The lysosomal inhibitor, chloroquine, increases cell surface BMPR-II levels and restores BMP9 signalling in endothelial cells harbouring BMPR-II mutations

Benjamin J. Dunmore¹, Kylie M. Drake², Paul D. Upton¹, Mark R. Toshner¹, Micheala A. Aldred²,³ and Nicholas W. Morrell¹,*

¹Division of Respiratory Medicine, Department of Medicine, University of Cambridge School of Clinical Medicine, Addenbrooke's and Papworth Hospitals, Cambridge, UK, ²Genomic Medicine Institute and ³Taussig Cancer Institute, Cleveland Clinic, Cleveland, OH, USA

Received March 1, 2013; Revised April 17, 2013; Accepted May 7, 2013

Pulmonary arterial hypertension (PAH) is characterized by dysregulated pulmonary artery endothelial cell (PAEC) proliferation, apoptosis and permeability. Loss-of-function mutations in the bone morphogenetic protein receptor type-II (BMPR-II) are the most common cause of heritable PAH, usually resulting in haploinsufficiency. We previously showed that BMPR-II expression is regulated via a lysosomal degradative pathway. Here, we show that the antimalarial drug, chloroquine, markedly increased cell surface expression of BMPR-II protein independent of transcription in PAECs. Inhibition of protein synthesis experiments revealed a rapid turnover of cell surface BMPR-II, which was inhibited by chloroquine treatment. Chloroquine enhanced PAEC expression of BMPR-II following siRNA knockdown of the BMPR-II transcript. Using blood outgrowth endothelial cells (BOECs), we confirmed that signalling in response to the endothelial BMPR-II ligand, BMP9, is compromised in BOECs from patients harbouring BMPR-II mutations, and in BMPR-II mutant PAECs. Chloroquine significantly increased gene expression of BMP9-BMPR-II signalling targets Id1, miR21 and miR27a in both mutant BMPR-II PAECs and BOECs. These findings provide support for the restoration of cell surface BMPR-II with agents such as chloroquine as a potential therapeutic approach for heritable PAH.

INTRODUCTION

Pulmonary arterial hypertension (PAH) is a progressive disease characterized by dysregulated endothelial cell proliferation, apoptosis and vascular permeability as well as smooth muscle cell proliferation in the pulmonary circulation (1). The transforming growth factor-β (TGFβ) superfamily, especially the bone morphogenetic proteins, plays a key role in the pathobiology of PAH (2,3). Mutations in bone morphogenetic protein receptor type-II (BMPR-II), the gene encoding the bone morphogenetic protein type II receptor (BMPR-II), underlie at least 70% of heritable and 10–40% of apparently sporadic PAH cases (4–6). In pulmonary artery smooth muscle cells, truncating or missense mutations result in reduced BMP-induced Smad1/5 signalling and reduced transcriptional induction of the inhibitors of DNA binding transcription factors (Id) (7,8). The majority of mutations reported in BMPR-II lead to a state of haploinsufficiency (6).

Endothelial cells from patients with mutations exhibit increased proliferation and an inability to form vascular networks (9). Even in the absence of a BMPR-II mutation, deficiency of the receptor contributes to the pathobiology of non-genetic forms of PAH (10,11). In addition, commonly used animal models of PAH, including chronic hypoxia in mice or monocrotaline exposure in rats, reveal a marked reduction in BMPR-II levels in the lung (12,13). Moreover, targeted gene delivery of BMPR-II to the pulmonary vasculature prevents pulmonary hypertension in these models (14).

Recent studies from our laboratory have suggested the possibility that lysosome inhibitors might increase cell surface...
BMPR-II levels. We previously showed that the Kaposi’s sarcoma herpes virus E3 ligase, K5, targets BMPR-II to the lysosome. K5-mediated degradation could be inhibited by the selective V-type ATPase inhibitor, concanamycin A. Exposure of both pulmonary artery endothelial cells (PAECs) and smooth muscle cells with concanamycin A resulted in a significant increase in BMPR-II expression (15).

Originally synthesized as a treatment for malaria, chloroquine or the closely related compound, hydroxychloroquine, is now widely used for the treatment of rheumatoid arthritis, lupus erythematosus and sarcoidosis and a number of dermatological conditions (16–20). In addition, we have recently shown that chloroquine prevents and reverses pulmonary hypertension in a rat model of pulmonary hypertension characterized by loss of BMPR-II expression in the lung (13,21). Chloroquine is a lysosomotropic agent as it is usually prepared as a diprotic weak base (pKa 8.5). The unprotonated form of chloroquine preferentially accumulates in lysosomes as it rapidly diffuses across cell/organellar membranes. Once in the lower pH (4.6), environment of the lysosome chloroquine becomes protonated and can no longer freely diffuse out (16).

In endothelial cells, BMP/TGFβ signalling is mediated through heterodimeric receptor complexes of type I and type II receptors (22). BMP9 and BMP10 were recently identified as specific ligands for the BMPR-II/Alk-1 receptor complex, stimulating the activation of the receptor Smad1/5/8 pathway, as well as downstream transcription of Id genes (23–25). Our laboratory recently reported that BMPR-II contributes to BMP9 stimulated induction of Smad1/5/8 phosphorylation and Id transcription in PAECs (26). Since mutations in Alk-1 have also been shown to lead to PAH, the endothelial BMPR-II/Alk-1 receptor complex and its cognate ligands are likely to play central roles in the pathobiology of this disease (27).

Canonical BMP signalling requires the phosphorylation of receptor Smads (R-Smads) by an activated receptor complex and subsequent association with Smad4 for translocation into the nucleus. It has been shown recently that non-canonical BMP signalling can directly influence the processing of microRNAs (miRs) (28). BMPs have been shown to regulate expression of miRs such as miR21, miR-100, miR-199a-5p and miR-27a (28,29). Drake et al. (30) have shown that miR21, miR27a and miR100 expression are regulated by BMP9 in PAECs, which is dependent on intact BMPR-II.

In the present study, we determined the effects of chloroquine on BMPR-II levels and BMP signalling in endothelial cells. We show that chloroquine, at pharmacologically relevant concentrations, rapidly increase cell surface localization of BMPR-II protein but does not alter Alk-1 protein levels. We determined for the first time that endogenous BMPR-II is rapidly turned over following protein synthesis blockade, an effect that can be inhibited by chloroquine. Chloroquine partially restored BMPR-II expression in endothelial cells in which BMPR-II mRNA was knocked down. Evaluation of BMP9/BMPR-II target genes Id1, miR21 and miR27a, revealed that chloroquine restored signalling in endothelial cells harbouring loss-of-function mutations in BMPR-II. Taken together, these findings support a role for increasing BMPR-II expression by chloroquine as a potential therapeutic intervention for heritable PAH.

RESULTS

Chloroquine increases BMPR-II protein levels in endothelial cells

We sought to investigate whether lysosomal blockade by chloroquine could significantly increase BMPR-II levels in endothelial cells. Treatment of PAECs for 16 h with either concanamycin A (50 nM) or chloroquine (100 µM) significantly increased BMPR-II protein levels by 5.6- and 3.5-fold, respectively (Fig. 1A). Transcription of BMPR-II mRNA was not significantly elevated suggesting that the increase in BMPR-II was likely due to lysosomal pathway inhibition (Fig. 1B). We also sought to determine whether the targeting of BMPR-II for lysosomal degradation by K5 mediated ubiquitination could be inhibited by chloroquine (15). Although not as marked as concanamycin A, chloroquine treatment of HeLa cells stably expressing K5 partially restored BMPR-II protein levels (Fig. 1C). Furthermore, in a microvascular endothelial cell line BMPR-II expression levels were strikingly increased by chloroquine (Fig. 1C). Again, chloroquine had no effect on BMPR-II gene expression in any of the cell lines (Fig. 1D).

Plasma levels of chloroquine in patients treated for rheumatoid arthritis vary from 36.6 to 3895 ng/ml (18). We conducted a concentration response assay encompassing this range. PAECs were treated for 16 h with the following concentrations 0, 0.5, 1, 5, 10 and 50 µM. Treatment with 0.5–50 µM chloroquine, increased BMPR-II protein expression in a dose response manner, compared with the no treatment control (Fig. 2A and Supplementary Material, Fig. S1). Even at the higher concentrations of chloroquine, expression of the endothelial specific type I receptor, Alk-1, was not significantly affected (Fig. 2A, grey bars).

Chloroquine increases cell surface localization of BMPR-II

We next sought to investigate whether lysosomal inhibition affected BMPR-II cell surface localization. A MCR5 lung fibroblast cell line stably expressing GFP-tagged BMPR-II was cultured in glass chamber slides and treated with the relevant, concanamycin A (50 nM) or chloroquine (100 µM) for 16 h. Using confocal microscopy, GFP-tagged BMPR-II was localized at the cell surface in the vehicle control (Fig. 2C–F). After treatment with concanamycin A, the GFP-tagged receptor co-localized with the lysosomal marker, LAMP-1 (Fig. 2G–J). Under these conditions, very little receptor was observed at the cell surface suggesting rapid turnover of the receptor and accumulation in the lysosome. Treatment with chloroquine also resulted in lysosomal accumulation, but also appeared to increase GFP-tagged BMPR-II at the cell surface (Fig. 2K–N; arrowheads).

To determine BMPR-II cell surface localization, biotinylation of cell surface receptors was utilized. Cells were treated for 16 h with vehicle, concanamycin A (50 nM) and chloroquine (100 µM). The non-biotinylation control showed basal expression of BMPR-II in the total lysate, but no surface expression with the avidin-agarose beads alone. Both concanamycin A and chloroquine increased total cell lysate BMPR-II expression compared with the vehicle control, but only chloroquine appeared to increase surface expression of BMPR-II (Fig. 3A). Biotinylation was also utilized to determine surface expression
of endogenous BMPR-II in PAECs after a chloroquine concentration response. Biotinylation analysis revealed that all chloroquine concentrations (0.5–50 μM) increased surface expression of BMPR-II (Fig. 3B; arrowhead). Therefore, a concentration of 10 μM chloroquine, which reflects high steady-state blood concentrations in patients, was chosen for further experiments. We next sought to determine the time course of chloroquine action on BMPR-II expression. PAECs were treated with chloroquine at 10 μM for 0.5, 1, 2, 4 and 16 h. BMPR-II protein levels were increased after 2–4 h chloroquine treatment (Fig. 3C). No significant increases in BMPR-II mRNA levels were observed at these time points (Fig. 3D).
Chloroquine inhibits the degradation of cell surface BMPR-II

In order to determine the effects of chloroquine on BMPR-II expression, the understanding of turnover of endogenous receptor is critical. The dynamics of BMPR-II regulation were investigated by blocking protein synthesis with cycloheximide over a time course. PAECs were treated with 20 μg/ml cycloheximide at 0, 0.5, 1, 2 and 4 h and assessed for BMPR-II protein and gene expression. Loss of total receptor expression was observed as early as 1 h (Fig. 4A). BMPR-II gene expression was unaffected across the time course (Fig. 4B; white bars).
Blockade of protein synthesis had no effect on Alk-1 protein and gene expression (Fig. 4A and B; grey bars).

To determine whether chloroquine alters the loss of BMPR-II following protein synthesis inhibition, PAECs were pre-treated with chloroquine (10 μM) for 16 h prior to cycloheximide treatment. As observed previously, BMPR-II expression was lost rapidly after 1 h, but treatment with chloroquine preserved expression after 2 h (Fig. 4C). Again no significant effect on BMPR-II gene expression was observed (Fig. 4D). Rapid loss of BMPR-II was also seen in PASMCs after 1–2 h (Supplementary Material, Fig. S2). Furthermore, 16 h chloroquine treatment of PASMCs maintained BMPR-II expression over 2–4 h of protein synthesis blockade.

Since the pre-treatment with chloroquine for 16 h inevitably increased BMPR-II expression, we also conducted experiments in which the level of BMPR-II protein was similar to time 0 by pre-treating PAECs for only 1 h with chloroquine (10 μM) (Fig. 5A). Normalization of chloroquine-treated BMPR-II...
expression prior to protein synthesis inhibition revealed that chloroquine increased and maintained BMPR-II expression significantly until 2 h (Fig. 5B).

**Chloroquine restores BMPR-II protein levels following siRNA knockdown**

Both genetic and non-genetic forms of PAH are often characterized by reduced BMPR-II protein expression (10). We therefore sought to recreate the diminished receptor expression seen in the disease using RNA interference. In our previous research, silencing of BMPR-II with 10 nM siRNA results in over 90% knockdown efficiency (26). Therefore, serial dilutions of siRNA were used to recreate the ‘haploinsufficient’ levels of BMPR-II protein expression. PAECs were transfected with 10, 1, 0.1 and 0.01 nM of BMPR-II. After 48 h, protein and transcript levels were assessed for knockdown efficiency. A concentration of 0.1 nM siRNA decreased BMPR-II protein (Fig. 6A) and mRNA (Fig. 6B) expression levels by ≏50% compared with the transfection control. To allow for variability between PAEC donors, concentrations of 0.1 and 1 nM siRNA were used in subsequent experiments to determine whether chloroquine can rescue BMPR-II protein expression. Knockdown of BMPR-II was conducted as before except that after 32 h cells were treated with chloroquine for 16 h. BMPR-II expression was reduced to ≏50% levels in the siBMPR-II knockdown at a concentration of 1 nM. Densitometry of three independent experiments revealed that chloroquine treatment increased BMPR-II levels by 2.2- and 6.5-fold following knockdown with 0.1 and 1 nM of siRNA, respectively (Fig. 6C).
Chloroquine does not inhibit BMP-mediated Smad signalling and transcription of target genes

Since chloroquine inhibits the internalization of BMPR-II, it is possible that signalling downstream of the receptor could be adversely affected by this intervention. In addition, off-target effects of chloroquine might negatively impact BMP signalling. To assess this, PAECs were stimulated with BMP9 (1 ng/ml) in the presence of chloroquine (10 μM). Downstream signalling was assessed by examining canonical Smad1/5/8 protein phosphorylation and Id1 transcription. Cells were pre-treated with chloroquine for 16 h prior to stimulation with BMP9 for 1 and 4 h. As previously observed, BMP9 stimulation increased BMPR-II protein and gene expression (26) (Fig. 7A and B). As previously described in this study, chloroquine substantially increased BMPR-II protein expression, but not mRNA (Fig. 7A and B). Phosphorylation of Smad1/5/8 was increased by BMP9 treatment at both 1 and 4 h, which was unaffected by chloroquine (Fig. 7A). BMP9 potently increased Id1 gene expression particularly after 1 h stimulation (Fig. 7C). Again, this was unaffected by chloroquine treatment suggesting no detrimental effect of blocking the lysosome on BMP signalling in endothelial cells. In fact, Smad1/5/8 phosphorylation and Id1 expression remained unaffected by chloroquine for up to 8 h of BMP9 exposure (Supplementary Material, Fig. S3A–C). Furthermore, no discernible increase in Smad-independent signalling was observed when examining p38MAPK phosphorylation after BMP9 treatment in the presence of chloroquine (Supplementary Material, Fig. S4).

Chloroquine increases BMPR-II protein expression and improves downstream signalling in endothelial cells harbouring BMPR-II mutations

Initially, we confirmed that endothelial cells derived from patients with BMPR-II mutations are deficient in BMP9-mediated signalling. After quiescence, control and BMPR-II haploinsufficient blood outgrowth endothelial cells (BOECs) were treated with BMP9 (1 ng/ml) for 4 and 12 h. After 12 h, mutant BOECs showed a significantly reduced Id1 expression compared with controls (Fig. 8A). Furthermore, Id1 expression in a haploinsufficient BMPR-II PAECs, after 20 h BMP9 stimulation, was also significantly reduced (Fig. 8B).

Drake et al. (30) recently observed that miR21 and miR27a expression are regulated by BMP9. In that study, BMP9-stimulated miR21 and miR27a levels were completely abrogated by RNA interference of BMPR-II. We therefore assessed the effect of chloroquine on the processing of these microRNAs and Id1 gene expression. Control and BMPR-II haploinsufficient PAECs were pre-treated with chloroquine for 4/16 h prior to stimulation with BMP9 for 20 h. BMP9 stimulation of control PAECs induced miR21 and miR27a expression (Fig. 8B). As expected, haploinsufficient PAECs showed very little induction of these targets in the presence of BMP9. Chloroquine exerted no effect on the processing of miR21 and miR27a in the control cells after 16 h chloroquine pre-treatment. PAECs from a PAH patient with a BMPR-II mutation (deletion of exons 1–8) showed a significant reduction in BMP9 stimulated miR21, miR27a and Id1 levels (Fig. 8C). Chloroquine treatment of haploinsufficient PAECs significantly increased the expression of Id1, miR21 and miR27a in the presence of BMP9 (Fig. 8C). Similar significant results were observed after 4 h chloroquine pre-treatment and subsequent exposure to BMP9 (Supplementary Material, Fig. S5).

Control and mutant PAECs were pre-treated with chloroquine for 4 and 16 h and BMPR-II protein expression was measured.
An increase in BMPR-II levels was observed in control cells after 4 and 16 h chloroquine treatment (Fig. 8D). Significantly, an increase in BMPR-II protein expression in haploinsufficient PAECs was observed in cells treated for 4 and 16 h with chloroquine (Fig. 8D). We further assessed the effect of chloroquine on BOECs from two patients with a BMPR-II mutation (R320X and R548X). Chloroquine treatment significantly increased total BMPR-II expression after 4 and 16 h in mutant BOECs (Fig. 9A and Supplementary Material, Fig. S6). Densitometry from the mutant PAEC line and haploinsufficient BOEC lines confirmed a significant increase in BMPR-II expression in the presence of chloroquine (Fig. 9B). The BMPR-II mutant R320X BOECs demonstrated significantly lower Id1 expression compared with controls after 20 h of BMP9 stimulation (Fig. 7C). Furthermore, 16 h chloroquine pre-treatment significantly increased Id1 expression in the presence of BMP9 (Fig. 9C).

**DISCUSSION**

The type II bone morphogenetic protein receptor plays a critical role in PAH. In those cases where a mutation is identified, reduced expression of BMPR-II is observed in the lung. Furthermore, idiopathic cases of the disease in the absence of BMPR-II mutation, and animal models of disease are all associated with a marked reduction in lung BMPR-II protein levels (10–13). Therefore, the ability to maintain the cell surface expression of BMPR-II is of particular interest in the treatment of PAH. Our recent study highlighted the potential in targeting the regulation of BMPR-II by inhibiting the lysosome (15). We have also recently reported that treatment with chloroquine significantly increased BMPR-II expression in lung BOECs (16). Furthermore, chloroquine treatment significantly increased total BMPR-II expression in mutant BOECs, consistent with our observation that lysosome blockade increases endogenous expression of the receptor.
here we report that chloroquine was able to partially restore K5 mediated ubiquitination and downregulation of BMPR-II in HeLa cells, similar to our previous findings with concanamycin A (15). Although both inhibitors block the lysosomal degradative pathway by affecting lysosomal acidification, their effect on BMPR-II localization differed. Concanamycin A is a selective inhibitor of vacuolar ATPases. Vacuolar ATPases are proton pumps localized to the membranes of many intracellular organelles and primarily regulate intracellular pH (31). Inhibition by concanamycin A immediately increases luminal pH (32). It is worth noting that bafilomycin A1, another macrolide antibiotic, has been shown to completely abolish EGF lysosomal degradation but had no affect on ligand internalization and endocytosis (33). The high toxicity of concanamycin A and other macrolides precludes their use in clinical therapy. The mode of action of chloroquine is as a weak lipophilic base where the free base passes easily through membranes (34). It accumulates in the acidic lysosome as it becomes protonated, increasing the pH of the lysosome (35,36). Following exposure to concanamycin A, BMPR-II accumulates in the lysosome, but with chloroquine treatment BMPR-II appeared to be increased at the plasma membrane in addition to a degree of lysosomal accumulation. Since BMPR-II is known to be degraded via the lysosome (15), we speculate that inhibition of lysosomal degradation of BMPR-II leads to the accumulation of the protein within this organelle, as was observed in our confocal imaging studies. Massague and Kelly (37) reported that upon TGFβ binding the ligand:receptor complex is rapidly internalized for lysosomal degradation and is blocked by chloroquine treatment. Furthermore, they postulated that TGFβ receptors are replenished by recycling of a large intracellular pool. Therefore, one of the possible therapeutic benefits of chloroquine could be in maintaining BMPR-II at the cell surface. Given the current lack of antibodies directed at the extracellular domain to assess cell surface expression of BMPR-II, we employed an alternative method. In order to measure increased cell surface expression of BMPR-II in the presence of chloroquine, biotin labelling of cell surface molecules was utilized.

In this study, we sought to characterize the effect of chloroquine on BMPR-II levels in the endothelium. Recent research using PAECs from a persistent pulmonary hypertension model in fetal lambs described impaired angiogenesis which could be rescued by chloroquine inhibition of autophagy (38). However, as yet there is no literature describing the regulation of BMPR-II by chloroquine in endothelial cells. The most striking observation from this study was the apparent ability of chloroquine to maintain surface expression of BMPR-II, especially at pharmacologically relevant concentrations. The increase in BMPR-II protein expression was not dependent on increased BMPR-II transcription. We also found that BMPR-II protein levels are rapidly reduced after protein synthesis inhibition. In contrast, the protein expression of the endothelial specific type I receptor, Alk-1, was unaffected. Hartung et al. (39) have previously reported that type I and II BMP receptors undergo constitutive endocytosis. These studies were conducted in fibroblast-like COS7 and mouse myoblast C2C12 cell lines. Nevertheless, these observations support our findings that BMPR-II expression is rapidly lost after protein synthesis blockade. The rapid loss of BMPR-II could be partially inhibited by chloroquine.

The ability to rescue reduced receptor expression could be a critical factor in the treatment of PAH. The majority of heritable or idiopathic PAH cases, where a mutation in BMPR-II is identified, are due to nonsense, frameshift and splice-site defects. This results in the premature termination of BMPR-II transcript and therefore loss of expression through nonsense-mediated decay (40). Haploinsufficiency for BMPR-II with a 50% reduction in BMPR-II expression is predicted in these individuals. We
attempted to recreate this expression level by titration of the BMPR-II siRNA previously used (26). Using 10–100-fold dilutions of siRNA, we were able to mimic the reduction in expression levels associated with BMPR-II mutations (10). Treatment with chloroquine partially restored the receptor expression levels where BMPR-II levels were 50% or lower. More importantly, chloroquine treatment of endothelial cells from patients with BMPR-II mutations partially rescued BMPR-II protein expression.

Preventing the cell surface turnover of BMPR-II might impair BMP signalling. We determined the effect of chloroquine on BMP9 induced Smad signalling and its downstream transcription factor, Id1. In control PAECs, chloroquine was not detrimental to the canonical signalling processes mediated by BMPR-II and ActR-IIa to show that induction of Id gene expression by BMP9 in PAECs was co-dependent on these receptors (26). This highlights important differences between the experimental knockdown of a receptor and study of the endogenous mutated receptor. Nevertheless, in cells harbouring BMPR-II mutations in the present study, we demonstrate that chloroquine treatment of BMPR-II mutant endothelial cells can rescue the expression of these downstream BMP9/BMPR-II targets. Our results suggest that enhancement of cell surface expression of BMPR-II in the normal endothelium does not further increase signalling in response to ligand, rather our findings suggest that BMPR-II limits BMP signalling at lower levels of receptor expression. Under these circumstances, in the presence of BMPR-II haploinsufficiency, chloroquine was capable of enhancing BMP signalling. This gene dosage effect of BMPR-II has been reported previously in vivo (41). At present, it remains uncertain whether the optimal point for intervention on the mutated BMPR-II pathway is at the level of the receptor itself, or the downstream signalling. Thus in a situation where BMP signalling was deficient downstream of the receptor, enhanced BMPR-II expression levels may be ineffective. Nevertheless, in vivo rat models of pulmonary hypertension where several mechanisms likely mediate loss of BMP signalling, we have shown that chloroquine can prevent onset and progression of disease (21).

This study is the first report of the dynamic regulation of BMPR-II and the possibility to modulate cell surface expression with a widely used therapeutic agent. However, several questions remain regarding the mechanism of BMPR-II degradation and turnover in the endothelium, in addition to the potential non-specific effects of chloroquine. It is well known that 4-aminooquinolones have a wide range of effects. Other than modifying lysosomal acidification, they have been shown to target other molecules involved in endocytic degradation. Accumulation of chloroquine in the lysosome inhibits phospholipase A2 (16). It has recently been shown that antagonists of cytoplasmic phospholipase A2 inhibit multiple endocytic pathways (42). In contrast, chloroquine could be maintaining BMPR-II at the cell surface via another mechanism other than lysosomal inhibition.

There have been several reports detailing the endocytic pathways involved in TGFβ superfamily receptor degradation. In particular, Hartung et al. (39) established roles for both clathrin and caveolae mediated endocytosis in the processing of BMPR-II. Furthermore, they identified that BMPR-II interacts with Eps15R, a key component of clathrin coated pits (CCPs), and caveolin-1, the main component of caveolae. BMPR-II has also been shown, using fluorescence resonance energy transfer, to bind another key component of CCPs, adaptor protein complex 2 (AP2). Disruption of CCPs increased Smad signalling and osteogenesis in C2C12s, suggesting that CCPs operate as an inhibitory membrane domain (43).

Recent research has highlighted the importance of caveolin-1 in vascular signalling and pulmonary hypertension. BMPR-II has been reported to localize in lipid rich membrane domains of PAECs and co-localize with caveolin-1 (44). Caveolin-1 has also been shown to be important in vascular smooth muscle cell signalling. Targeted reduction of caveolin-1 using RNA interference resulted in reduced BMP signalling (45). Furthermore, caveolin-1 knockout mice develop right ventricular hypertrophy and an increase in pulmonary artery pressure (46). Mutations in several members of the BMP/Smad signalling cascade have been identified in PAH patients, including Alk-1, endoglin and Smad8. Recently, Austin et al. (47) were the first to identify a frameshift mutation in caveolin-1 in a family with heritable PAH and an individual with idiopathic PAH. This, providing a link between the regulation of BMP signalling and endocytosis in pulmonary hypertension. Despite these considerations, chloroquine and hydroxychloroquine are widely used in clinical practise and would appear on the basis of our present and recent findings to be worth pursuing in clinical studies as potential targets of BMP signalling in PAH, where BMP signalling is compromised (21).

Taken together, our findings provide proof of concept for targeting the degradation of the BMPR-II receptor in PAH associated with BMPR-II deficiency or mutation to restore downstream signalling and function. Further elucidation of the mechanisms by which BMPR-II is degraded from the cell surface via the lysosome may provide additional specific targets for intervention.

**MATERIALS AND METHODS**

**Cell culture**

Human PAECs were purchased from Lonza, Workingham, UK. Cells were maintained in complete endothelial cell growth medium-2 (EGM-2) and were used at passages 4–8. PAECs from a PAH patient with a germline mutation in BMPR-II (deletion of exons 1–8) were isolated as previously described (26,48,49). BOECs were isolated as previously described (9). Cells were maintained in complete EGM-2 and were used at passages 5–7. The transformed human microvascular endothelial cell line (HMEC-1) was obtained from the Centre for Disease Control (CDC, Atlanta, Georgia, USA) and maintained in the MDCB131 medium (Life Technologies, Paisley, UK) containing 15% fetal bovine serum (FBS) (Life Technologies), 10 ng/ml EGF, 1 ng/ml hydrocortisone (Sigma-Aldrich, Poole, Dorset, UK) and antibiotics. Human pulmonary artery smooth muscle cells (PASMCs) were isolated in our laboratory by explants and cultured as previously described (50). Immortalized MRC5 (SV40T) lung fibroblasts stably expressing...
human wild-type BMPR-II-GFP (MRC5-BMPR-II-GFP) were cultured as previously described (51). HeLa cell lines were grown in DMEM supplemented with 10% FBS and antibiotics. The HeLa K5 stable cell line was created and cultured as previously described (15). Concanamycin A was dissolved in DMSO and used at a final concentration of 50 nm for 16 h. Chloroquine (N4-(7-Chloro-4-quinolinyl)-N1,N1-dimethyl-1,4-panenidoamine diphosphate salt) was dissolved in sterile nuclelease-free water and used at differing concentrations and times (both Sigma-Aldrich). Cycloheximide was dissolved in sterile nuclease-free water and used at 20 μg/ml (Sigma-Aldrich). For BMP9 treatments, see relevant results section.

**mRNA quantitative reverse transcriptase-PCR**

Total RNA was extracted using the RNasy mini kit (Qiagen, Crawley, UK) according to the manufacturer’s protocol along with on-column DNase digestion. Total RNA (1000 ng) was reverse transcribed using the high capacity reverse transcription kit (Applied Biosystems, Warrington, UK) as described in the manufacturer’s instructions. Synthetic complementary DNA was amplified using SYBR®-Green JumpStart™ Taq Ready-Mix™ (Sigma-Aldrich) and the relevant sense and antisense primers along with ROX Reference dye (Life Technologies). The following primer sequences were used for BMPR-II (sense 5′-caaatctgtgagcccaacagtcaa-3′; anti-sense 5′-gaggaagaataatctgg-3′); β-actin (sense 5′-gccacaccaactctaca-3′, antisense 5′-gtcatcttctcgcggttggc-3′); QuantiTect Primer Assays were used for Ak-1, ID1, GAPDH and β-2-microglobulin (B2M) (Qiagen). Reactions were amplified on a StepOnePlus™ Real-Time PCR System (Applied Biosystems). Relative expression of target mRNA was normalized to GAPDH, β-actin or B2M using the ΔΔCT method (52) and expressed as fold change relative to the relevant control.

**MicroRNA quantitative reverse transcriptase-PCR**

Total RNA was extracted using miRNeasy mini kit (Qiagen, Valencia, CA, USA). mir21 and mir27a were quantified using TaqMan microRNA kits (Applied Biosystems, Foster City, CA, USA) and normalized to RNU48 as previously described (30).

**RNA interference**

PAECs were seeded in 60 mm dishes (4.38 × 10^5 cells/well) for protein or six-well plates (2 × 10^5 cells/well) for RNA and cultured for 48 h in EGM-2. Before transfection, PAECs were incubated in Opti-MEM I (Life Technologies) for 3–4 h. PAECs were transfected with 0.01, 0.1, 1 or 10 nm siRNA (BMPR-II (Dharmacon siGENOME SMARTpool) or siControl non-targeting (both Dharmacon On-TARGETplus) (Perbio Science, Erembodegem-Aalst, Belgium) complexed with DharmaFECT1 (8.75 μl/well for 60 mm dish or 4 μl/well for six-well plate) diluted in Opti-MEM I. Cells were incubated with the siRNA:DharmaFECT1 complexes for 4 h at 37°C, and then replaced with EGM-2. Knockdown efficiency was confirmed by qPCR and western blotting where possible.

**Western blotting**

Cells were grown to confluence in 60 mm dishes prior to the relevant treatment as detailed in the results section. Cells were lysed in 150 μl of ice cold lysis buffer (50 nm Tris–HCl, pH 8; 150 mm NaCl; 1% IGE-PAL CA-630; 0.5% deoxycholate; 0.1% SDS and 1x EDTA-free protease inhibitor cocktail) (Roche, West Sussex, UK) and centrifuged for 10 min at 10 000g. Protein concentration was determined using the Bio-Rad Lowry assay (Bio-Rad Laboratories, Hemel Hempstead, UK), using bovine serum albumin (BSA) as the standard. An equal amount of protein from each sample was diluted with 5 × sample loading buffer and boiled for 5 min. Cell lysates (40–80 μg of total protein) were separated by SDS–PAGE gels and proteins transferred to polyvinylidene fluoride membranes by semi-dry blotting. Blots were blocked and probed with the relevant antibodies. BMPR-II mouse monoclonal (BD Transduction Laboratories, NJ, USA); GFP mouse monoclonal (Roche); phospho-Smad1/5/8 rabbit polyclonal, total Smad1 rabbit polyclonal, phospho-p38MAPK and total p38MAPK (Cell Signaling Technology, Danvers, MA, USA). The Alk-1 rabbit polyclonal was a kind gift from Professor D Marchuk (Duke University, NC, USA). Blots were incubated with an appropriate horseradish-peroxidase-conjugated antibody and enhanced chemiluminescence reagent (GE Bioscience, Little Chalfont, UK). To confirm equal loading blots were incubated with an anti-α-tubulin antibody (Sigma-Aldrich).

**Cell surface biotinylation**

Method adapted from Rennolds et al. (53). PAECs or MRC5-BMPR-II-GFP cells were seeded in 60 mm dishes (4.38 × 10^5 or 7 × 10^5 cells/well, respectively) and cultured for 48 h prior to treatment. Cells were treated as described in the relevant results section. After treatment cells were placed on ice and washed twice with ice-cold PBS. Cells were washed once with PBS pH 8 containing 1 mM MgCl2 and 0.1 mM CaCl2 (PBS-pH8), and then incubated for 10 min at 4°C with freshly prepared EZ-Link™ NHS-Ss-biotin at 3 mg/ml (Perbio Science) in PBS-pH8. Biotinylation was terminated by washing the dishes twice with PBS containing 1% BSA (quenching any unbound NHS-Ss-biotin) followed by a 10 min incubation. After incubation, cells were washed with PBS and then lysed with 1 ml of PBS (with 1% Triton X100 and 1x EDTA-free protease inhibitor cocktail). Avidin-agarose beads (Pierce Protein Research Products, Rockford, IL, USA) were added to 900 μl of lysate, and rotated overnight at 4°C. The remaining 100 μl was used for total protein assessment. The biotin–avidin agarose complexes were then harvested by centrifugation and washed three times with lysis buffer. The beads were then resuspended in 5 × sample loading buffer and boiled for 5 min prior to SDS–PAGE.

**Immunofluorescence**

MRC5-BMPR-II-GFP cells were seeded onto BD Falcon™ glass chamber slides (BD Biosciences) and cultured for 48 h prior to treatment. After treatment, the chamber slides were washed with PBS and fixed and permeabilized with 1:1 acetone-methanol. Prior to staining cells were blocked with 10% FBS in...
PBS. LAMP-1 was detected with the primary antibody mouse anti-human-LAMP-1 at 1:200 (Dako, Ely, UK) and a secondary rabbit anti-mouse TRITC (Dako) antibody at 1:500. Chamber-slides were washed three times with PBS and mounted in glycerol/PBS solution DAPI (Vectorshied, Peterborough, UK). Cells were viewed and photographed using a confocal microscope (Leica TCS SPE) and images captured using Leica LAS AF software.

Statistical analysis
Statistical analysis was performed using Student’s t-test (*P < 0.05, **P < 0.01 and ***P < 0.001).

SUPPLEMENTARY MATERIAL
Supplementary Material is available at HMG online.

ACKNOWLEDGEMENTS
We thank Suzy Comhair and Serpil Erzurum (Department of Pathobiology and Respiratory Institute, Cleveland Clinic, Cleveland, Ohio) for providing cells with the BMPR-II mutation. The authors would also like to thank Professor D.A. Marchuk (Department of Molecular Genetics and Microbiology, Duke University Medical Center, Durham, NC) for kindly providing the Alk-1 antibody.

Conflict of Interest statement. None declared.

FUNDING
This work was supported through a British Heart Foundation Programme Grant RG/03/005 (N.W.M.). The Cambridge NIHR Biomedical Research Centre provided infrastructure support. Additional support was provided by the Fondation Leducq (N.W.M.) and supported in part by the NHLBI/NIH, Leducq (N.W.M.) and supported in part by the NHLBI/NIH, Marchuk (Department of Molecular Genetics and Microbiology, Duke University Medical Center, Durham, NC) for kindly providing the Alk-1 antibody.

REFERENCES
1. Morrell, N.W., Adnot, S., Archer, S.L., Dupuis, J., Jones, P.L., MacLean, M.R., McMurtry, I.F., Stemmark, K.R., Thistlethwaite, P.A., Weissman, N., Yuan, J.X. and Weir, E.K. (2009) Cellular and molecular basis of pulmonary arterial hypertension. J. Am. Coll. Cardiol., 54, S20–S31.
2. Davies, R.J. and Morrell, N.W. (2006) Molecular mechanisms of pulmonary arterial hypertension: role of mutations in the bone morphogenetic protein type II receptor. Chest, 134, 1271–1277.
3. Morrell, N.W. (2006) Pulmonary hypertension due to bmp2 mutation: A new paradigm for tissue remodeling? Proc. Am. Thorac. Soc., 3, 680–686.
4. The International PPHC-Lane, K.B., Machado, R.D., Pauculco, M.W., Thomson, J.R., Philips, J.A., Joyd, E.J., Nichols, W.C. and Trembath, R.C. (2000) Heterozygous germ-line mutations in BMPR2, encoding a TGF-beta receptor, cause familial primary pulmonary hypertension. Nat. Genet., 26, 81–84.
5. Machado, R.D., Pauculco, M.W., Thomson, J.R., Lane, K.B., Morgan, N.V., Wheeler, L., Philips, J.A, 3rd., Newman, J., Williams, D., Galie, N, et al. (2001) BMPR2 haploinsufficiency as the inherited molecular mechanism for primary pulmonary hypertension. Am. J. Hum. Genet., 68, 92–102.
6. Thomson, J.R., Machado, R.D., Pauculco, M.W., Morgan, N.V., Humbert, M., Elliot, G.C., Ward, K., Yacoub, M., Mikhail, G., Rogers, P. et al. (2000) Sporadic primary pulmonary hypertension is associated with germline mutations of the gene encoding BMPR-II, a receptor member of the TGF-β family. J. Med. Genet., 37, 741–745.
7. Yang, X., Long, L., Southwood, M., Rudarakanchana, N., Upton, P.D., Jeffery, T.K., Atkinson, C., Chen, H., Trembath, R.C. and Morrell, N.W. (2005) Dysfunctional Smad signaling contributes to abnormal smooth muscle cell proliferation in familial pulmonary arterial hypertension. Circ. Res., 96, 1053–1063.
8. Yang, J., Davies, R.J., Southwood, M., Long, L., Yang, X., Sobolewski, A., Upton, P.D., Trembach, R.C. and Morrell, N.W. (2008) Mutations in bone morphogenetic protein type II receptor cause dysregulation of Id gene expression in pulmonary arterial smooth muscle cells: implications for familial pulmonary arterial hypertension. Circ. Res., 102, 1212–1221.
9. Toshner, M., Voswinckel, R., Southwood, M., Al-Lamki, R., Howard, L.S., Marchesan, D., Yang, J., Sunharalingam, J., Soon, E., Exley, A. et al. (2009) Evidence of dysfunction of endothelial progenitors in pulmonary arterial hypertension. Am. J. Respir. Crit. Care Med., 180, 780–787.
10. Atkinson, C., Stewart, S., Upton, P.D., Machado, R., Thomson, J.R., Trembath, R.C. and Morrell, N.W. (2002) Primary pulmonary hypertension is associated with reduced pulmonary vascular expression of type II bone morphogenetic protein receptor. Circulation, 105, 1672–1678.
11. Dewachter, L., Adnot, S., Guignabert, C., Tu, L., Marcos, E., Fadel, E., Humbert, M., Darteville, P., Simonneau, G., Naeije, R. and Eddahibi, S. (2009) Bone morphogenetic protein signaling in heritable versus idiopathic pulmonary hypertension. Eur. Respir. J., 34, 1100–1110.
12. Long, L., MacLean, M.R., Jeffery, T.K., Morecroft, I., Yang, X., Rudarakanchana, N., Southwood, M., James, V., Trembath, R.C. and Morrell, N.W. (2006) Serotonin increases susceptibility to pulmonary hypertension in BMPR2-deficient mice. Circ. Res., 98, 818–827.
13. Long, L., Crosby, A., Yang, X., Southwood, M., Upton, P.D., Kim, D.K. and Morrell, N.W. (2009) Altered bone morphogenetic protein and transforming growth factor-beta signaling in rat models of pulmonary hypertension: potential for activin receptor-like kinase-5 inhibition in prevention and progression of disease. Circulation, 119, 566–576.
14. Reynolds, A.M., Holmes, M.D., Danilov, S.M. and Reynolds, P.N. (2012) Targeted gene delivery of BMPR-2 attenuates pulmonary hypertension. Eur. Respir. J., 39, 329–343.
15. Durrington, H.J., Upton, P.D., Hoer, S., Boname, J., Dummore, B.J., Yang, J., Crilley, T.K., Butler, L.M., Blackburn, D.J., Nash, G.B., Lehner, P.J. and Morrell, N.W. (2010) Identification of a lysosomal pathway regulating degradation of the bone morphogenetic protein receptor type II. J. Biol. Chem., 285, 37641–37649.
16. Solomon, V.R. and Lee, H. (2009) Chloroquine and its analogs: a new promise of an old drug for effective and safe cancer therapies. Eur. J. Pharmacol., 625, 220–233.
17. Dalby, K.N., Tekedereli, I., Lopez-Berestein, G. and Ozpolat, B. (2010) Targeting the prodeath and prosurvival functions of autophagy as novel therapeutic strategies in cancer. Autophagy, 6, 322–329.
18. Augustijns, P., Geusens, P. and Verbeke, N. (1992) Chloroquine levels in blood during chronic treatment of patients with rheumatoid arthritis. Eur. J. Clin Pharmacol., 42, 429–433.
19. Ben-Zvi, I., Kivity, S., Langevitz, P. and Shoenfeld, Y. (2012) Hydroxychloroquine: from malaria to autoimmunity. Clin. Rev. Aller. Immunol., 42, 145–153.
20. Kalia, S. and Dutz, J. P. (2007) New concepts in antimalarial use and mode of action in dermatology. Dermatol. Ther., 20, 160–174.
21. Long, L., Yang, X., Southwood, M., Lu, J., Marciniak, S.J., Dummore, B.J. and Morrell, N.W. (2013) Chloroquine prevents progression of experimental pulmonary hypertension via inhibition of autophagy and lysosomal BMPR-II degradation. Circ, Res., 112, 1159–1170.
22. van den Driesche, S., Mummery, C.L. and Westermann, C.J. (2003) Hereditary hemorrhagic telangiectasia: an update on transforming growth factor beta signaling in vasculogenesis and angiogenesis. Cardiovasc. Res., 58, 20–31.
23. David, L., Mallet, C., Mazerbourg, S., Feige, J.D. and Bailly, S. (2007) Identification of BMP9 and BMP10 as functional activators of the orphan activin receptor-like kinase 1 (ALK1) in endothelial cells. Blood, 109, 1953–1961.
24. Scharpfenecker, M., van Dinther, M., Liu, Z., van Bezoijn, R.L, Zhao, Q., Pukac, L., Lőwik, C.W. and ten Dijke, P. (2007) BMP-9 signals via ALK1 and inhibits bFGF-induced endothelial cell proliferation and VEGF-stimulated angiogenesis. J. Cell Sci., 120, 964–972.
25. David, L., Mallet, C., Keramidas, M., Lamanè, N., Gasc, J.M., Dupuis-Giroud, S., Plaucho, H., Feige, J.J. and Baillly, S. (2008) Bone morphogenetic protein-9 is a circulating vascular quiescence factor. *Circ. Res.*, **102**, 914–922.

26. Upton, P.D., Davies, R.J., Trembath, R.C. and Morrell, N.W. (2009) Bone morphogenic protein (BMP) and activin type II receptors balance BMP9 signals mediated by activin receptor-like kinase-1 in human pulmonary artery endothelial cells. *J. Biol. Chem.*, **284**, 15794–15804.

27. Trembath, R.C., Thomson, J.R., Machado, R.D., Morgan, N.V., Atkinson, C., Winship, I., Simonneau, G., Galic, N., Loyd, J.E., Humbert, M. et al. (2001) Clinical and molecular genetic features of pulmonary hypertension in patients with hereditary hemorrhagic telangiectasia. *N. Engl. J. Med.*, **345**, 325–334.

28. Davis, B.N., Hilyard, A.C., Lagna, G. and Hata, A. (2008) SMAD proteins control DROSHA-mediated microRNA maturation. *Nature*, **454**, 56–61.

29. Davis, B.N., Hilyard, A.C., Nguyen, P.H., Lagna, G. and Hata, A. (2010) Smad proteins bind a conserved RNA sequence to promote microRNA maturation by Drosophila. *Mol. Cell.*, **39**, 373–384.

30. Drake, K.M., Zygmun, D., Mavrick, L., Harbor, P., Wang, L., Comhair, S.A., Erzurum, S.C. and Aldred, M.A. (2011) Altered MicroRNA processing in heritable pulmonary arterial hypertension: an important role for Smad-8. *Am. J. Respir. Crit. Care Med.*, **184**, 1400–1408.

31. Fongrac, M. (2007) Vacuolar ATPases: rotary proton pumps in physiology and pathophysiology. *Nat. Rev. Mol. Cell Biol.*, **8**, 917–929.

32. Dröse, S. and Altenhof, K. (1997) Bafilomycin and concanamycins as inhibitors of V-ATPases and P-ATPases. *J. Exp. Biol.*, **200**, 1–8.

33. Yoshimori, T., Yamamoto, A., Moriyama, Y., Futai, M. and Tashiro, Y. (1991) Bafilomycin A1, a specific inhibitor of vacuolar-type H(+)-ATPase, inhibits acidification and protein degradation in lysosomes of cultured cells. *J. Biol. Chem.*, **266**, 17707–17712.

34. Kaufmann, A.M. and Krise, J.P. (2007) Lysosomal sequestration of amine-containing drugs: analysis and therapeutic implications. *J. Pharm. Sci.*, **96**, 729–746.

35. de Duve, C., de Barsy, T., Poole, B., Trouet, A., Tulkens, P. and van Hoof, F. (1978) Fluorescence probe measurement of the intralysosomal pH in living cells and the perturbation of pH by various agents. *Proc. Natl Acad. Sci. USA*, **75**, 3327–3331.

36. Ohkuma, S. and Poole, B. (1978) Fluorescence probe measurement of the intralysosomal pH in living cells and the perturbation of pH by various agents. *Proc. Natl Acad. Sci. USA*, **75**, 3327–3331.

37. Massague, J. and Kitay, B. (1986) Internalization of transforming growth factor-beta and its receptor in BALB/c 3T3 fibroblasts. *J. Cell Physiol.*, **128**, 216–222.

38. Teng, R.J., Du, J., Wilak, S., Guan, T., Eas, A., Shi, Y. and Konduh, G.G. (2012) Cross-talk between NADPH oxidase and autophagy in pulmonary artery endothelial cells with intrauterine persistent pulmonary hypertension. *Am. J. Physiol. Lung Cell Mol. Physiol.*, **302**, L651–663.

39. Hartung, A., Bitton-Worms, K., Rechtman, M.M., Wenzel, V., Boergermann, J.H., Hassel, S., Henis, Y.I. and Knaus, P. (2006) Different routes of bone morphogenic protein (BMP) receptor endocytosis influence BMP signaling. *Mol. Cell Biol.*, **26**, 7791–7805.

40. Machado, R.D., Aldred, M.A., James, V., Harrison, R.E., Patel, B., Schwalbe, E.C., Gruenig, E., Janssen, B., Koehler, R., Seeger, W. et al. (2006) Mutations of the TGF-beta type II receptor BMPR2 in pulmonary arterial hypertension. *Hum. Mol. Genet.*, **15**, 121–132.

41. Liu, D., Wang, J., Kinzel, B., Mieeler, M., Mao, X., Valdez, R., Liu, Y. and Li, E. (2007) Dosage-dependent requirement of BMP type II receptor for maintenance of vascular integrity. *Blood*, **110**, 1502–1510.

42. Doody, A.M., Antosh, A.L. and Brown, W.J. (2009) Cytoplasmic phospholipase A2 antagonists inhibit multiple endocytic membrane trafficking pathways. *Biochem. Biophys. Res. Commun.*, **388**, 695–699.

43. Bradin, B., Thinkaran, S., Bonor, J., Underhill, T.M., Petersen, N.O. and Nohe, A. (2009) FRET reveals novel protein–receptor interaction of bone morphogenetic proteins receptors and adaptor protein 2 at the cell surface. *Biochim. Biophys. Acta., 97*, 1428–1435.

44. Ramos, M., Lamé, M.W., Segall, H.J. and Wilson, D.W. (2006) The BMP type II receptor is located in lipid rafts, including caveolae, of pulmonary endothelium in vivo and in vitro. *Vasc. Pharmacol.*, **44**, 50–59.

45. Wertz, J.W. and Bauer, P.M. (2008) Caveolin-1 regulates BMPRII localization and signaling in vascular smooth muscle cells. *Biochem. Biophys. Res. Commun.*, **375**, 557–561.

46. Sha, Y.Y., Liu, Y., Stan, R.V., Fan, L., Gu, Y., Dalton, N., Chu, P.H., Peterson, K., Ross, J. and Chrien, K. (2002) Defects in caveolin-1 cause dilated cardiomyopathy and pulmonary hypertension in knockout mice. *Proc. Natl Acad. Sci. USA*, **99**, 11375–11380.

47. Austin, E.D., Ma, L., Leduc, C., Berman Rosenweig, E., Borozuk, A., Phillips, J.A. 3rd., Palomero, T., Sumamz, P., Kim, H.R., Talati, M.H. et al. (2012) Whole exome sequencing to identify a novel gene (caveolin-1) associated with human pulmonary arterial hypertension. *Circ. Cardiovasc. Genet.*, **5**, 336–343.

48. Masri, F.A., Xu, W., Comhair, S.A., Assosignk, K., Koo, M., Vasani, J., Drazba, J., Anand-Apte, B. and Erzurum, S.C. (2007) Hypertrophic apoptosis-resistant endothelial cells in idiopathic pulmonary arterial hypertension. *Am. J. Physiol. Lung Cell Mol. Physiol.*, **293**, L548–L554.

49. Comhair, S.A., Xu, W., Mavrikas, L., Aldred, M.A., Assosignk, K. and Erzurum, S.C. (2012) Human primary lung endothelial cells in culture. *Am. J. Respir. Cell Mol. Biol.*, **46**, 723–730.

50. Morrell, N.W., Yang, X., Upton, P.D., Jourdan, K.B., Morgan, N., Shaebers, K.K. and Trembath, R.C. (2001) Altered growth responses of pulmonary artery smooth muscle cells from patients with primary pulmonary hypertension to transforming growth factor-beta1 and bone morphogenetic proteins. *Circulation*, **104**, 790–795.

51. Sobolewski, A., Rudarakanchana, N., Upton, P.D., Yang, J., Crilley, T.K., Trembath, R.C. and Morrell, N.W. (2008) Failure of bone morphogenetic protein receptor trafficking in pulmonary arterial hypertension: potential for rescue. *Hum. Mol. Genet.*, **17**, 3180–3190.

52. Livak, K.J. and Schmittgen, T.D. (2001) Analysis of relative gene expression data using real-time quantitative PCR and the 2-Delta Delta C(T) method. *Methods*, **25**, 402–408.

53. Rennolds, J., Boyaka, P.N., Bellis, S.L. and Cormet-Boyaka, E. (2008) Low temperature induces the delivery of mature and immature CFTR to the plasma membrane. *Biochem. Biophys. Res. Commun.*, **366**, 1025–1029.