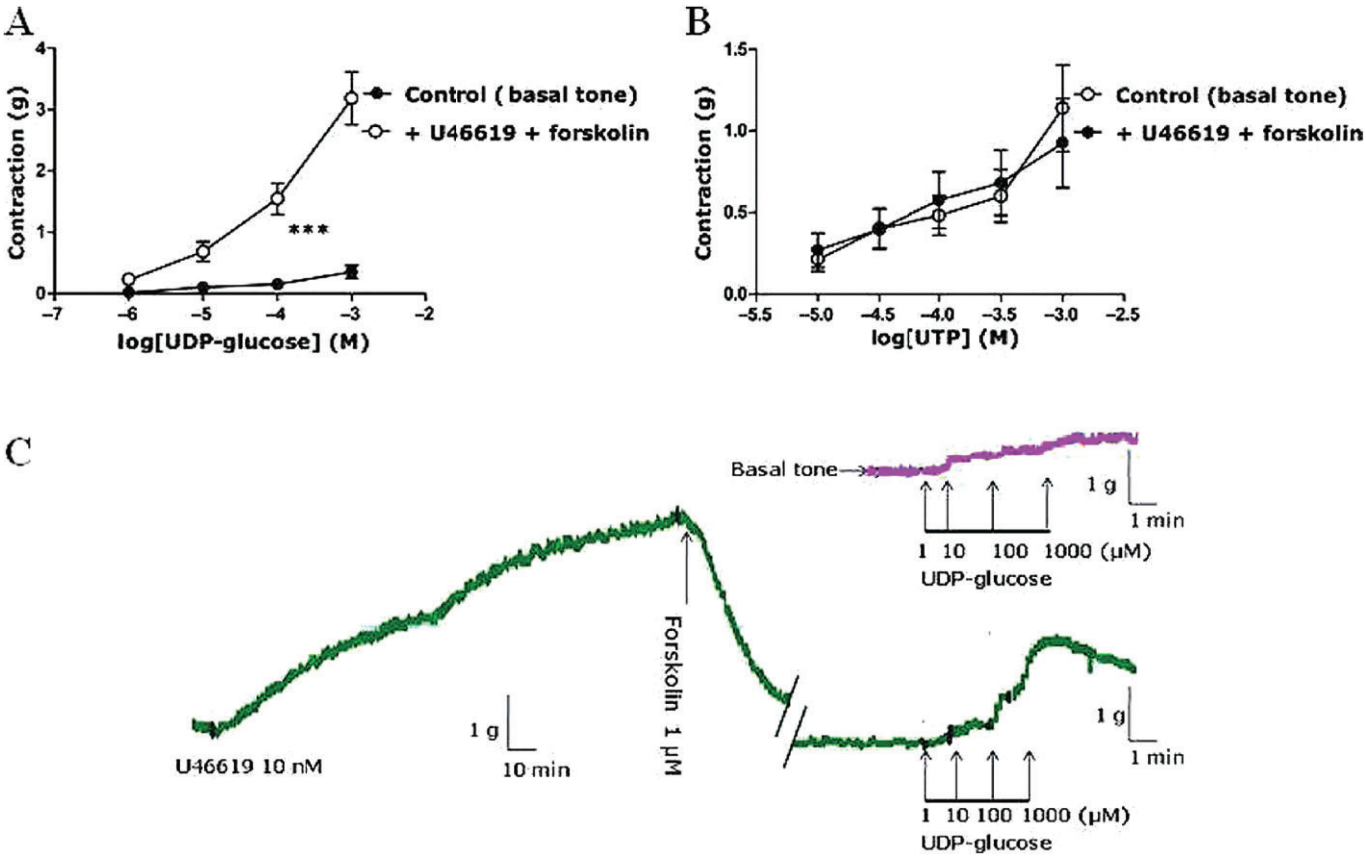

Figure 10

Effect of preconstriction with U46619 followed by relaxation with forskolin (1 μM) on the responses to (A) UDP-glucose and (B) UTP in porcine pancreatic arteries. (A) Exposing the tissues to U46619 followed by forskolin significantly enhanced the contraction evoked by UDP-glucose (***P < 0.001, two-way ANOVA, F = 54.34; n = 8–13). Data are presented as mean ± SEM. (B) Exposing the tissues to U66619 followed by forskolin failed to affect the response to UTP. (C) Typical traces showing the effect of UDP-glucose on basal tone (inset) and after the tissues were preconstricted with U46619 and then relaxed with forskolin (main).

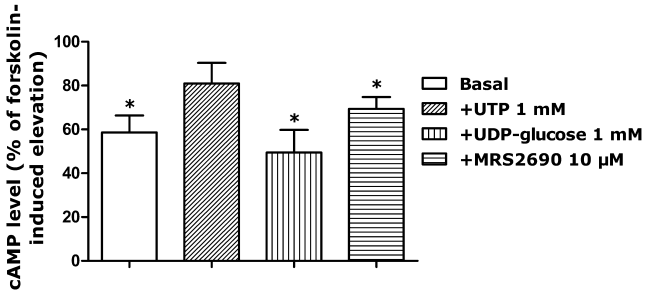

Figure 11

Effect of UTP (1 mM), UDP-glucose 1 (mM) and MRS2690 (10 μM) on the cAMP concentrations in porcine pancreatic arteries exposed to U46619 followed by forskolin. UTP had no significant effect on cAMP level, while UDP-glucose and MRS2690 significantly reduced the cAMP level (*P < 0.05, Student's unpaired t-test, the response to UTP or UDP-glucose or MRS2690 vs. their respective controls, n = 4). Basal cAMP level represents the level of cAMP in the absence of forskolin, which was also significantly different from that in the presence of forskolin (*P < 0.05, Student's unpaired t-test, n = 4). Data are presented as mean ± SEM.

is happening through the activation of $P2Y_{14}$ receptors (Figures 8C and 9).

It is well established that the $P2Y_{14}$ receptor is coupled to G_i protein, leading to the inhibition of AC activity, and hence inhibition of the cAMP level. Accordingly, the $P2Y_{14}$ receptor is PTX-sensitive (Jacobson *et al.*, 2009). It is notoriously difficult to successfully block G_i coupled receptors with PTX in isolated blood vessels, as we have also found. However, in tissues that had been preconstricted with U46619 and relaxed with forskolin (to elevate the cAMP levels), subsequent addition of UDP-glucose produced a significantly greater contraction compared with the controls (UDP-glucose added at basal tone, or UTP applied after preconstriction with U46619 and relaxation with forskolin) (Figure 10), consistent with an involvement of G_i coupled receptors. Other purine receptors, namely $P2Y_1$, $P2Y_2$, $P2Y_4$ and $P2Y_6$ receptors, are generally G_q protein-coupled. Furthermore, relaxation with SNP (to elevate cGMP levels) after preconstriction with U46619 had no effect on the contractile response to UDP-glucose (data not shown). These findings, together with the data obtained from cAMP assay (Figure 11), indicate that the enhanced contraction to UDP-glucose is mainly dependent on the agonist's ability to lower cAMP levels.

Reduction in pancreatic blood flow has been observed in acute and chronic pancreatitis and some other pancreatic diseases (Satoh *et al*., 2000; Nguyen *et al*., 2010), implicating pancreatic tissue perfusion as an important factor in pathogenesis of pancreatic diseases and symptoms. There is increasing evidence for the role of purinergic signalling in the pathophysiology of the pancreas (Burnstock and Novak, 2012). Drugs designed to target specific components of the purinergic system may be of relevance to the management of pancreatitis, cystic fibrosis, pancreatic cancer and diabetes.

In conclusion, this study has shown a novel vasocontractor action of UDP-glucose, which appears to be mediated by the $P2Y_{14}$ receptor in porcine isolated pancreatic arteries.$P2Y_{14}$ receptors induce contraction via an involvement of endothelin-1, TxA_2 and PGs released from the endothelium. In addition, $P2Y_{14}$-mediated contraction involves the activation of Rho kinase and the subsequent phosphorylation of MLC2. The ability of $P2Y_{14}$ receptor agonist to inhibit cAMP levels indicates $P2Y_{14}$ receptor coupling to G_i proteins. This study identifies a novel role for the $P2Y_{14}$ receptor as a mediator of vasoconstriction.

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Conflict of interest

The authors declare that they have not any conflict of interest.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

http://dx.doi.org/10.1111/bph.12473

Figure S1 Effect of BQ123 (1 μM) in endothelium-denuded arteries and the effect of endothelium removal on responses to UDP-glucose in U46619-preconstricted porcine pancreatic arteries. BQ123 in endothelium-denuded arteries did not induce further reduction of the contraction to UDP-glucose (***$P < 0.001$, two-way ANOVA, $F = 8.149, 9.294$; $n = 14$). Data are presented as mean ± SEM.

Figure S2 Effect of BQ788 (1 μM) on response to UDP-glucose in U46619-preconstricted porcine pancreatic arteries. BQ788 had no effect on the contraction to UDP-glucose (n = 7–8). Data are presented as mean ± SEM.

Figure S3 Effect of MRS2578 (10 μM) on responses to UDP, UDP-glucose and MRS2690 in U46619-preconstricted porcine pancreatic arteries. (A) MRS2578 enhanced significantly the contraction evoked by UDP (**$P < 0.01$, two-way ANOVA, $F = 9.953$; n = 8–13). (B, C) MRS2578 failed to alter the contraction to UDP-glucose and MRS2690 (n = 6–13). Data are presented as mean ± SEM.

Figure S4 Concentration-dependent contraction evoked by UDP-glucose, in porcine pancreatic arteries in the presence and absence of PPTN (1 μM) (***$P < 0.001$, two-way ANOVA, $F = 24.37$; $n = 12$).