Assessment of Inhaled Treprostinil Palmitil, Inhaled and Intravenous Treprostinil, and Oral Selexipag in a Sugen/Hypoxia Rat Model of Pulmonary Arterial Hypertension


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ABSTRACT

Treprostinil palmitil (TP), a long-acting inhaled pulmonary vasodilator prodrug of treprostinil (TRE), has beneficial effects in a Sugen5416/hypoxia (Su/Hx) rat model of pulmonary arterial hypertension (PAH) that compare favorably to the oral phosphodiesterase 5 inhibitor (PDE5) sildenafil. In this study, male Sprague-Dawley rats, a dry powder formulation of TP (TPIP) was compared with inhaled and intravenous TRE and oral selexipag to evaluate inhibition of hemodynamic and pathologic changes in the lungs and heart induced by Su/Hx challenge. Su (20 mg/kg) was injected subcutaneously followed by 3 weeks of Hx (10% O2/balance N2) and then initiation of test article administration over 5 weeks with room air breathing. Hemodynamics and histopathology were measured at the end of the study. Su/Hx challenge approximately doubled the mean pulmonary arterial blood pressure (mPAP) and the Fulton index, decreased cardiac output (CO), doubled the wall thickness and muscularization of the small (10–50 μm) and medium (51–100 μm) sized pulmonary arteries, and increased the percentage of obliterated pulmonary blood vessels. Even though inhaled TRE (65 μg/kg, 4x daily), intravenous TRE (810 ng/kg/min), and oral selexipag (30 mg/kg, twice daily) provided some beneficial effects against the Su/Hx challenge, the overall benefit was generally greater with TPIP at high dose (117 μg/kg, once daily). These results demonstrate that TPIP compares favorably to inhaled and intravenous TRE and oral selexipag with respect to inhibition of the pathophysiological changes induced by Su/Hx challenge in rats.

SIGNIFICANCE STATEMENT

Treprostinil palmitil (TP) is a long-acting pulmonary vasodilator prodrug of treprostinil (TRE) formulated for inhaled administration by dry powder [treprostinil palmitil inhalation powder (TPIP)]. Comparison of the activity of TPIP, inhaled and intravenous TRE, and oral selexipag in a Sugen5416/hypoxia (Su/Hx) rat model of pulmonary arterial hypertension demonstrated that each of these drugs exert protection against the hemodynamic and histopathological changes induced by the Su/Hx challenge, with the greatest effect on these changes produced by TPIP.

Introduction

Treprostinil palmitil (TP) is an ester-linked prodrug of treprostinil (TRE) in development for the treatment of pulmonary arterial hypertension (PAH) and pulmonary hypertension associated with interstitial lung disease that has been formulated for inhaled delivery as a nebulized suspension [treprostinil palmitil inhalation suspension (TPIS)], as a dry powder [treprostinil palmitil inhalation powder (TPIP)], and as an aerosol for delivery with a metered dose inhaler [treprostinil palmitil inhalation aerosol (TPIA)] (Corboz et al., 2017; Chapman et al., 2018, 2020; Plaunt et al., 2021). TP has many attributes that may prove to be beneficial, including long-acting pulmonary vasodilation (Corboz et al., 2017; Chapman et al., 2018), no evidence of tachyphylaxis with repeated administration (Chapman et al., 2021b), a reduced propensity to cause cough (Corboz et al., 2017; Chapman et al., 2021a), and robust efficacy in a Sugen5416/hypoxia (Su/Hx) rat model of PAH that compared favorably to results from the phosphodiesterase 5 (PDE5) inhibitor sildenafil (Corboz et al., 2022).

Inhaled TP has several important features that may prove to be extremely important to treat PAH pathology. Administration by inhalation results in a locally high concentration of TP in the pulmonary arteriolar wall.
lungs, and after a slow conversion of TP to TRE by the action of lung esterase (Leifer et al., 2018) leads to a greater duration of TRE exposure in the lungs, resulting in beneficial effects such as long-acting pulmonary vasodilation (Sandifer et al., 2005; Chapman et al., 2018); TRE binds to the prostanycin (IP), prosta-
glandin E type 2 (EP2), prostaglandin E type 4 (EP4), pros-
glandin D2 receptor 1 (DP1), and the peroxisome proliferator-
activated (PPAR) receptors (Ali et al., 2006; Falcetti et al., 2007;
Whittle et al., 2012; Clapp and Gurung, 2015; Corboz et al.,
2017, 2021a), mostly found on structural, inflammatory, and
immune cells involved with PAH pathology, which discrimi-
nates it from oral selexipag that is a selective IP receptor ago-
nist (Gatfield et al., 2017). Also, TP does not induce
tachyphylaxis after inhalation for up to 32 consecutive days,
whereas tachyphylaxis and IP receptor desensitization are
found when TRE is continuously infused by the intravenous
route (Gatfield et al., 2017; Chapman et al., 2021b). Finally,
inhaled TP inhibits much of the pulmonary vascular remodeling
that is induced by Su/Hx challenge in rats (Corboz et al., 2022),
which is a feature not observed for subcutaneously infused TRE
(Chaudhary et al., 2018).

The present study was designed to compare the activity of
TPIP to that produced by different drugs that act on the pro-
sanycin pathway that are currently used to treat PAH sub-
jects, including inhaled and intravenous TRE and oral selexipag. For this evaluation, we used a Sugen5416/hypoxia
(Su/Hx) rat model of PAH, as it recapitulates many of the im-
portant features of human PAH pathology such as increased
pulmonary vascular resistance, pulmonary vascular remodel-
ning, occlusion of small pulmonary blood vessels, an increase
in right heart size, and reduced cardiac performance (Tarasevi-
ciene-Stewart et al., 2001; de Raaf et al., 2014; Toba et al.,
2014; Jiang et al., 2016; Bhat et al., 2017; Corboz et al.,
2022). The dose selection for the compounds tested was based upon a combination of published data (Chaudhary et al., 2018; Honda et al., 2020) and efficacy studies in healthy rats measuring the
inhibition of pulmonary vasoconstriction induced by challenge
with an inhaled hypoxic mixture (Corboz et al., 2021b).

Materials and Methods

Details of the methods and supporting data can be found in the online Supplemental Material.

Materials

TPIP was manufactured by Bend Research Inc. (Bend, OR) as a
dry powder for inhalation, composed of 68.50% mannitol, 29.25% leu-
cine, 1.50% TP, and 0.75% 1,2-disteroyl-sn-glycero-3-phosphoethanol-
and TP were obtained from Chiroteg International (Taoyuan County,
Taiwan, China). TRE was prepared for nebulization by dissolving
0.5 mM TRE in phosphate buffered saline (PBS). TRE for intravenous
administration was prepared by dissolving 8.75 or 10.70 mg/ml of
TRE with 3.0 mg/ml m-Cresol, 5.3 mg/ml sodium chloride (NaCl), and
6.3 mg/ml sodium citrate dihydrate. PBS was purchased from Medi-
atech (Manassas, VA), m-Cresol and methylcellulose (MC) from Sigma-Aldrich (St. Louis, MO), and NaCl and sodium citrate di-
hydrate from Fisher (Waltham, MA). Selexipag was suspended in 0.5% (w/v) MC and given by oral gavage in a volume of 10 ml/kg body
weight. Selexipag was purchased from MedChemExpress (Monmouth
Junction, NJ). The vehicles for TPIP, inhaled and intravenous TRE,
and oral selexipag contained each excipient but no drug. Su was
obtained from Adooq Bioscience (Irvine, CA) and dissolved in 100% di-
methyl sulfoxide (DMSO).

Animals

Experiments were performed in adult male Sprague-Dawley rats
(Charles River Laboratories, Saint-Constant, Quebec, Canada). The
animals’ weights, between 200 and 250 g at the beginning of the
Su/Hx study, were measured weekly throughout the study. The rats
were housed in temperature- (21°C) and humidity-controlled condi-
tions and were acclimated to the laboratory surroundings for 6 to 7
days before commencement of the study. All experimental procedures
were performed in accordance with the Canadian Council on Animal
Care (CCAC) guidelines and followed the principles of Good Labora-
tory Practice (GLP) Regulations of the US Food and Drug Administra-
tion (FDA) (21 CFR Part 58) and current Organization for Economic
Co-operation and Development (OECD)/Ministry of Health, Labor and
Welfare (MHLW) and International Conference on Harmonization
(ICH) guidelines.

Inhaled Hypoxia Challenge

Rats were prepared with telemetry probes inserted into the right
ventricle and descending aorta to measure the right ventricular pulse
pressure (RVPP) and mean systemic arterial blood pressure (mSAP)
in response to an inhaled hypoxic gas mixture as described previously
(Chapman et al., 2021b). The rats were placed in individual plexiglass
chambers through which normoxic (Nx) air (21% O2/balance N2) from a
compressed gas source was circulated at a flow rate of 8.75 l/min
(Chapman et al., 2021b). After an equilibration period of 30 minutes,
data were collected for the baseline Nx exposure followed by transition
to a 10-minute exposure of Hx with hypoxic gas (10% O2/90% N2), also
delivered from a compressed gas source, followed by a return to a 10-
minute period of room air breathing. The study design for the acute
Hx challenge in telemetered rats is illustrated in Supplemental Fig. 1.
From these results, the increase in RVPP (∆RVPP) due to Hx from the
Nx values and change in mSAP were measured. Each rat was ex-
posed to Hx on three separate occasions on the day before the admin-
istration of test articles with the baseline response representing the
average of these three Hx exposures. The following day, the rats were
treated with the test articles or vehicles with additional Hx challenges
performed intermittently over the next 24 hours.

Sugen/Hypoxia Challenge

Rats received a subcutaneous injection of Su at 20 mg/kg followed
by 3 weeks of exposure to an inhaled hypoxic gas mixture (10% O2
/90% N2) and then a return to room air breathing for 5 weeks. The
test articles (drugs or drug vehicles) were administered immediately
after the Hx challenge and were dosed daily throughout the 5-week
room air breathing period. A control group of rats received the vehicle
for Su (100% DMSO) followed by 8 weeks of room air breathing. The
study design for the acute Hx challenge in telemetered rats is illus-
trated in Supplemental Fig. 2, and details of the transition from Nx to
Hx and return to room air breathing and drug administrations are
shown in Supplemental Table 1. All animals were maintained on a
light-dark (12-hour/12-hour) cycle receiving water and food ad libitum.

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catheterized for the measurement of systolic, diastolic, mean pulmonary arterial blood pressure (mPAP), and mSAP as previously described (Corboz et al., 2022). A pulse oximeter was placed on the paw for the measurement of heart rate (HR) and pulse oximeter oxygen saturation (SpO₂). Echocardiography was performed intermittently throughout the study using a GE Healthcare echocardiography system (Model Vivid 7, GE Healthcare, Chicago, IL) to measure the pulmonary artery acceleration time (PAAT), right ventricular anterior wall thickness (RVWATT), and HR as previously described (Urboniene et al., 2010; Zhu et al., 2019). From these data, the cardiac output (CO) and stroke volume (SV) were calculated according to the relationships previously described (Lewis et al., 1984).

As a surrogate measure, pulmonary vascular resistance (PVR) was estimated using the following ratio (Wang et al., 2013):

\[
PVR = \frac{RVSP}{CO} \tag{1}
\]

with PVR as pulmonary vascular resistance (mmHg/ml-min⁻¹), RVSP as right ventricular systolic pressure (mmHg), and CO as cardiac output (ml/min).

At the end of the hemodynamic recording, the rats were euthanized and the heart and lungs were removed for histologic analysis and derivation of the Fulton index (Corboz et al., 2022). The Fulton index was calculated from measurements of the right ventricle and left ventricle plus septum weights as described previously (Fulton et al., 1952; Hangartner et al., 1985).

\[
\text{Fulton Index} = \frac{\text{left ventricle weight (g)}}{\left(\text{right ventricle weight} + \text{septum weight}\right) (g)} \tag{2}
\]

Histologic Procedure of the Lung

For the histologic evaluations on the lungs, tissues were embedded, sliced at 5 μm thickness, and stained with hematoxylin and eosin (H&E); the pulmonary arteries/arterioles were identified and categorized into small (10–50 μm), medium (51–100 μm), and large diameter vessels (>100 μm); and the percentage of these pulmonary blood vessels demonstrating the presence of a muscular (completely surrounded by a smooth muscle layer, >90% circumference), semi-muscular (incompletely surrounded by a smooth muscle layer, 10%–90% circumference) or nonmuscular (no apparent smooth muscle layer, <10% circumference) appearance were quantified. The tissues were also stained with alpha smooth muscle actin (αSMA) to quantify the presence of smooth muscle present in the vascular wall of the pulmonary arteries (Corboz et al., 2022).

To identify and quantify the occlusive lesions of the small pulmonary arteries, the tissues were embedded, sliced at 5 μm thickness, and stained with von Willebrand factor (vWF) and categorized into vessels having no evidence of neo-intimal formation (nonoccluded), as partially obliterated with <50% of luminal occlusion (semi-occluded), or as mostly obliterated with ≥50% of luminal occlusion (mostly occluded).

Only intra-acinar vessels within the gas exchange regions of the lung (alveoli, alveolar ducts, and respiratory bronchioles) were used in these analyses. All vessels associated with terminal bronchioles were excluded. For the histologic analysis of cardiac tissue, the tissues were embedded, sliced at 5 μm thickness, and stained with H&E for the assessment of morphology and with Masson’s trichrome stain to identify the presence of collagen (Corboz et al., 2022).

Histologic Procedure of the Heart

The hearts from each treatment were separated into two groups, with half of the samples designated for the histology and stained with H&E or Masson’s trichrome. The other half were used for measurement of the Fulton index determination and proteomic parameters. The heart tissues harvested for histologic analysis were fixed in 10% neutral buffered formalin (NBF) for 24 hours. A transversal section in the middle of the heart was cut and sent to the Institute for Research in Immunology and Cancer (IRIC, Montreal, Quebec, Canada) in 10% NBF embedded in paraffin, sliced at 5 μm thickness, mounted, and stained with either H&E for overall assessment of the cardiomyocyte morphology or with Masson trichrome for collagen fiber visualization and quantification. Stained tissues were then scanned at 20x magnitude resolution for analysis. High resolution images were analyzed using NDD.view 2.7.25 Zoomer Digital Pathology (Hamamatsu) software for the general analysis and Infinity Analyze 5.0.3 for collagen quantification.

Drug Administrations in the Acute Inhaled Hypoxia and Sugen/Hypoxia Challenges

Inhaled delivery of the test articles was performed using a 12-port nose-only inhalation chamber (CH Technologies, Westwood, NJ) that was adapted for administration of either dry powder aerosols of TPPI or nebulized administration of TRE (Corboz et al., 2017; Chapman et al., 2021a). Dry powder aerosol was generated using a Vilnius Aerosol Generator (VAG) (CH Technologies, Westwood, NJ) and dispersed into the nose-only chamber with air from a compressed gas source at a flow rate of 7 l/min, and nebulized aerosol was generated with an Aeroneb Pro nebulizer (Aerogen, Galway, Ireland) that was dispersed into the nose-only chamber with compressed air at a flow rate of 6 l/min. To administer different inhaled doses of TPPI, the VAG was loaded with different amounts of material (25–170 mg) set at output values ranging from 0.125 to 1 Volt and continued until all of the powder had been aerosolized. Exposure of rats to TPPI at VAG outputs of 0.125, 0.25, 0.5, and 1 V resulted in total inhaled doses of 6, 23, 57, and 138 μg/kg, respectively, in the inhaled Hx study, and exposure of rats to TPPI at VAG outputs of 0.5 and 1 Volt resulted in total inhaled doses of 59 and 117 μg/kg, respectively, in the Su/Hx study. The aerosol concentration was maintained at the desired level with the aid of a portable aerosol monitor (Casella MicroDust Pro, Sterling, MA) providing an autofeedback circuit to the VAG. For the nebulization of TRE or PBS vehicle, 6 ml of material was placed into the Aeroneb Pro nebulizer with the output set to the “FULLY ON” position until all the material had been nebulized. Nebulized TRE at concentrations of 0.125, 0.25, 0.50, and 1 mM resulted in delivered doses of 15, 46, 110, and 215 μg/kg in the inhaled Hx study and nebulized TRE at concentrations of 0.50 mM resulted in delivered doses of 65 μg/kg in the Su/Hx challenge.

The time for aerosolization of the dry powder and nebulized test articles was recorded. A filter was connected to one of the outlet ports and attached to a vacuum pump from which a vacuum flow of 0.5 l/min was established for a 5-minute period to collect the drug. The quantitation of drug deposited on the filter was performed using high-performance liquid chromatography with mass spectrometry (HPLC/MS Single Quad) and a charged aerosol detector as described previously (Corboz et al., 2017). The inhaled drug dose was calculated using the algorithm previously described with the deposition fraction (DF) established at 1.0 (Alexander et al., 2008) and incorporating the deposition fraction previously (Corboz et al., 2017). The inhaled drug dose was calculated using the algorithm previously described with the deposition fraction (DF) established at 1.0 (Alexander et al., 2008) and incorporating the values for the concentration (C) of drug sampled from the nose-only inhalation chamber, the duration (D) of drug exposure, respiratory minute volume (RMV), and body weight (BW) (Table 1). A deposition factor of 0.1 was used for the derivation of the delivered pulmonary dose based upon the amount of drug deposited on the filter (Wolff and Dorato, 1993).

For the intravenous infusion of TRE and its vehicle, an Alzet pump (Alzet Osmotic Pumps, Cupertino, CA) was implanted subcutaneously in the neck region 1 day before the start of the infusions; details of the Alzet pump implantation and infusion of TRE have been previously described (Chapman et al., 2021b). For the TRE infusion, the Alzet pump was filled with 2 ml of 8.75 mg/ml TRE solution on day 21 and refilled on day 42 with a 10.7 mg/ml solution to account for the increase in BW. It should be noted that after this surgical procedure on day 21 of the intravenous infusions, some of the catheters were found to be disconnected from the jugular vein and had to be reinserted to continue the intravenous infusions, but no differences in plasma TRE
concentrations were observed between rats with intact and disconnected catheters (Supplemental Fig. 3).

For oral selexipag or vehicle administrations, selexipag was suspended in 0.5% MC and administered by oral gavage to rats in a volume of 10 ml/kg. The concentrations of selexipag ranged between 0.3 and 3 mg/ml to provide the appropriate testing dose of the drug, both in the acute hypoxia challenge studies and in the Su/Hx challenge experiments. The rats were given food and water throughout these studies.

Details of the different groups with treatments at targeted and delivered drug doses and routes of administration are listed in Supplemental Table 1.

Pharmacokinetics

Blood and lung tissue samples were intermittently collected, prepared for shipment to Insmed Incorporated (Bridgewater, NJ) and analyzed for their drug concentrations by high-performance liquid chromatography–tandem mass spectrometry (HPLC-MS/MS) using techniques that have been previously described (Corboz et al., 2022).

Administration of the drugs started at day 21 and ended at day 55. Blood samples were collected at: 1) day 22 (24 hours after the first dose administered at day 21), day 38 (24 hours after the dose administered at day 37), and day 56 (24 hours after the last dose administered at day 55) for the TPip groups (once daily); 2) day 22 (12 hours after the fourth dose administered at day 21), day 38 (12 hours after the fourth dose administered at day 37), and day 56 (12 hours after the last dose administered at day 55) for the inhaled TRE group (4× daily); 3) during the drug infusion at days 22, 38, and 56 for the intravenous TRE group; and 4) day 22 (16 hours after the second dose administered at day 21), day 38 (16 hours after the second dose administered at day 37), and day 56 (16 hours after the last dose administered at day 55) for the oral selexipag group (twice daily).

Lung and heart were collected at day 56 for all groups, 24 hours after the last TPip dose administered at day 55 (once daily), 12 hours after the last inhaled TRE dose at day 55 (4× daily), immediately after the interruption of the continuous TRE injection, and 16 hours after the last selexipag dose administered orally at day 55 (twice daily).

The following pharmacokinetics (PK) parameters were measured: lambda z (terminal elimination rate constant), t_{1/2z} (elimination halftime), T_{max} (time of maximal concentration), C_{max} (maximal concentration), AUC_{0–24h} (area under the concentration curve between time zero and 24 hours), and AUC_{inf} (area under the concentration curve extrapolated to infinity) using the PKSolver program in Microsoft Excel (Zhang et al., 2010). For the conversion of TP concentrations into a molar equivalent for TRE (TREeq), TP values were multiplied by a factor of 0.635 based upon the molecular weights of TP (614.9) and TRE (390.5).

Data Analysis and Statistics

All values are presented as the mean ± S.E.M. In the acute inhaled Hx experiments, a t test with repeated measures was used to determine statistically significant differences between the baseline data and that obtained at different times after initiation of test agents. In the Su/Hx studies, the hemodynamic and echocardiography data of the different drug treatments were compared with their appropriate vehicles or Nx controls using a repeat ANOVA. A post hoc analysis was performed with an unpaired Student’s t test for repeated measures. For the histologic evaluations, a repeat ANOVA was performed with post hoc analysis performed with a Tukey’s test to determine statistically significant effects within the different treatment groups. A P value of ≤0.05 was set to denote statistically significant effects.

The formula below was used to calculate the percentage inhibition produced by TPip, inhaled and intravenous TRE, and oral selexipag in each rat on mPAP, CO, Fulton index, wall thickness, percentage of muscularization, and percentage of nonobliterated blood vessels after Su/Hx challenge. From these results, a combined average percentage inhibition was calculated for each drug.

\[
\% \text{ inhibition} = \frac{(\text{Su/Hx} + \text{vehicle control}) - (\text{Su/Hx} + \text{drug})}{(\text{Su/Hx} + \text{vehicle}) - (\text{Nx control})} \times 100.
\]

Calculations for the inhaled drug dose of TPip and TRE are shown in Table 1.

Results

Inhaled Hypoxia Challenge

Inhaled TPip (6–138 μg/kg) inhibited the ΔRVPP due to Hx with the greatest inhibition occurring between 1 and 6 hours and was still significant (P ≤ 0.05) by 12 hours and slowly returned to the baseline values by 24 hours at all doses (Fig. 1A). At 24 hours, the highest TPip dose (138 μg/kg) had 48% inhibition of the ΔRVPP response to Hx but failed to reach statistical significance (P = 0.11) as it could only be measured in three rats due to technical problems with the telemetry probe. In contrast, inhaled TRE had a relatively short duration of activity and significantly (P ≤ 0.05) inhibited the ΔRVPP response to Hx only up to 1 hour at doses between 15–110 μg/kg that increased to 2 hours at the highest dose of 215 μg/kg (Fig. 1B). Oral selexipag (30 mg/kg) significantly (P ≤ 0.05) inhibited the ΔRVPP response to Hx up to 2 hours but not at times beyond this and had no significant effects at a lower dose of 10
mg/kg (Fig. 1C). Continuous infusion of intravenous TRE (810 ng/kg/min) significantly ($P \leq 0.05$) inhibited the $\Delta$RVPP response to Hx on the first day of infusion (day 0) but did not have a significant effect on days 4 through 16 (Fig. 1D).

**Sugen/Hypoxia Challenge**

**Hemodynamics.** Su/Hx induced a statistically significant ($P \leq 0.05$) increase in mPAP and reduction in CO that resulted in a 3-fold increase in PVR compared with values in the Nx controls (Fig. 2, A–C). Echocardiography parameters of SV and PAAT were significantly ($P \leq 0.05$) reduced by the Su/Hx challenge, with the greatest reductions occurring on day 21 immediately after the inhaled Hx exposure (data not shown), and were still reduced on day 56 at the end of the study (Fig. 3, A and B). Su/Hx also significantly ($P \leq 0.05$) increased the RVAWT (Fig. 3C) with a significant ($P \leq 0.05$) increase in right heart size, measured by the Fulton index (Fig. 4). There were no significant changes in mSAP or HR in the Su/Hx rats compared with the Nx controls (data not shown).

TPIP (59 and 117 µg/kg, once daily) dose-dependently inhibited the increase in mPAP and PVR and the reduction of CO that was induced by the Su/Hx challenge (Fig. 2, A–C). Statistically significant ($P \leq 0.05$) effects on mPAP and PVR were observed for both doses of TPIP and on CO with the high TPIP dose. A dose-dependent inhibition by TPIP was also observed on the changes in SV, PAAT, and RVAWT induced by Su/Hx with significant ($P \leq 0.05$) effects on each parameter observed for the high TPIP dose (Fig. 3, A–C). In contrast, inhaled TRE (65 µg/kg, 4× daily) had no significant effects on mPAP, CO, PVR, SV, and RVAWT and had a small but significant ($P \leq 0.05$) effect on PAAT induced by the Su/Hx challenge (Figs. 2 and 3). Treatments with intravenous TRE (810 ng/kg per min) and oral selexipag (30 mg/kg, twice daily) also showed no significant improvement in the changes of CO, PAAT, and RVAWT induced by Su/Hx and less effect on mPAP, PVR, and SV than that observed with the high dose of TPIP (Figs. 2 and 3).

The increase in Fulton index induced by Su/Hx was dose-dependently inhibited by treatment with TPIP and by oral selexipag (Fig. 4). In contrast, treatment with inhaled and intravenous TRE did not significantly inhibit the increase in Fulton index induced by the Su/Hx challenge.

**Histopathology.** Su/Hx challenge significantly increased ($P \leq 0.05$) the wall thickness of the small and medium sized pulmonary arteries (Fig. 5A), which was almost entirely due to an increase in the percentage of smooth muscle in the vascular wall evaluated by αSMA (Fig. 5B). There was a redistribution of the percentage of muscular, semi-muscular, and nonmuscular blood vessels in the pulmonary arteries with the
in the right ventricle was not affected by TPIP, of the treatment groups (Fig. 7A). The percentage of collagen staining in most arteries. Thickness, muscularization, and obliteration of the pulmonary lungs stained with ipag (30 mg/kg, twice daily). Representative photomicrographs 4× daily), intravenous TRE (810 ng/kg per min), and oral selexipag. Treatment of Su/Hx rats with TPIP (59 and 117 μg/kg, once daily) dose-dependently inhibited the increased wall thickness, muscularization, and obliteration of the small-diameter pulmonary blood vessels (Fig. 5A–D). The effects of TPIP were generally greater than those produced by inhaled TRE (65 μg/kg, 4x daily), intravenous TRE (810 ng/kg per min), and oral selexipag (30 mg/kg, twice daily). Representative photomicrographs of the lungs stained with zSMA (Fig. 6A) and vWF (Fig. 6B) for the different treatment groups illustrate the increased wall thickness, muscularization, and obliteration of the pulmonary arteries.

In cardiac tissue, Su/Hx challenge produced an increase in RVAWT with the presence of collagen staining in most of the treatment groups (Fig. 7A). The percentage of collagen in the right ventricle was not affected by TPIP, intravenous TRE, or oral selexipag but was significantly reduced by inhaled TRE (data not shown). However, the vehicle group for inhaled TRE (nebulized PBS) unexpectedly showed a higher percentage of collagen compared with the other vehicle groups used in the study, and there was no difference in the collagen content between the different treatment groups that received TPIP, intravenous TRE, or oral selexipag.

Histologic examination of cardiac tissues showing an enlarged vessel with perivascular/interstitial fibrosis and cardiomyocyte hypertrophy after Su/Hx challenge is displayed in Fig. 7B. Right ventricles were stained with Masson’s trichrome for collagen fiber visualization, and severity of collagen deposition was depicted by the intensity and magnitude of the blue staining (Masson’s trichrome). Fibrotic areas with increases of collagen deposition (high blue staining intensity) were observed in the cardiac perivascular region of the Su/Hx + TPIP vehicle group relative to the normoxic control group. Perivascular and interstitial fibrosis were slightly reduced by treatment with 117 μg/kg TPIP (Fig. 7B).

![Graphs](https://example.com/graphs.png)

**Fig. 2.** Effect of TPIP, inhaled TRE, intravenous TRE, and oral selexipag on (A) mean pulmonary arterial blood pressure (mPAP); (B) cardiac output (CO); and (C) pulmonary vascular resistance (PVR) in the 8-week Sugen 5416/hypoxia (Su/Hx) study. Data represent mean ± S.E.M. *P ≤ 0.05 compared to Normoxic control; #P ≤ 0.05 compared to Su/Hx + Vehicle.

**Fig. 3.** Effect of TPIP, inhaled TRE, intravenous TRE, and oral selexipag on (A) stroke volume (SV); (B) pulmonary artery acceleration time (PAAT); and (C) right ventricle wall thickness (RVAWT) in the 8-week Sugen 5416/hypoxia (Su/Hx) study. Data represent mean ± S.E.M. *P ≤ 0.05 compared to Normoxic control; #P ≥ 0.05 compared with Su/Hx + Vehicle.
Overall Comparison between TPIP, Inhaled and Intravenous TRE, and Oral Selexipag

The overall inhibition of the changes in mPAP, CO, Fulton index, wall thickness, muscularization, and obliteration of the pulmonary arteries induced by Su/Hx was greater for TPIP at high dose (117 μg/kg, once daily) than for selexipag (30 mg/kg, twice daily), inhaled TRE (65 μg/kg, 4× daily), low dose of TPIP (59 μg/kg, once daily), and intravenous TRE (810 ng/kg per min) (Table 2). A multiparameter comparison graph illustrating these results is shown in Fig. 8.

Pharmacokinetics

The concentration of TRE in the plasma measured 24 hours after the first administration of inhaled TPIP (59 and 117 μg/kg, once daily) was below the level of detection (Table 3A) and was also very low 12 hours after the fourth dose administered on the first day of dosing with inhaled TRE (65 μg/kg, 4× daily), inhaled TRE (65 μg/kg, 4× daily), low dose of TPIP (59 μg/kg, once daily), and intravenous TRE (810 ng/kg per min) (Table 2). A multiparameter comparison graph illustrating these results is shown in Fig. 8.

Discussion

In this study, we compared the activity of TPIP, a long-acting prodrug of TRE, in a Su/Hx rat model of PAH to that of three other drugs that act on the prostacyclin pathway that have been approved for use in PAH subjects: inhaled and intravenous TRE and oral selexipag. The dose and frequency of administration with each compound for these Su/Hx studies was selected from experiments that measured their acute pulmonary vasodilator activity in rats challenged with Hx (Chapman et al., 2021b). Each of these four drugs offered some degree of protection against the hemodynamic and histopathological changes that were induced by the Su/Hx challenge, but the greatest and most consistent effect was produced by TPIP at high dose. Using a combined numerical average for the inhibition of the changes in mPAP, CO, Fulton index, wall
thickness, muscularization, and obliteration of the pulmonary arteries induced by Su/Hx, the activity of TPIP at high dose (117 μg/kg, once daily) showed advantageous effects, generally greater than for oral selexipag (30 mg/kg, twice daily), inhaled TRE (65 μg/kg, 4x daily), and intravenous TRE (810 ng/kg per min), whereas the activity of TPIP at low dose (59 μg/kg, once daily) was comparable to slightly favorable across most parameters tested. These results build upon the findings from a previous study that demonstrated effects of inhaled TP that compared favorably to those of the oral phosphodiesterase 5 (PDE5) inhibitor sildenafil (Corboz et al., 2022) and suggest that TPIP may offer additional benefits for the treatment of PAH compared with other drugs acting on the prostacyclin pathway that are currently approved for clinical use.

To select the dosing frequency of each compound for the Su/Hx studies, dose-response and duration of activity studies were performed in rats challenged with acute inhaled Hx that measured the inhibition of pulmonary vasoconstriction (Chapman et al., 2021b). As expected, TPIP produced a dose-dependent and long-acting pulmonary vasodilation over 12–24 hours from which targeted doses of 57 and 138 μg/kg given once daily were selected. The actual average delivered doses of TPIP in the Su/Hx studies, 59 and 117 μg/kg, were very close to these targeted doses. On the other hand, dose-response studies with inhaled TRE in the acute Hx-challenged rats found a relatively short duration of action lasting between 1 and 2 hours. From these results, a targeted inhaled TRE dose of 110 μg/kg given four times daily was selected, although the average delivered dose measured in the Su/Hx studies was 65 μg/kg due to variations such as room humidity, VAG conditions, and flowability of dry powder. For intravenous TRE, we used a dose infusion rate of 810 ng/kg per minute that was based upon data from a previous study in Su/Hx-challenged rats (Chaudhary et al., 2018) and demonstrated acute pulmonary vasodilation in our experiments. Furthermore, based upon previously published data in Su/Hx-challenged rats, an oral dosing frequency of 30 mg/kg selexipag administered twice daily was selected (Honda et al., 2020), with pulmonary vasodilation at this dose observed up to 4 hours in our acute Hx-challenged rats.

* Fig. 5. Effect of TPIP, inhaled TRE, intravenous TRE, and oral selexipag in the 8-week Sugen 5416/hypoxia (Su/Hx) study on (A) vascular wall thickness of pulmonary arteries stained with hematoxylin and eosin (H&E); (B) vascular wall thickness of pulmonary arteries stained with alpha smooth muscle actin (α-SMA); (C) pulmonary vessel muscularization; and (D) pulmonary blood vessel obliteration in the 8-week Su/Hx study. Data represent mean ± S.E.M. *P ≤ 0.05 compared with normoxic control group; #P ≤ 0.05 compared with Su/Hx + vehicle groups.
In Su/Hx-challenged rats, TPIP inhibited most of the hemodynamic and histopathological changes in the lungs and heart, including effects on the increased mPAP and PVR, the reduction in CO, the increases in wall thickness, muscularization and obliteration of small-diameter (10–50 µm) pulmonary arteries, and the enlargement in right heart size measured by the increase in Fulton index and RVAWT. Furthermore, using glycoproteomic analysis on tissue from the right heart (Supplemental Figs. 4–6; Supplemental Tables 2–4), TPIP inhibited the over- and underexpression of several proteins that are associated with cardiac and vascular diseases, including heart failure, arrhythmias, vascular stenosis, endothelial dysfunction, and hypertension (Ahmed et al., 2003; Vitello et al., 2012; Engebretsen et al., 2013; Vistnes et al., 2014; Dey et al., 2015; Gao and McNally 2015; Matsushima and Sadoshima, 2015; Perrucci et al., 2015; Pang et al., 2017; Zhang et al., 2017). In summary, TPIP demonstrated protective effects on nearly all of the hemodynamic and pathologic changes induced by a Su/Hx challenge in rats. The same consistency of effect was not demonstrated by inhaled and intravenous TRE or oral selexipag. For example, the increase in the Fulton index was not inhibited by inhaled or intravenous TRE, and there were only modest effects of these drugs on the increases in mPAP, right ventricular systolic pressure (RVSP), and PVR compared with the high dose of TPIP. Furthermore, although selexipag inhibited the increased Fulton index, mPAP, PVR, wall thickness, and muscularization of the pulmonary arteries, it had no effect on the obliteration of small pulmonary arteries or on the reductions in cardiac performance such as CO and SV induced.

**Fig. 6.** Representative photomicrograph of the effects of TPIP, inhaled TRE, intravenous TRE, and oral selexipag on (A) the remodeling of the smooth muscle cell of the left lung stained with α-smooth muscle actin (α-SMA) and on (B) the histopathology of the pulmonary blood vessels of the left lung stained with von Willebrand Factor (vWF) in the 8-week Sugen 5416/hypoxia (Su/Hx)-induced pulmonary arterial hypertension (PAH) in rats. Photomicrographs represent (A) normoxic control group; (B) Su/Hx + TPIP vehicle (once daily) group; (C) Su/Hx + 59 µg/kg TPIP (once daily) group; (D) Su/Hx + 117 µg/kg TPIP (once daily) group; (E) Su/Hx + nebulized phosphate buffered saline (PBS) group; (F) Su/Hx + 65 µg/kg nebulized TRE (4x daily) group; (G) Su/Hx + intravenous TRE vehicle group; (H) Su/Hx + 810 µg/kg intravenous TRE group; (I) Su/Hx + oral methylcellulose (MC) group; and (J) Su/Hx + 30 mg/kg selexipag (twice daily) group, respectively. Scale bar = 100 µm. (A) Red arrows indicate increased muscularization of small arteries in vehicle or drug treatment groups, and black arrow indicates normal thin muscular small arteries. Lung tissues were immunohistochemically stained with α-SMA that stained the smooth muscle cells. (B) Red arrows indicate occluded arteries in vehicle groups, black arrow indicates normal thin endothelial cells, yellow arrow indicates the muscularized arteries, and green arrow indicates the nonmuscularized arteries. Lung tissues were immunohistochemically stained with vWF that stained the endothelial cells responsible for the occlusion.
by the Su/Hx challenge. To numerically demonstrate the superiority of TPIP over the other prostacyclin analogs used in our study, a percent inhibition was calculated for the changes in mPAP, Fulton index, CO, wall thickness, muscularization, and obliteration of the pulmonary arteries in Su/Hx rats and represented as an average of these values (Fig. 8). With this...
analysis, the effects of TPIP at high dose (117 μg/kg, once daily) were greater than selexipag (30 mg/kg twice daily), inhaled TRE (65 μg/kg, 4× daily), TPIP at low dose (59 μg/kg, once daily), and intravenous TRE (810 ng/kg per min).

Several factors likely contribute to the beneficial effects of TPIP and discriminate it from the other prostacyclin analogs used in this study. First, TPIP was administered by inhalation, which offers the advantage over systemically administered drugs like intravenous TRE and oral selexipag by delivering relatively high concentrations of the drug directly to the target organ. The presence of high TP and TRE concentrations in the lungs is extremely important to manifest the full biology with these drugs (Sandifer et al., 2005; Chapman et al., 2018). Second, TP is a prodrug of TRE that is slowly converted to TRE by the action of lung esterase (Leifer et al., 2018), which contributes to the prolonged TRE exposure in the lungs after inhalation (Corboz et al., 2017). This is in stark contrast to inhaled TRE, which is rapidly eliminated from the lungs after inhalation and requires frequent administration to maintain lung concentrations above the threshold required to produce its biology (Kumar et al., 2016). Third, pulmonary vasodilator activity is maintained with repeat daily dosing with inhaled TP for up to 32 consecutive days, whereas intravenous-infused TRE loses pulmonary vasodilator activity, which we speculate is due to desensitization of the IP receptor on the vascular endothelium (Nilius et al., 2000; Gatfield et al., 2017; Chapman et al., 2021b). And finally, TRE activates several prostanoid (IP, prostaglandin E type 2 (EP2), prostaglandin

### TABLE 2

Hemodynamics and airway remodeling in the 8-week Sugen 5416/hypoxia (Su/Hx) study

Values represent the mean ± S.E.M % inhibition due to treatments of the mPAP, CO, Fulton index, percentage of wall thickness, percentage of muscularization, percentage of nonobliterated pulmonary arteries, or the combined total of these values in Su/Hx rats. n represents the number of determinations. The last column shows the average of all six individual parameters.

<table>
<thead>
<tr>
<th>Drug</th>
<th>Dose</th>
<th>mPAP</th>
<th>CO</th>
<th>Fulton Index</th>
<th>Wall Thickness</th>
<th>Muscularization</th>
<th>Obliteration</th>
<th>Combined Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPIP (inhaled, once daily)</td>
<td>59 μg/kg</td>
<td>53 ± 6</td>
<td>29 ± 14</td>
<td>41 ± 18</td>
<td>50 ± 8</td>
<td>25 ± 3</td>
<td>17 ± 13</td>
<td>36 ± 4</td>
</tr>
<tr>
<td>TPIP (inhaled, once daily)</td>
<td>117 μg/kg</td>
<td>80 ± 8</td>
<td>66 ± 15</td>
<td>69 ± 7</td>
<td>55 ± 13</td>
<td>45 ± 7</td>
<td>69 ± 7</td>
<td>63 ± 4</td>
</tr>
<tr>
<td>TRE (inhaled, 4× daily)</td>
<td>65 μg/kg</td>
<td>34 ± 17</td>
<td>58 ± 41</td>
<td>7 ± 33</td>
<td>19 ± 18</td>
<td>26 ± 7</td>
<td>63 ± 13</td>
<td>37 ± 9</td>
</tr>
<tr>
<td>TRE (i.v.)</td>
<td>810 ng/kg per min</td>
<td>43 ± 10</td>
<td>48 ± 22</td>
<td>16 ± 13</td>
<td>43 ± 7</td>
<td>15 ± 4</td>
<td>31 ± 9</td>
<td>34 ± 5</td>
</tr>
<tr>
<td>Selexipag (oral, twice daily)</td>
<td>30 mg/kg</td>
<td>59 ± 15</td>
<td>11 ± 26</td>
<td>53 ± 15</td>
<td>58 ± 16</td>
<td>35 ± 10</td>
<td>29 ± 7</td>
<td>40 ± 7</td>
</tr>
</tbody>
</table>

† % inhibition = (Su/Hx + vehicle) – (Su/Hx + drug)/(Su/Hx + vehicle) – (Nx control) × 100.

![Radar chart using a multiparameter scoring summary that includes the measurement of mean pulmonary arterial pressure (mPAP), Fulton index, cardiac output (CO), and the wall thickness, muscularization, and obliteration of pulmonary arteries for the different treatment groups in the 8-week Sugen 5416/hypoxia study. Fulton index, weight ratio of right ventricle/(left ventricle + septum); muscularization, percentage of muscularized vessels; obliteration, percentage of nonobliterated vessels; wall thickness, small vessel wall thickness.](image)
D₂ receptor 1 (DP₁), and prostaglandin E type 4 (EP₄) and PPAR receptors that provide TRE with a broad spectrum of activities on many different structural, inflammatory, and immune cells in the lungs (Kolodsick et al., 2003; Foudi et al., 2008; Frumkin 2012; Benyahia et al., 2013; Zaslona and Peters-Golden, 2015; Lambers et al., 2018; Patel et al., 2018; Corboz et al., 2022) and distinguish it from drugs like selexipag that target only the IP receptor (Gatfield et al., 2017).

There are several limitations to the conclusions reached from these studies. First, the experiments were performed in Su/Hx-challenged rats, and although this animal model is considered to be superior to other PAH models used for drug evaluations (Stenmark et al., 2009; de Raaf et al., 2014), it does not recapitulate all of the PAH pathology in human subjects. Second, the doses of the drugs used for this evaluation are different from those used clinically and may not translate to clinically relevant doses in humans due to differences in the metabolism and pharmacokinetics of these drugs (Kumar et al., 2016; Chaudhary et al., 2018; Ichikawa et al., 2018), and different binding affinity to the prostanoid and PPAR receptors between rats and humans (Nguyen et al., 2022). Third, pulmonary vasodilation was used to select the dosing frequency of the drugs, and although this effect is largely mediated via IP receptor activation (Corboz et al., 2021a), a different dosing frequency may be required to ensure target engagement at other prostanoid and PPAR receptors.

In conclusion, TPIP had beneficial effects on the hemodynamic and pathologic changes in the lungs induced by Su/Hx in rats, with overall effects that compared favorably to the effects produced by inhaled and intravenous TRE and oral selexipag. Several factors may contribute to the beneficial effects of TPIP over these other prostacyclin analogs and include: 1) delivery by inhalation to maximize exposure in the target organ; 2) the slow release of TRE into the lung via the actions of lung esterase catalyzed hydrolysis of the prodrug bond of TP to produce TRE; and 3) TRE has relatively high binding affinity.

### TABLE 3
Plasma pharmacokinetic in the 8-week Sugen 5416/hypoxia study
(A) Concentration of treprostinil (TRE) in the plasma after inhalation of TPIP at 59 and 117 µg/kg (once daily), inhaled TRE at 65 mg/kg (4× daily), and intravenous (i.v.) TRE at 810 ng/kg per min.

<table>
<thead>
<tr>
<th>Plasma TRE (ng/ml)</th>
<th>59 µg/kg TPIP (once daily)</th>
<th>117 µg/kg TPIP (once daily)</th>
<th>65 mg/kg inhaled TRE (4× daily)</th>
<th>810 ng/kg per min i.v. TRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>22</td>
<td>38</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Average</td>
<td>0.00</td>
<td>0.19</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>n</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

(B) Concentration of selexipag and its metabolite ACT-333679 in the plasma after oral administration of selexipag at 30 mg/kg.

Blood samples for all groups were collected at day 22, day 38, and day 56. Details of the blood sample collection are described in the Materials and Methods section.

<table>
<thead>
<tr>
<th>Plasma Selexipag and Metabolite (ng/ml)</th>
<th>30 mg/kg selexipag (twice daily)</th>
<th>30 mg/kg selexipag metabolite (ACT-333679) (twice daily)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>22</td>
<td>38</td>
</tr>
<tr>
<td>Average</td>
<td>11.37</td>
<td>5.40</td>
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<tr>
<td>S.E.M.</td>
<td>3.03</td>
<td>3.00</td>
</tr>
<tr>
<td>n</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>

### TABLE 4
Lung pharmacokinetic in the 8-week Sugen 5416/hypoxia study
(A) Concentration of treprostinil (TRE) in the lung after inhalation of TPIP at 59 and 117 µg/kg (once daily), inhaled TRE at 65 mg/kg (4× daily), and intravenous (i.v.) TRE at 810 ng/kg per min.

<table>
<thead>
<tr>
<th>Lung TRE (ng/g)</th>
<th>59 mg/kg TPIP (once daily)</th>
<th>117 mg/kg TPIP (once daily)</th>
<th>65 mg/kg inhaled TRE (4× daily)</th>
<th>810 ng/kg per min i.v. TRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>3.32</td>
<td>6.35</td>
<td>0.06</td>
<td>1.75</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.67</td>
<td>1.56</td>
<td>0.04</td>
<td>0.51</td>
</tr>
<tr>
<td>n</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

(B) Concentration of selexipag and its metabolite ACT-333679 in the plasma after oral administration of selexipag at 30 mg/kg.

<table>
<thead>
<tr>
<th>Lung Selexipag and Metabolite (ng/g)</th>
<th>30 mg/kg selexipag (twice daily)</th>
<th>30 mg/kg selexipag metabolite (ACT-333679) (twice daily)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>7.02</td>
<td>270.63</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>2.05</td>
<td>71.17</td>
</tr>
<tr>
<td>n</td>
<td>9</td>
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</table>
to several prostanoid and TP receptors, which provides a broader spectrum of activity to improve PAH pathophysiology compared with drugs like selexipag that target just the IP receptor.

Acknowledgments

Tam Nguyen, of Insmed Incorporated, conducted in vitro experiments with human primary smooth muscle and endothelial cells. The authors gratefully acknowledge the scientists at IPS Therapeutics (Sherbrooke, Quebec, Canada) for their expertise in the design and completion of these experiments.

Authorship Contributions

Participated in research design: Corboz, Chapman. Performed data analysis: Corboz, Li, Gauani, Chun, Chapman. Wrote or contributed to the writing of the manuscript: Corboz, Cipolla, Perkins, Chapman.

References


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Online data supplement

Assessment of Inhaled Treprostinil Palmitil, Inhaled and Intravenous Treprostinil and Oral Selexipag in a Sugen/Hypoxia Rat Model of Pulmonary Arterial Hypertension

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Section Assignment: Cardiovascular
Paper ID: 84039503
Supplemental Methods and Results

A. Experimental study design

1. Acute inhaled hypoxia.

Rats were prepared with telemetry probes implanted in the right ventricle for the measurement of RVPP and descending aorta to measure the changes in RVPP and SAP that was induced by exposure to a 10% O₂ gas mixture, respectively. For each Hx challenge, RVPP and SAP were measured for 10 min before (Baseline), during and after (Post) Hx (Figure 1). The Hx challenges were performed on 3 separate occasions 24 h before the administration of TPIP, inhaled and IV TRE and oral selexipag, or their respective vehicles with data represented as the average from these 3 Hx challenges. The following day, test articles were administered with the Hx challenge performed at different times over a 24-48 h period. The study design for the experiments with acute inhaled Hx challenge in telemetered rats is illustrated in Figure 1.

Figure 1. Study design for acute hypoxia challenge in telemetered rats

2. Su/Hx challenged rats

One hundred and twenty (120) male Sprague Dawley rats, ranging in weight from 250 - 300 g at the beginning of the study, were separated into 10 cohorts that received either a SC
injection of Su (20 mg/kg, 2 mL/kg) dissolved in 100% DMSO followed by 3 weeks of daily exposure to an inhaled hypoxic gas mixture (10% O₂/balance N₂) or 100% DMSO (2 mL/kg) followed by 3 weeks of room air breathing for the Nx control group. Day 0 was defined as the day of the Su or DMSO injection with Day 21 defined as the transition from Hx to Nx. All rats were then switched to 5 weeks of room air breathing which was defined as Day 55, during which time the Su/Hx rats received daily administration of the test articles or their respective vehicles. The Nx control rats that received 100% DMSO, instead of Su/Hx with no treatment, were exposed to room air breathing for 8 weeks. Twenty-four hours after the last dose of TPIP which was defined as Day 56, inhaled TRE and oral selexipag, the rats were anesthetized and prepared for the collection of hemodynamic, lung and cardiac tissues for histology and blood samples for PK analysis. For studies with IV TRE, the infusion continued until after the hemodynamic data was collected on Day 56 at which time a blood sample was taken for PK analysis with cardiac and histological data collected thereafter. The overall study design for the experiments involving the Su/Hx challenge is illustrated in Figure 2 and details of the different treatments at their targeted and delivered drug doses are listed in Table 1.

Figure 2. Su/Hx challenge and drug administration in rats
Table 1. Treatment Group Assignment and Treatment Information

<table>
<thead>
<tr>
<th>Group</th>
<th>Group Description</th>
<th>Target Treatment Dose</th>
<th>Dosing Route</th>
<th>Route of Administration</th>
<th>Delivered Dose</th>
<th>Treatment Starting Day</th>
<th>Treatment Ending Day</th>
<th>Surgery Day</th>
<th>Group Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normoxic control</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>56</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>Su-Hx + TPIP vehicle</td>
<td>n/a</td>
<td>170 mg at 1.0 V</td>
<td>Inhalation (QD)</td>
<td>n/a</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Su-Hx + TPIP low dose</td>
<td>57 µg/kg</td>
<td>90 mg at 0.5 V</td>
<td>Inhalation (QD)</td>
<td>59 µg/kg</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>Su-Hx + TPIP high dose</td>
<td>138 µg/kg</td>
<td>170 mg at 1.0 V</td>
<td>Inhalation (QD)</td>
<td>117 µg/kg</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>Su-Hx + nebulized</td>
<td>n/a</td>
<td>6 mL</td>
<td>Inhalation (QID)</td>
<td>n/a</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
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<tr>
<td></td>
<td>PBS</td>
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<tr>
<td></td>
<td>Su-Hx + nebulized TRE</td>
<td>110 µg/kg</td>
<td>6 mL of 0.5mM</td>
<td>Inhalation (QID)</td>
<td>65 µg/kg</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>Su-Hx + IV vehicle†</td>
<td>n/a</td>
<td>2.5 µL/h</td>
<td>Continuous intravenous infusion</td>
<td>n/a</td>
<td>21</td>
<td>56</td>
<td>56</td>
<td>17 †</td>
</tr>
<tr>
<td>8</td>
<td>Su-Hx + IV TRE†</td>
<td>810 ng/kg/min</td>
<td>8.75 mg/mL (Day 21 to 39) and 10.7 mg/mL (Day 40 to 56) at 2.5 µL/h</td>
<td>Continuous intravenous infusion</td>
<td>810 ng/kg/min</td>
<td>21</td>
<td>56</td>
<td>56</td>
<td>18 †</td>
</tr>
<tr>
<td>9</td>
<td>Su-Hx + oral MC</td>
<td>n/a</td>
<td>10 mL/kg</td>
<td>Oral (BID)</td>
<td>n/a</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>Su-Hx + Selexipag</td>
<td>30 mg/kg</td>
<td>10 mL/kg of 3mg/mL</td>
<td>Oral (BID)</td>
<td>30 mg/kg</td>
<td>21</td>
<td>55</td>
<td>56</td>
<td>11</td>
</tr>
</tbody>
</table>

**Abbreviations:**  
BID: Twice a day; IV: Intravenous; MC: methylcellulose; n/a: non applicable; PBS: phosphate buffered saline; QD: Once a day; QID: Four times a day; Su-Hx: Sugen-Hypoxia; TRE: Treprostinil; V: Volt.

† Additional animals were included in these groups because of some rats, initially included in the study, had disconnected IV catheters when the Alzet pumps were refilled on Day 21 of the infusion.

‡ Blood collected 24 hours after TPIP, inhaled TRE, and oral selexipag on Day 55 and immediately after the collection of hemodynamic data on Day 56 for IV TRE.

**B. Pharmacokinetics with IV TRE infusions**

Rats received an IV infusion of TRE using an implanted osmotic pump (ALZET pump) that was filled with 2 mL of TRE at 8.75 mg/mL at the start of the infusion on Day 21. The Alzet pump was replaced on the 19th day of the infusion that contained 2 mL a TRE solution at a concentration of 10.7 mg/mL. The higher TRE concentration was to
account for the increase in body weight from 450 to 550 g. Blood samples were collected on Days 22, 36-38 and 56 and analyzed for the concentration of TRE in the plasma using HPLC/MS/MS methods that have been previously described (Corboz et al., 2017).

When the Alzet pumps were refilled on the 19th day of the TRE infusion, some of the catheters were disconnected from the jugular vein. However, there was no difference in the plasma TRE concentrations in rats with “intact connected” (n = 6) and with “disconnected catheters (n = 7)” (Figure 3) and on the basis of these results, all rats were used for studies involving IV TRE.

Figure 3. Concentration of TRE in the plasma with IV TRE infusion for 5 weeks

![Bar chart showing the concentration of TRE in the plasma with IV TRE infusion for 5 weeks.](image)
Concentration of TRE in the plasma following IV TRE administration at 810 ng/kg/min. Values are mean ± SEM. Blood samples were collected during the drug infusion at day 22, 36-38 and 56 (start of the infusion on Day 21).

C. Proteomics in the right heart

The protein content in the right heart was measured using the SWATH technology (PhenoSwitch Bioscience, Sherbrooke, Qc, Canada) that uses mass spectrometry (MS/MS) to identify ion fragments of glycosolated peptide fragments from each protein. The ion library was generated with 10 peptide fragments from each protein from which the samples were combined to yield a value for each protein. Signal intensity of each peptide was log2 transformed and normalized with a R script using retention time-based loss and signal normalization. The normalized signal of the peptides from both green fluorescent protein (GFP) was summed for each protein and used to report an individual protein signal. Multivariate analysis, heatmap, volcano plot and gene ontology analysis were done using internal Python scripts. For gene ontology, pathways were fetched using orthologue human gene names using reactome plugging in Cytoscape. Statistically significant differences between the vehicle-treated Su/Hx controls and the TPIP (117 µg/kg)-treated rats were determined using a T-test in conjunction with false discovery rate (FDR) in multiple testing using the Benjamini/Hochberg method.

The results from this proteomic analysis on 1673 proteins found significant differences between the vehicle-treated Su/Hx control group and the TPIP-treated Su/Hx group for pathways involved with eicosanoid metabolism, extracellular matrix organization, oxidative stress induced gene expression, 5-hydroxytryptamine degradation, nicotinate and nicotinamide metabolism. Listed below are the proteins in some of these pathways that had statistically significant differences between TPIP vehicle and TPIP treatments.

**Extracellular matrix organization**
Numerous changes in proteomics occurred with proteins associated with the extracellular matrix organization in the heart, with 43 proteins identified. Of these 43 proteins, statistically significant (P ≤ 0.05) differences were found in 16 proteins comparing the values in TPIP and TPIP-vehicle treated Su/Hx rats (Table 2). Representative examples with 5 of these proteins (protein disulfide isomerase, biglycan, lumican, versican, and dystroglycan 1) are also discussed and shown in the Figure 4.

Table 2: Differentially expressed proteins associated with extracellular matrix organization in the right ventricle myocardium of TPIP treated Su/Hx rats) as compared to vehicle treated Su/Hx animals.

<table>
<thead>
<tr>
<th>UniProt_id</th>
<th>Gene_name</th>
<th>Protein_name</th>
<th>Fold change</th>
</tr>
</thead>
<tbody>
<tr>
<td>P04785</td>
<td>P4HB</td>
<td>Protein disulfide-isomerase</td>
<td>-1.79 *</td>
</tr>
<tr>
<td>P47853</td>
<td>BGN</td>
<td>Biglycan</td>
<td>-1.87 *</td>
</tr>
<tr>
<td>P51886</td>
<td>LUM</td>
<td>Lumican</td>
<td>-1.01 *</td>
</tr>
<tr>
<td>Q01177</td>
<td>PLG</td>
<td>Plasminogen</td>
<td>-2.02 *</td>
</tr>
<tr>
<td>Q9ERB4</td>
<td>VCAN</td>
<td>Versican</td>
<td>-2.28 *</td>
</tr>
<tr>
<td>Q9QZA6</td>
<td>CD151</td>
<td>Ralph blood group</td>
<td>-1.04 *</td>
</tr>
<tr>
<td>Q9WVH8</td>
<td>FBLN5</td>
<td>Fibulin 5</td>
<td>-0.70 *</td>
</tr>
<tr>
<td>D4A917</td>
<td>LTBP4</td>
<td>Latent Transforming Growth Factor Beta Binding Protein 4</td>
<td>-4.85 *</td>
</tr>
<tr>
<td>F1LNY3</td>
<td>NCAM1</td>
<td>Neural Cell Adhesion Molecule 1</td>
<td>-4.24 *</td>
</tr>
<tr>
<td>F1LPD0</td>
<td>COL15A1</td>
<td>Collagen Type XV Alpha 1 Chain</td>
<td>0.71 *</td>
</tr>
<tr>
<td>F1LS29</td>
<td>CAPN1</td>
<td>Calpain 1</td>
<td>0.96 *</td>
</tr>
<tr>
<td>F1M8K0</td>
<td>DAG1</td>
<td>Dystroglycan 1</td>
<td>0.55 *</td>
</tr>
<tr>
<td>F1MAN8</td>
<td>LAMA5</td>
<td>Laminin Subunit Alpha 5</td>
<td>1.46 *</td>
</tr>
<tr>
<td>F1MAN8</td>
<td>CAPNS1</td>
<td>Calpain Small Subunit 1</td>
<td>1.59 *</td>
</tr>
<tr>
<td>Q6IN22</td>
<td>CTSB</td>
<td>Cathepsin B</td>
<td>-1.96 *</td>
</tr>
<tr>
<td>Q6P6T6</td>
<td>CTSD</td>
<td>Cathepsin D</td>
<td>-0.73 *</td>
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Fold change, expressed in log2 transformed data, was calculated by converting the average value of the TPIP treated Su/Hx group in log2 – the average value of the vehicle treated Su/Hx group in log2. * indicates statistical significance (p ≤ 0.05) between the vehicle treated Su/Hx group (n = 6) and the TPIP treated Su/Hx group (n = 5). p was calculated using a student T-test in conjunction for false discovery rate (FDR) in multiple testing using the Benjamini/Hochberg method.

Positive fold change means that the proteins were upregulated by TPIP treatment when compared to the vehicle group and negative fold change means that the proteins were downregulated by TPIP treatment when compared to the vehicle group.

- **Protein disulfide isomerase** is a redox chaperone of the endoplasmic reticulum that is induced during stress and serves as a vital defense against general misfolding of
proteins that possess disulphide bonds. Protein disulfide isomerase is upregulated in the endoplasmic reticulum of cardiac tissue in both animals and humans with right and left heart failure (Vitello et al., 2012). In this study, protein disulfide isomerase was increased on average in Su/Hx rats and decreased in TPIP treated rats compared to both the Nx control and Su/Hx rats (Figure 4a).

- **Biglycan** is an important proteoglycan for matrix reorganization and interacts with collagen and binding to lipoprotein in blood vessels. Myocardial biglycan is induced in heart failure in rats (Ahmed et al., 2003) and was increased in our study in Su/Hx rats and reduced back to the Nx controls with TPIP (Figure 4b).

- **Lumican** is an extracellular matrix proteoglycan that binds to collagen and is involved with collagen fibril assembly. Lumican is involved with angiogenesis and is increased in experimental and clinical heart failure (Engebretsen et al., 2013). Lumican levels were increased by challenge with Su/Hx and reduced back to Nx values by treatment with TPIP (Figure 4c).

- **Versican** is another extracellular matrix proteoglycan that provides extracellular scaffold for inflammatory cells as they invade tissues from the circulation. Versican has been implicated in the pathology of a number of different cardiovascular and lung diseases and levels of this proteoglycan are increased in pressure-overloaded heart tissue (Vistnes et al., 2014). In our Su/Hx challenged rats, levels of versican increase over the Nx controls and were reduced by treatment with TPIP (Figure 4d).

**Dystroglycan 1** is a component of the dystrophin-associated glycoprotein complex which bridges the inner cytoskeleton of the extracellular matrix (Ervasti et al., 1991). Deletion of the gene synthesizing dystrophin results in Duchenne muscular dystrophy, cardiomyopathy and a number of other disorders involving the extracellular matrix (Eklund et al., 2001) and loss of the dystroglycan function in cardiac mouse myocytes results in myocyte damage and progressive cardiomyopathy (Michele et al., 2009). In our study, the level of dystroglycan in the right heart was reduced following the Su/Hx challenge and improved after treatment with TPIP (Figure 4e), suggesting an effect of TPIP to maintain myofibril integrity due to an interaction with dystrophin synthesis.
Figure 4. Protein expression associated with extracellular matrix organization

a) Disulfide isomerase (PDIA1)

b) PGS1 Biglycan

c) Lumican
d) CSPG2 Versican

e) Dystroglycan 1

Values of the y axis for Figures 4a-e refer to an area under the curve unit from the LC-MS/MS integration.
5-hydroxytryptamine degradation

Three proteins in the 5-hydroxytryptamine degradation pathway were quantified, and two of them identified from the proteomic analysis, aldehyde dehydrogenase 2 and retinaldehyde dehydrogenase 1, demonstrated statistically significant ($P \leq 0.05$) differences between TPIP treatment and the TPIP-vehicle control (Table 3).

Table 3: Aldehyde dehydrogenase and retinaldehyde dehydrogenase expression associated with 5-hydroxytryptamine in the right ventricle myocardium of TPIP treated Su/Hx rats as compared to vehicle treated Su/Hx animals.

<table>
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<tr>
<th>UniProt_id</th>
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<th>Fold change</th>
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<tr>
<td>P11884</td>
<td>ALDH2</td>
<td>Aldehyde dehydrogenase, mitochondrial</td>
<td>-1.04*</td>
</tr>
<tr>
<td>A0A0H2UHP1</td>
<td>ALDH1A1</td>
<td>Retinaldehyde dehydrogenase Raldh1</td>
<td>-1.57*</td>
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</table>

Fold change, expressed in log2 transformed data, was calculated by converting the average value of the TPIP treated Su/Hx group in log2 – the average value of the vehicle treated Su/Hx group in log2.

* indicates statistical significance ($p \leq 0.05$) between the vehicle treated Su/Hx group ($n = 6$) and the TPIP treated Su/Hx group ($n = 5$). $p$ was calculated using a student T-test in conjunction for false discovery rate (FDR) in multiple testing using the Benjamini/Hochberg method.

Negative fold change means that the proteins were downregulated by TPIP treatment when compared to the vehicle group.

- **Aldehyde dehydrogenase 2 (ALDH2)** is an enzyme located in the mitochondria that metabolizes 5-hydroxyindole acetaldehyde, a product of serotonin degradation. Serotonin is a key mediator of PAH pathology and is a potent pulmonary vasoconstrictor. Furthermore, ALDH2 is an etiological factor of heart failure (Pang et al., 2017). ALDH2 levels were increased by Su/Hx and reversed below Nx control levels with TPIP (Figure 5a).

- **Retinaldehyde dehydrogenase 1 (Aldh1α1 also known as Raldh1)** is the other protein in the 5-HT degradation pathway changed by TPIP (Figure 5b) and an association of retinal dehydrogenase 1 in the development of embryonic heart muscle
and in cardiac remodelling in heart failure has been previously described (Dey et al., 2015).

Figure 5. Protein expression associated with 5-hydroxytryptamine degradation

a) Aldehyde dehydrogenase (ALDH2)

![Graph showing protein expression values for ALDH2](image)

b) Retinal dehydrogenase (ALDH1α1)

![Graph showing protein expression values for ALDH1α1](image)

Values of the y axis for Figures 5a-b refer to an area under the curve unit from the LC-MS/MS integration.

Nictinate/nicotinamide metabolism
The proteomic analysis identified ten proteins in the nicotinate/nicotinamide metabolic pathway and three of them demonstrated statistically significant (P ≤ 0.05) differences between the TPIP treatment and the TPIP-vehicle control groups (Table 4).

**Table 4:** Nicotinate phosphoribosyltransferase, NAD-dependent protein deacetylase and proton-translocating NAD(P)(+) transhydrogenase expression associated with Nictinate/nicotinamide metabolism in the right ventricle myocardium of TPIP treated Su/Hx rats as compared to vehicle treated Su/Hx animals.

<table>
<thead>
<tr>
<th>UniProt_id</th>
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<th>Protein_name</th>
<th>Fold change</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3V709</td>
<td>NAPRT</td>
<td>Nicotinate phosphoribosyltransferase</td>
<td>1.81*</td>
</tr>
<tr>
<td>C6ZII9</td>
<td>SIRT3</td>
<td>NAD-dependent protein deacetylase</td>
<td>0.76*</td>
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<tr>
<td>Q5BJZ3</td>
<td>NNT</td>
<td>Proton-translocating NAD(P)(+) transhydrogenase</td>
<td>1.20*</td>
</tr>
</tbody>
</table>

Fold change, expressed in log2 transformed data, was calculated by converting the average value of the TPIP treated Su/Hx group in log2 – the average value of the vehicle treated Su/Hx group in log2.

* indicates statistical significance (p ≤ 0.05) between the vehicle treated Su/Hx group (n = 6) and the TPIP treated Su/Hx group (n = 5). p was calculated using a student T-test in conjunction for false discovery rate (FDR) in multiple testing using the Benjamini/Hochberg method.

Positive fold change means that the proteins were upregulated by TPIP treatment when compared to the vehicle group.

Nictinate phosphoribosyltransferase (NAPRT) has been identified as a damage-associated molecular pattern (DAMP) molecule by acting as a ligand for toll-like receptor 4 (TLR4) that is a critical mediator of inflammation (Manago et al., 2019). Its functional role in PAH pathology is not clear, but has been shown to have a protective role in lipopolysaccharide injury (Manago et al., 2019) and its mild elevation in the presence of TPIP may have protective effects in Su/Hx challenged heart (Figure 6a).

- The **NAD-dependent protein deacetylase** includes the sirtuin family of proteins and are critical regulators for a variety of cellular processes such as energy metabolism and stress responses. Sirtuins protect cardiac myocytes from oxidative stress, suppress cardiac hypertrophy and regulate apoptosis and stress responses in the heart (Matsushima et al., 2015). Levels of NAD-dependent protein deacetylase were reduced in Su/Hx rats and restored back to levels observed in Nx rats by TPIP (Figure 6b).
Proton-translocating NAD (P)(+) transhydrogenase is present in the mitochondria and facilitates the transfer of protons across the mitochondrial membrane where it drives the formation of NADPH, a key defense against the presence of reactive oxygen species. This enzyme has been implicated in the pathological conditions observed in a number of diseases including hypertension and heart disease (Zhang et al., 2017). In Su/Hx rats, levels of this enzyme were decreased in the right ventricle, possibly leaving the cardiac tissue more susceptible to the pathology associated with oxidative stress, and levels were returned back to the levels seen in the Nx controls by treatment with TPIP (Figure 6c).

Figure 6. Protein expression associated with nictinate/nicotinamide metabolism

a) Nicotinate phosphoribosyltransferase

b) NAD-dependent protein deacetylase

c) Proton-translocating NAD(P)(+) transhydrogenase
Values of the y axis for Figures 6a-c refer to an area under the curve unit from the LC-MS/MS integration.

References


Engebretsen KV, Lunde IG, Strand ME, Waehre A, Sjaastad I, Marstein HS, Skrbic B,


