Gender–dependent Influence of Endogenous Estrogen in Pulmonary Hypertension.

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At a Glance Commentary: Females develop pulmonary arterial hypertension (PAH) more frequently that males. The role of estrogen in this female susceptibility is poorly understood. Our research shows that inhibition of endogenous estrogen synthesis using an aromatase inihibitor or inhibition of estrogen receptor alpha has therapeutic effects and restores BMPR2 expression in female but not male models of PAH. These findings suggest estrogen plays a pathogenic role in the pathology of PAH specifically in females

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Abstract

Rationale: The incidence of pulmonary arterial hypertension (PAH) is greater in women suggesting estrogens may play a role in the disease pathogenesis. Experimentally, in males, exogenously administered estrogen can protect against PH. However, in models that display female susceptibility, estrogens may play a causative role.

Objectives: To clarify the influence of endogenous estrogen and gender in PH and assess the therapeutic potential of a clinically available aromatase inhibitor.

Methods: We interrogated the effect of reduced endogenous estrogen in males and females using the aromatase inhibitor, anastrozole, in two models of PH; the hypoxic mouse and Sugen 5416/hypoxic rat. We also determined the effects of gender on pulmonary expression of aromatase in these models and in lungs from PAH patients.

Results: Anastrozole attenuated PH in both models studied, but only in females. To verify this effect was due to reduced estrogenic activity we confirmed that in hypoxic mice inhibition of estrogen receptor alpha also has a therapeutic effect specifically in females. Female rodent lung displays increased aromatase and decreased BMPR2 and Id1 expression compared to male. Anastrozole treatment reversed the impaired BMPR2 pathway in females. Increased aromatase expression was also detected in female human pulmonary artery smooth muscle cells compared to male.

Conclusions: The unique phenotype of female pulmonary arteries facilitates the therapeutic effects of anastrozole in experimental PH confirming a role for endogenous estrogen in the disease pathogenesis in females and suggests aromatase inhibitors may have therapeutic potential.

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Introduction

Pulmonary arterial hypertension (PAH) is characterised by severe pulmonary arterial remodelling and occlusive pulmonary vascular lesions, leading to right ventricular failure. Epidemiological studies report a greater incidence of the disease in females; depending on the disease classification the female to male ratio can be as great as 4:1 (1, 2). The female predisposition to PAH has given rise to the hypothesis that female sex hormones, primarily estrogens, may play a causative role in the development of the condition (3). However, the role of estrogen in PAH remains controversial.

The majority of preclinical studies into the role of estrogens in PH have utilised male animals (4-6) and describe protective effects of estrogen when administered exogenously. However, there is compelling evidence that endogenous estrogen may contribute to the pathogenesis of PH. Recently, we have described novel murine models where only female animals develop PH such as mice over-expressing the serotonin transporter gene (SERT+ mouse) (7) and Mts1(8). In these models the predominant circulating estrogen 17β-estradiol plays an essential role in the development of the PH phenotype (7-9). Estrogen can also induce proliferation of human pulmonary artery smooth muscle cell (hPASMCs) and may therefore contribute to the pulmonary artery remodelling observed in PAH (7, 10).

One explanation of the current controversies is that there are gender differences in the influence of endogenous estrogens on the pathophysiology of PH. Determining any gender differences in pulmonary responses to estrogen is vitally important for understanding the nature and origins of PAH. To our knowledge, there have been no comprehensive male *versus* female comparative studies into the role of *endogenous* estrogen in the pulmonary circulation.

Aromatase (CYP19A1), a member of the cytochrome P450 superfamily, synthesizes estrogens through the aromatization of androgens. In pre-menopausal women estrogen synthesis occurs mainly in the ovarian follicles and corpus luteum, but also to a lesser extent in non-glandular tissues such as adipose tissue and liver. In postmenopausal women and men, adipose tissue is a major source of estrogen (11). Little is known of the role aromatase plays within the pulmonary circulation. Therefore, to characterise the role of endogenous estrogen in PAH, the effects of an aromatase inhibitor were studied in two models of PH in male and female animals. We also assessed aromatase expression in the lung tissue of these animal models and in lung samples from PAH patients.

Methods

An expanded methods section is available in the Online Supplement

Hypoxic Studies

The ability of anastrozole to reduce progression of, and reverse, established PH in hypoxic mice was assessed. Hypoxic PH in C57BL/6 mice was achieved with 14 days hypoxia as described previously (10, 12). Mice were then maintained in hypoxic conditions for a further 14 days during which time the aromatase inhibitor, anastrozole was administered (Tocris) 0.3 $mgkg^{-1}$ or 3 $mgkg^{-1}$ or vehicle (1% carboxymethylcellulose) daily (s.c.). Another cohort of mice were administered with an ER± antagonist, MPP 2 $mgkg^{-1}day^{-1}$ for 14days (s.c.). Age-matched mice housed in normoxic conditions were studied as controls. See online supplement for ethical considerations and housing details.

Sugen 5416 + hypoxia (Su/Hx) Study

The ability of anastrozole to reduce progression of, and reverse, established PH was also assessed in the rat model of hypoxia + Sugen5416 (Su) as described in detail in online supplement. Briefly, Wistar Kyoto rats were given a single injection of Su 20mgkg^{-1} (s.c.) or 0.9% (s.c.) saline and exposed to hypoxia for 14 days then retained in normoxia for two weeks during which time they were dosed with anastrozole (0.03, 0.3 or 3 mgkg^{-1}day^{-1}) or vehicle (1% carboxymethylcellulose) orally.

Hemodynamic Measurements

Heart rate, right ventricular systolic pressure (RVSP), systemic arterial pressure and cardiac output were measured and analyzed as previously described (10, 12, 13). See online supplement for details.

Right Ventricular Hypertrophy

Right ventricular hypertrophy (RVH) was assessed by weighing the right ventricular free wall and left ventricle plus septum. The ratio expressed as RV/LV+S. See online supplement for details.

Lung Histopathology

3µm lung sagittal sections were stained with ±-smooth-muscle actin (<80 µm external diameter) and microscopically assessed for degree of muscularisation in a blinded fashion, as previously described (14) and in online supplement.

qRT-PCR

mRNA expression was assessed in lungs of mice by qRT-PCR as described previously and in online supplement (10).

Immunoblotting

Protein expression was assessed by immunoblotting in lung and hPASMCs as described previously and in online supplement (10).

Lung Immunolocalization

Aromatase expression was investigated in murine, rat and human lung by immunohistochemistry as described previously and in online supplement (10).

Measurement of Estradiol Concentrations.

Circulating estradiol was quantified in plasma by ELISA (Estradiol ELISA, Life Technologies).

hPASMCs and PAH-PASMCs

hPASMCs were prepared and cultured as described previously and in online supplement (10).

Statistics

All data are expressed as mean ± SEM. Data were analysed using one-way ANOVA with Dunnett's or Bonferroni post-hoc analyses and Student's unpaired t-test (as appropriate and indicated in figure legends) using GraphPad Prism 5 software. A P value < 0.05 was considered statistically significant.

Results

Inhibition of aromatase attenuates experimental PH in female but not male mice.

In female mice anastrozole reduced hypoxia-induced increases in RVSP, RVH and pulmonary vascular remodelling (PVR) (Figure 1A-D). However, in male mice, anastrozole when used at the most effective dose ($3mgkg^{-1}day^{-1}$) had no significant effect on hypoxia-induced elevations in RVSP, RVH or PVR (Figure 1E-H). Anastrozole had no significant effect on mean systemic arterial blood pressure or heart rate (Figure E1 online supplement).

To confirm that this effect was not due to any off-target effects of anastrozole, the effect of MPP, an ER± antagonist was assessed. MPP was selected as ER± protein levels were found to be significantly elevated in pulmonary arteries from female hypoxic mice, whilst ER² was significantly reduced. No significant differences in the expression of ER± or ER² were observed in pulmonary arteries from male mice (Figure E2 online supplement). MPP markedly attenuated hypoxia-induced increases in RVSP and PVR in females but had no therapeutic effect in males (Figure E3 online supplement).

In female Su/Hx rats anastrozole reduced increases in RVSP, RVH, PVR and reversed the development of occlusive vascular lesions (Figure 2A-E). In contrast to females, anastrozole had no significant effect on Su/Hx-induced changes in RVSP, RVH or PVR in male animals (Figure 3A-E).

Cardiac and pulmonary function were assessed by echocardiography. In female rats anastrozole had no effect on cardiac output, but did slightly restore decreased pulmonary artery acceleration time (PAAT) (Figure E4 online supplement). In Su/Hx

male rats anastrozole had no effect on cardiac output or PAAT (Figure E4 online supplement).

Aromatase expression in hypoxic and Su/Hx-induced PH.

Weak aromatase expression was observed in pulmonary arteries from normoxic mice whilst expression was abundant in hypoxic mice, localising to the smooth muscle layer (Figure 4A). Analysis of whole lung tissue by immunoblotting showed that female mice express significantly higher levels of aromatase protein in whole lung compared to male in both normoxic and hypoxic conditions (Figure 4B). Similarly, in pulmonary arteries from normoxic rats negligible to weak aromatase staining was observed whilst expression was abundant in arteries from Su/Hx rats, localising within the vascular smooth muscle (Figure 5A). Aromatase staining was absent from the endothelial layer of rat pulmonary arteries (Figure 5B). In addition, aromatase was absent from endothelial cells within the small occlusive vascular lesions observed in Su/Hx rat lung (Figure 5C). Male rats also express significantly lower aromatase protein levels in the whole lung compared to female under both normoxic and Su/Hx conditions (Figure 5D). Exposure to Su/Hx had no effect on aromatase expression in female or male rat lung when compared to normoxic control (Figure 5D).

Aromatase expression in human lung.

Aromatase was found to be expressed in pulmonary arteries of control, female PAH and male PAH patients localising mainly within the smooth muscle layer (Figure 6A). Aromatase immunostaining was also present in vascular lesions from PAH patients (Figure 6B) also localising to the smooth muscle layer. Aromatase immunoreactivity

was absent in the endothelium of most PAH patients regardless of BMPR2 status (Figure 6B and E5B). In addition, there was no evidence of aromatase expression in human microvascular pulmonary artery endothelial cells (hMPAECs) (Figure E5C online supplement). PASMCs isolated from control postmenopausal females express significantly higher levels of aromatase than those from males (Figure 6C), however, no significant difference in aromatase expression in PASMCs from female control *versus* female PAH patients was observed (Figure 6D).

Effect of anastrozole on circulating estrogen levels.

Anastrozole 0.3mgkg^{-1} and 3mgkg^{-1} decreased levels of circulating estradiol, the major bioactive estrogen in female mice and had no effect on circulating estrogen levels in the male mice. Furthermore, hypoxia alone had no effect of circulating estrogen levels in either female or male mice (Figure 7A)

In the Su/Hx rat model, estradiol levels were undetectable in male rats. However, in female rats, circulating estradiol levels were found to be significantly elevated in the Su/Hx rats compared to normoxic controls (Figure 7B). Anastrozole reduced circulating estradiol levels in a dose-dependent fashion. Analysis across the female Su/Hx treatment groups revealed a significant correlation between circulating estradiol concentrations and RVH (Figure 7C) as well as the percentage of muscularised pulmonary arteries (Figure 7D).

Effects of anastrozole on hypoxia and Su/Hx-mediated changes in bone morphogenetic protein receptor 2 (BMPR2).

In normoxic conditions lung transcript levels of BMPR2 were significantly lower in female mice than male. Administration of anastrozole resulted in a significant

upregulation of BMPR2 in female lung, restoring levels to that of males whilst having no effect on BMPR2 levels in male lung (Figure 8A). In hypoxia, BMPR2 transcript and protein levels were significantly reduced in both male and female lung. Anastrozole treatment restored the hypoxia-mediated downregulation in BMPR2 in females (Figure 8A-B) but not males (Figure 8A&C). In the Su/Hx rat model, BMPR2 transcript was also found to be significantly decreased in both male and female lung compared to normoxic controls (Figure 8D-F). This effect was reversed in female rats treated with anastrozole $3mgkg^{-1}day^{-1}$ (Figure 8D-E) but not male rats (Figure 8F). The male rats had significantly higher normoxic transcript levels of BMPR2 compared to females, consistent with our observations in mice (Figure 8D).

Female normoxic mouse and rat lung demonstrated significantly lower levels of Id1 and Id3 (Figure E6 online supplement) than males. In females anastrozole significantly elevated Id1 and Id3 to levels similar to that observed in males but had no effect on Id1 and Id3 expression in male lung. Id1 expression was significantly reduced in both male and female disease models, whilst Id3 was specifically downregulated in males. The PH-mediated decreases in Id1 were rescued by administration of anastrozole in female animals but not male (Figure E6 online supplement). ER± antagonist MPP also restored hypoxia-mediated reductions in BMPR2 and Id1 (Figure E7 online supplement).

Discussion

Increased synthesis of estrogen has been clinically associated with porto-pulmonary hypertension (15) and estrogen is causative in female susceptible models of PH (7-

9). Studies into the role of estrogen in PAH have failed to reach a concensus, mainly due to the variety of experimental approaches adopted. Indeed, many experimental studies have demonstrated a protective effect of estrogen in male animals (4-6). These valuable studies examined the influence of estrogen administered to males where estrogen levels are normally extremely low or undetectable. In addition, these studies utilise intact males, hence the presence of high endogenous testosterone combined with high circulating estrogen levels (due to the exogenously added estradiol) are not a state that would normally occur physiologically and may influence interpretation of results. In the instance of monocrotaline (MCT)-induced PH the beneficial effects of estrogen may be owing to the fact that MCT is a toxin reported to cause gonadal toxicity and reduce estrogen levels (16). In our experimental design we wished to compare males and females and address a different question: 'what is the role of *endogenous* estrogen and is it different in intact males and females'?

The data presented in this study explains some of these current controversies by providing several unique insights into the influence of gender and endogenous estrogen in the development of PH. We demonstrate that endogenous estrogen contributes to the pathophysiology of PH in females and that there is potential for local estrogen synthesis in PASMCs. Given the previously demonstrated mitogenic effects of estrogen in PASMCs (7), we also describe a unique pro-proliferative phenotype in female PASMCs owing to elevated aromatase and reduced BMPR2 and Id1 expression.

Using anastrozole we inhibited the enzyme aromatase, which is responsible for estrogen synthesis, to determine the role of endogenous estrogen on established PH in females and males. Anastrozole reduced plasma estrogen and attenuated hypoxia and Su/Hx-induced changes in RVSP, RVH and PVR in females.

Furthermore, in the female Su/Hx model a positive correlation between circulating estrogen concentrations and disease severity was established, suggesting the therapeutic effects of anastrozole were related to a decrease in plasma estrogen levels. In the males, there was no therapeutic effect of anastrozole; plasma estrogen was below the level of detection and unaffected by anastrozole.

We also demonstrated that there is a dysregulation in the expression of estrogen receptors in hypoxic female mice but not male, with ER± expression significantly increased and ER² decreased in female pulmonary artery whilst both receptors remain unaffected in males. Furthermore, we show that an ER± antagonist, MPP, has selective therapeutic effect in female hypoxic mice, not male. This corroborates our hypothesis that endogenous estrogen is pathogenic in female models of PH. Anastrozole is a third generation highly selective competitive inhibitor of aromatase and as such has few off-target actions. Preclinical studies show that even when used up to doses of $10mgkg^{-1}$ in rats no reported disturbances in adrenal steroidogenesis were observed (17).

Estrogen is widely described to be cardioprotective due to its direct action on the heart. Epidemiological evidence shows that pre-menopausal women have a lower risk for mortality from cardiovascular diseases than men (18-20). Given the cardioprotective effects of estrogen there is concern that treatment with aromatase inhibitors may facilitate right ventricular dysfunction. Hence we interrogated the influence of anastrozole on heart function in the Su/Hx rat model by echocardiography. Anastrozole had no detrimental effects on cardiac output or pulmonary artery acceleration time in rats. These findings suggest that depletion of estrogen is not having detrimental effects on the heart that might limit the use of anastrozole in the treatment of PAH. Aromatase inhibitors are currently widely

prescribed to patients with estrogen receptor-sensitive breast cancer and many systemic side-effects have been investigated Available data do not support an association between aromatase inhibitors and an increased risk of cardiovascular disease, PAH or a deleterious effect on lipid metabolism in humans (21).

Aromatase was expressed in small pulmonary arteries of both female and male rodents localising within the smooth muscle layer. However, aromatase expression was significantly higher in the lungs from female rats and mice than males. This may partially explain the increased therapeutic effect of anastrozole in the females. We also verified that aromatase is expressed in the smooth muscle of pulmonary arteries in human lung, demonstrating that aromatase is abundantly expressed in vascular smooth muscle from control non-PAH lung sections and in complex vascular lesions. This coupled with the elevated aromatase expression observed in female PASMCs suggests female PASMCs have the ability to synthesis higher levels of estradiol that male. This may contribute to the female susceptibility to PAH given the mitogenic properties of estradiol.

This is the first study to report that there is the potential for local estrogen production in pulmonary arteries. We could find no evidence for aromatase expression in the endothelium of rats, mice or human in our studies regardless of their disease status. Likewise, hMPAECs do not express aromatase. This suggests that estrogen produced by PASMCs that exerts a paracrine proliferative effect on adjacent PASMCs. Indeed, we have previously demonstrated that estrogen induces proliferation in human PASMCs (7, 8). Estrogen synthesized within extragonadal compartments has been postulated to act at a local tissue level in a paracrine fashion (22). Thus, the total amount of estrogen synthesized by these extragonadal sites may be small but the local tissue concentrations achieved high enough to exert

significant biologic influence locally (11). Given the expression of aromatase in the smooth muscle layer of the pulmonary artery the local concentration of estrogen in the pulmonary artery may be much greater than circulating concentrations. Estrogen levels will also be affected by metabolism. We have previously shown that expression of cytochrome P450 1B1 (CYP1B1) an estrogen metabolising enzyme is dysregulated in the Su/Hx mouse model of PH (10). Differences in estrogen metabolism between the hypoxic mouse model and Su/Hx rat model of PH may explain why circulating estrogen levels are elevated in Su/Hx rats but not hypoxic mice.

Loss of function associated with BMPR2 mutations in PAH results in reduction of the growth inhibitory effects of BMPs, facilitating the proliferation of PASMCs and contributing to pulmonary vascular remodelling (23). BMPR2 is also often observed to be down-regulated in animal models of PAH (24, 25). Here we showed that expression of BMPR2 and its downstream mediator Id1 are significantly decreased in the lungs of normoxic female rodents compared with males. The significantly lower levels of BMPR2 and Id1 in females can be restored to levels similar to that observed in males by anastrozole, suggesting estrogen may be responsible for the suppressed BMPR2 signaling axis in females. Furthermore, anastrozole treatment restored hypoxic and Su/Hx-mediated reductions in BMPR2 mRNA and protein levels in female rodents whilst having no effect on males. These observations provide one further explanation for the selective therapeutic effect of anastrozole on the development of PH in female models, i.e. endogenous estrogen in the lungs of females is greater due to increased aromatase expression; this combined with the effects of hypoxia or Su/Hx, decreases expression of BMPR2 which is already

significantly reduced in females. Consequently anastrozole, by decreasing endogenous estrogen levels, has a selective therapeutic effect in females.

In hPAH families, penetrance of PAH in BMPR2 mutation carriers is low, suggesting other risk factors must influence the emergence of the PAH phenotype. Indeed, further predisposing genes such as KCNK3 and TOPBP4 have been recently identified (26, 27). Whilst increased aromatase expression combined with decreased BMPR2 signaling may predispose susceptible females to PAH it is unlikely that these factors alone are responsible for the clinical presentation of disease in all females; and clearly males develop PAH, displaying poorer survival rates than females (1). Our results suggest that once the disease is established, the increased influence of both circulating and locally produced estrogen in women, results in an enhanced pathogenic effect on the pulmonary circulation compared to males. Consistent with this, female PAH patients have 2.8-fold higher number of plexiform lesions compared with their male counterparts (20).

However, in some patient sub-groups including PAH associated with HIV, sleep apnea and portopulmonary hypertension the prevalence of PAH is greater in males (1). However, these primary conditions occur more frequently in men, potentially influencing the male:female ratio of those developing PAH (e.g.(28-30)). In addition, estrogen may contribute to the disease pathophysiology in males within these subgroups. For instance, in HIV dysregulation in sex hormone concentrations have been reported in both sexes. In one study estradiol was reported to significantly increase over an 18 month period in male HIV patients (31). Furthermore, obstructive sleep apnea is most common in obese men (29), in which elevated circulating estrogen levels are common due to the high expression and activity of aromatase within adipose tissue (32, 33). Polymorphisms in the aromatase gene

have also been associated with increased risk of portopulmonary hypertension in patients with liver disease. These polymorphisms are associated with increased estradiol production, supporting a functional effect of aromatase activity in both male and female patients (15). Thus, elevated estrogen is observed in the males in these PAH subgroups. This is not incompatible with the suggestion that when elevated, endogenous estrogen may contribute to the pathobiology PAH in males as well as females.

The results of this study also suggests that non-estrogenic contraceptives be recommended to pre-menopausal PAH patients, although these are already contra-indicated for PAH patients due to the increased risk of venous thromboembolic disease (34).

In summary, we have demonstrated that endogenous estrogen plays a causative role in the development of experimental PH in female animal models of the disease. Inhibition of aromatase with anastrozole reduces moderate and severe experimental PH in female animals via reduction in endogenous estrogen. The reason for the sexual dimorphism in the therapeutic effects of anastrozole may be due to a unique phenotype of female pulmonary arteries. We propose that increased capability of female PASMCs to produce estrogen locally via aromatase contributes to a reduction in the BMPR2 signalling axis and may contribute to the pathology and increased incidence of the disease in females. The results partly explain the 'estrogen paradox' and suggest that aromatase inhibitors may have therapeutic potential in the treatment of PAH in females.

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Figure 1

Inhibition of aromatase attenuates chronic hypoxia-induced PH in female mice. **Female mice:** Effects of the aromatase inhibitor, anastrozole (ANA) 0.3 $mgkg^{-1}day^{-1}$ and 3 $mgkg^{-1}day^{-1}$ for 14 days on (**A**) RVSP (n=8-10 per group), (**B**) RVH (n=8-10 per group) (as determined by RV/LV+S ratio) and (**C**) the % of remodelled pulmonary arteries in normoxic mice and hypoxic female mice with established PH (n=6 per group). (**D**) Representative images of pulmonary arteries from normoxic and hypoxic female mice treated with or without anastrozole 3 $mgkg^{-1}day^{-1}$ (brown staining indicates ±-smooth muscle actin; scale bar (**-**) indicates 20µm). **Male mice:** Effects of ANA 3 $mgkg^{-1}day^{-1}$ for 14 days on (**E**) RVSP (n=8-10 per group), (**F**) RVH (n=8-10 per group) (as determined by RV/LV+S ratio) and (**G**) the % of remodelled pulmonary arteries in normoxic mice and hypoxic male mice with established PH (n=6 per group). (**H**) Representative images of pulmonary arteries from normoxic and hypoxic male mice treated with or without anastrozole 3 $mgkg^{-1}day^{-1}$ (brown staining indicates ±-smooth muscle actin; scale bar (**-**) indicates 20µm). Data displayed as mean ± SEM. **p<0.01 and ***p<0.001 as indicated, determined by one-way ANOVA with Bonferroni post test. RVSP = right ventricular systolic pressure, RVH = right ventricular hypertrophy and RV/LV+S = right ventricle/left ventricle + septum.

Figure 2

Inhibition of aromatase attenuates Su5416/hypoxia (Su/Hx)-induced PH in female rats. (**A**) RVSP (n=5-8 per group), (**B**) RVH (n=5-8 per group) (as determined by RV/LV+S) and (**C**) the % remodelled pulmonary arteries (n=5-8 per group) were assessed on day 14 (D14) and day 28 (D28) following administration of Su/Hx in female rats treated with or without anastrozole (ANA) 0.03 $mgkg^{-1}day^{-1}$, 0.3 $mgkg^{-1}day^{-1}$ or 3 $mgkg^{-1}day^{-1}$ for 14 days in female rats (from D14-28). Representative images showing (**D**) ±-smooth muscle actin (±-SMA) staining in pulmonary arteries from Su/Hx female rats treated with or without anastrozole (±-SMA = brown staining; scale bar (**-**) indicates 20µm). (**E**) The percentage of pulmonary arteries which are fully occluded in female rats treated with or without anastrozole (n=5-8) and (**F**) representative image of an occluded pulmonary artery (±-SMA = pink, vWF = black; scale bar (**-**) indicates 20µm). Data displayed as mean ± SEM. * p<0.05, **p<0.01 and ***p<0.001 as indicated, # p<0.01 versus D14 Su/Hx as determined by one-way ANOVA with Dunnett's post test. RVSP = right ventricular systolic pressure and RVH = right ventricular hypertrophy.

Figure 3

Inhibition of aromatase does not attenuate Su5416/hypoxia (Su/Hx)-induced PH in male rats. (A) RVSP (n=5-8 per group), (B) RVH (n=5-8 per group) and (C) the % remodelled pulmonary arteries (n=5-8 per group) were assessed on day 14 (D14) and day 28 (D28) following administration of Su/Hx in male rats treated with or without anastrozole (ANA) 3 $mgkg^{-1}$ (from D14-28) Representative images showing (D) ±-SMA staining in pulmonary arteries from SU/Hx male rats treated with or without anastrozole (±-SMA = brown; scale bar (-) indicates 20µm). (E) The percentage of pulmonary arteries which are fully occluded (n=5-8 per group) in male rats treated with or without anastrozole $3mgkg^{-1}$ and (F) representative image of an occluded pulmonary artery (±-SMA = pink, vWF = black ; scale bar (-) indicates 10µm). Data displayed as mean ± SEM. * $p<0.05$, ** $p<0.01$ and *** $p<0.001$ as indicated, determined by one-way ANOVA with Dunnett's post test. RVSP = right ventricular systolic pressure and RVH = right ventricular hypertrophy .

Figure 4

Effect of chronic hypoxia on aromatase expression in mouse pulmonary artery and whole lung. Representative images showing (**A**) aromatase immunolocalisation in pulmonary arteries (scale bar (**-**) indicates 20µm) with 3µm consecutive sections showing ±-smooth muscle actin (±-SMA) and von Willebrand factor (vWF) (representative of n=4 per group, brown staining). For IgG control see online supplement Figure E5. (**B**) Representative immunoblot and quantification of aromatase protein expression in whole lung from normoxic and hypoxic, female and male mice (n=5-6 per group). Data displayed as mean ± SEM. *p<0.05 and ** p<0.01 as indicated, determined by one-way ANOVA with Bonferroni post test.

Figure 5

Effect of Su5416/hypoxia (Su/Hx) on aromatase expression in rat pulmonary artery and whole lung. Representative images showing (**A**) aromatase immunolocalisation in pulmonary arteries (scale bar (**-**) indicates 20µm) with 3µm consecutive sections showing ±-smooth muscle actin (±-SMA) and von Willebrand factor (vWF) (representative of n=4 per group, brown staining) (for IgG control refer to online supplement Figure E5. (**B**) Representative image showing the absence of aromatase immunolocalisation in the endothelial layer of rat pulmonary artery (scale bar (**-**) indicates 50µm (x400 magnification)) with 3µm consecutive sections showing ±-smooth muscle actin (±-SMA) and von Willebrand factor (vWF) (brown staining). (**C**) Representative image showing aromatase immunolocalisation in small occlusive vascular lesions from SuHx rat (scale bar (**-**) indicates 20µm) with 3µm consecutive sections showing ±-smooth muscle actin (±-SMA) and von Willebrand factor (vWF) (brown staining). (**D**) Representative immunoblot and quantification of aromatase protein expression in whole lung from normoxic and hypoxic, female and male rats (n=5-6 per group). Data displayed as mean ± SEM. *p<0.05 and ** p<0.01 as indicated, determined by one-way ANOVA with Bonferroni post test.

Figure 6

Aromatase expression in human PAH. (**A**) Representative images showing aromatase immunolocalisation in control and female and male PAH patients. (**B**) Representative images showing examples of aromatase immunolocalisation in vascular lesions from PAH patients (aromatase (AROM) = pink; ±-smooth muscle actin (±-SMA) and von Williebrand factor (vWF) = brown; scale bar (**-**) indicates 100µm; for IgG control see online supplement Figure E5). Aromatase protein expression was also assessed by immunoblotting using human pulmonary artery smooth muscle cells (hPASMCs). (**C**) Representative immunoblots and graph showing quantification comparing aromatase expression in hPASMCs isolated from male and female control (n=4 samples per group) and (**D**) female control and female PAH patients (n=4 samples per group). Data displayed as mean ± SEM. ***p<0.001 as indicated, determined by two-tailed, unpaired t-test. **1-11, a,e,i** and **j** correspond to patient information on human tissues and cells referred to in online supplement Table E3.

Figure 7

Effect of aromatase inhibition on circulating estradiol (E2) levels in models of pulmonary hypertension. (**A**) Circulating plasma E2 levels in normoxic and hypoxic female and male mice treated with or without anastrozole (ANA) for 14 days (n=5 per group)**.** Data displayed as mean ± SEM. *p<0.05, **p<0.01 and ** p<0.001 as indicated, determined by one-way ANOVA with Bonferroni post test. (**B**) Circulating E2 levels in female Su/Hx rats treated with or without 0.3 $mg^{-1}kg^{-1}day^{-1}$, 1 $mg^{-1}kg^{-1}day^{-1}$ or 3 $mg^{-1}kg^{-1}day^{-1}$ anastrozole (n=4-5 per group). Data displayed as mean ± SEM. *p<0.05 and *** p<0.001 as indicated, determined by one-way ANOVA with Dunnett's post test. Plasma E2 levels from female Su/Hx rats were used to determine if there was any correlation with disease severity using Pearson's coefficient. Significant correlation between plasma E2 levels and (**C**) RVH (as determined by RV/LV+S) (n=30) and (**D**) the percentage of muscularised pulmonary arteries (n=30). *p<0.05 and **p<0.01 as indicated. All E2 concentrations are expressed as a percentage relative to normoxic set at 100%.

Figure 8

Effects of aromatase inhibition on hypoxia and Su/Hx-induced changes in BMPR2 expression. **A-C: hypoxic mice**. (**A**) Relative gene expression levels of BMPR2 in male and female normoxic and hypoxic mouse lung treated with or without anastrozole 3 $mgkg^{-1}day^{-1}$ (n=6 per group). Representative immunoblot and quantification showing effects of anastrozole 3 $mgkg^{-1}day^{-1}$ on BMPR2 protein expression in (**B**) female and (**C**) male normoxic and hypoxic mouse lung (n=6 per group). **D-F: Su/Hx rats.** (**D**) Relative gene expression levels of BMPR2 in female and male normoxic and Su/Hx rat lung treated with or without anastrozole 3 $mgkg^{-1}day^{-1}$ for 14 days (n=5-6 per group). Representative immunoblot and quantification showing effects of anastrozole 3 $mgkg^{-1}day^{-1}$ on BMPR2 protein expression in (**E**) female and (**F**) male lung from normoxic and Su/Hx rats treated with or without anastrozole 3 $mgkg^{-1}day^{-1}$ for 14 days (n=5-6 per group). Gene expression levels are normalised to ² -2-microglobulin (² 2M). Data displayed as mean ± SEM. *p<0.05 and **p<0.01 as indicated, determined by one-way ANOVA with Bonferroni post test.