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


Insmed Incorporated, Bridgewater, New Jersey

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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 in 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 anterior wall thickness; RVPP, increase in right ventricular pulse pressure; ΔRVPP, increase in right ventricular pulse pressure; αSMA, alpha smooth muscle actin; SpO2, pulse oximeter oxygen saturation; SV, stroke volume; TP, treprostinil palmitil; TPIP, treprostinil palmitil inhalation powder; TRE, treprostinil; Su, Sugen5416; VAG, Vilnius Aerosol Generator; vWF, von Willebrand factor.
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% leucine, 15.00% TP, and 0.75% 1,2-distearoyl-sn-glycero-3-phosphoethanolamine-N-[methoxy(polyethylene glycol)-2000] (DSPE-PEG-2000). TPIP and TP were obtained from Chirogate International (Taoyuan County, Taiwan, China). TRE was prepared for nebulization by dissolving 3.0 mg/ml m-Cresol, 5.3 mg/ml sodium chloride (NaCl), and 0.75% 1,2-distearoyl-sn-glycero-3-phosphatidylethanolamine-N-[methoxy(polyethylene glycol)-2000] (DSPE-PEG-2000). TRE was manufactured by Bend Research Inc. (Bend, OR) as a dry powder for inhalation, composed of 68.50% mannitol, 29.25% leucine, 15.00% TP, and 0.75% 1,2-distearoyl-sn-glycero-3-phosphoethanolamine-N-[methoxy(polyethylene glycol)-2000] (DSPE-PEG-2000). TPIP and TP were obtained from Chirogate International (Taoyuan County, Taiwan, China). TRE was prepared for nebulization by dissolving 3.0 mg/ml m-Cresol, 5.3 mg/ml sodium chloride (NaCl), and 0.75% 1,2-distearoyl-sn-glycero-3-phosphatidylethanolamine-N-[methoxy(polyethylene glycol)-2000] (DSPE-PEG-2000).}

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 conditions 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 Laboratory Practice (GLP) Regulations of the US Food and Drug Administration (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 derived 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 (ΔRVPP) due to Hx from the Nx values and change in mSAP were measured. Each rat was exposed to Hx on three separate occasions on the day before the administration 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 illustrated 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. Daily observations were made of the behavior and general health status of the animals, and body weights were recorded weekly. For the test article administrations, the animals were randomized after the 3-week Hx exposure to the different treatment groups based on their body weight and transthoracic echocardiography measures. Animals within the same treatment group were pair-housed except for the intravenous TRE groups implanted with an Alzet pump who were single-housed.

At the end of the study, the rats were anesthetized with a mixture of 2% to 2.5% isoflurane in oxygen (Abbot Laboratories, Montreal, Quebec, Canada), catheters were inserted into the trachea to facilitate artificial ventilation, and the pulmonary artery and aorta were obtained from Adooq Bioscience (Irvine, CA) and dissolved in 100% dimethyl sulfoxide (DMSO).
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 (RVAWT), 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).

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

**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 a 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 embedded, 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 NDI.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 TPIP 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 TPIP, 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 TPIP 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 TPIP 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 of the material had been nebulized. Nebulized TRE at concentrations of 0.125, 0.25, 0.50, and 1 mM resulted in delivered doses of 6, 23, 57, and 138 µg/kg in the inhaled Hx challenge 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 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 TP Dose Pulmonary (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 inhaled TRE dose at day 55 (4× daily), immediately after the last TPIP dose administered at day 55 (once daily), 12 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), t1/2 (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_{0-\infty} (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 articles. 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.

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 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 µg/kg.

Table 1

Inhalation drug dose calculations for administration of TPIP and TRE in the 8-week Sugen 5416/hypoxia study

<table>
<thead>
<tr>
<th>Drug</th>
<th>Aerosolization (mg)</th>
<th>Treatment</th>
<th>Duration (weeks)</th>
<th>Aerosol Concentration (µg/l)</th>
<th>RMV (l/min)</th>
<th>D (min)</th>
<th>BW (kg)</th>
<th>DF</th>
<th>TP Dose* Total (µg/kg)</th>
<th>DF</th>
<th>TP Dose** Pulmonary (µg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPIP</td>
<td>90</td>
<td>once daily</td>
<td>5</td>
<td>2.6</td>
<td>0.32</td>
<td>33</td>
<td>0.48</td>
<td>1</td>
<td>58.5</td>
<td>0.1</td>
<td>5.8</td>
</tr>
<tr>
<td>TPIP</td>
<td>170</td>
<td>once daily</td>
<td>5</td>
<td>4.7</td>
<td>0.32</td>
<td>37</td>
<td>0.47</td>
<td>1</td>
<td>116.8</td>
<td>0.1</td>
<td>11.7</td>
</tr>
</tbody>
</table>

*TP Dose (µg/kg) = C (µg/L) × RMV (L/min) × D (min) × DF / BW (kg)

**TP Dose Pulmonary (µg/kg) = TP Dose Total (µg/kg) × DF
mg/kg (Fig. 1C). Continuous infusion of intravenous TRE (810 ng/kg/min) significantly ($P \leq 0.05$) inhibited the ΔRVP 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
majority of vessels having full muscularization after Su/Hx challenge (Fig. 5C). Su/Hx challenge also increased the percentage of semi- and totally obliterated small-diameter (10–50 μm) pulmonary blood vessels along with a parallel reduction in the percentage of nonobiterated blood vessels (Fig. 5D).

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. 5, A–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 αSMA (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).
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 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 (Chaudhary et al., 2018) and demonstrated acute 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.
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 ng/kg/min 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.

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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

Fig. 7. Representative cardiac photomicrographs of the effects of TPIP, inhaled TRE, intravenous TRE, and oral selexipag on right ventricular cardiac tissue in the 8-week Sugen 5416/hypoxia (Su/Hx)-induced pulmonary arterial hypertension (PAH) in rats. Histologic examination was performed on a cross-section of the right ventricle stained with Masson’s trichrome from (A) the normoxic control group; (B) the Su/Hx + TPIP vehicle (once daily) group; (C) the Su/Hx + 59 \(\mu\)g/kg TPIP (once daily) group; (D) the Su/Hx + 117 \(\mu\)g/kg TPIP (once daily) group; (E) the Su/Hx + nebulized phosphate buffered saline (PBS) group; (F) the Su/Hx + 65 \(\mu\)g/kg inhaled TRE (4x daily) group; (G) the Su/Hx + intravenous TRE vehicle group; (H) the Su/Hx + 810 \(\mu\)g/kg intravenous TRE group; (I) the Su/Hx + oral methylcellulose (MC) group; and (J) the Su/Hx + 30 mg/kg selexipag (twice daily) group, respectively. Scale bar = 400 \(\mu\)m. Yellow arrows indicate fibrotic area (blue coloration). Staining with Masson’s trichrome demonstrates increased fibrotic area in vehicle groups as shown by the blue stain in Su/Hx + TPIP vehicle (B); Su/Hx + nebulized PBS (E); Su/Hx + intravenous TRE vehicle (G); and Su/Hx + oral MC (I) groups compared with normoxic control (A); Su/Hx + 117 \(\mu\)g/kg TPIP (D); Su/Hx + 65 \(\mu\)g/kg inhaled TRE (F); and Su/Hx + 810 \(\mu\)g/kg intravenous TRE (H) groups. (B) Representative photomicrographs of cardiac tissue showing an enlarged vessel with perivascular/interstitial fibrosis and cardiomyocyte hypertrophy. The right ventricle was embedded in paraffin wax and then stained with Masson’s trichrome for evaluation of collagen deposition. Higher intensity and magnitude of the blue staining (Masson’s trichrome), consistent with an increased and more pronounced collagen deposition in the perivascular region, was observed in the Su/Hx + TPIP vehicle group, relative to the normoxic control group as represented by the yellow arrows. Black arrows show increased interstitial fibrosis, more apparent within cardiomyocyte cross-sectional area, in the Su/Hx groups. Treatment with 117 \(\mu\)g/kg TPIP (once daily) slightly reduced the appearance of perivascular and interstitial fibrosis.
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, 4x 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

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

† % inhibition = (Su/Hx + vehicle) − (Su/Hx + drug)/(Su/Hx + vehicle) − (Nx control) × 100.
D$_2$ receptor 1 (DP$_1$), and prostaglandin E type 4 (EP$_4$) 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 a number of factors such as 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></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 22</td>
<td>38</td>
<td>56</td>
<td>22</td>
<td>38</td>
</tr>
<tr>
<td>Average 0.00</td>
<td>0.19</td>
<td>0.12</td>
<td>0.00</td>
<td>0.14</td>
</tr>
<tr>
<td>S.E.M. 0.05</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>n 11</td>
<td>11</td>
<td>11</td>
<td>10</td>
<td>10</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 22 38 56</td>
<td>30 mg/kg selexipag (twice daily)</td>
<td>30 mg/kg selexipag metabolite (ACT-333679) (twice daily)</td>
</tr>
<tr>
<td>Average 11.37 0.56 5.40</td>
<td>2512.94 817.58 330.89</td>
<td></td>
</tr>
<tr>
<td>S.E.M. 3.03 0.31 3.00</td>
<td>268.61 147.25 80.96</td>
<td></td>
</tr>
<tr>
<td>n 10 9 9</td>
<td></td>
<td>9 9 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 7.02 270.63</td>
<td>817.58 330.89</td>
<td></td>
</tr>
<tr>
<td>S.E.M. 2.05 71.17</td>
<td>147.25 80.96</td>
<td></td>
</tr>
<tr>
<td>n 9 9</td>
<td>9 9</td>
<td></td>
</tr>
</tbody>
</table>
to several prostanoid and PPAR receptors, which provides a broader spectrum of activity to improve PAH pathophysiology compared with drugs like selexipag that target just the IP receptor.

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Authorship Contributions

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Address correspondence to: Michel R. Corboz, Insmed Incorporated, 700 US Highway 202/206, Bridgewater, NJ 08807. E-mail: michel.corboz@insmed.com