ORIGINAL ARTICLE

Combination Therapy with Oral Treprostinil for Pulmonary Arterial Hypertension

A Double-Blind Placebo-controlled Clinical Trial

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Abstract

Rationale: Oral treprostinil improves exercise capacity in patients with pulmonary arterial hypertension (PAH), but the effect on clinical outcomes was unknown.

Objectives: To evaluate the effect of oral treprostinil compared with placebo on time to first adjudicated clinical worsening event in participants with PAH who recently began approved oral monotherapy.

Methods: In this event-driven, double-blind study, we randomly allocated 690 participants (1:1 ratio) with PAH to receive placebo or oral treprostinil extended-release tablets three times daily. Eligible participants were using approved oral monotherapy for over 30 days before randomization and had a 6-minute-walk distance 150 m or greater. The primary endpoint was the time to first adjudicated clinical worsening event: death; hospitalization due to worsening PAH; initiation of inhaled or parenteral prostacyclin therapy; disease progression; or unsatisfactory long-term clinical response.

Measurements and Main Results: Clinical worsening occurred in 26% of the oral treprostinil group compared with 36% of placebo participants (hazard ratio, 0.74; 95% confidence interval, 0.56–0.97; $P = 0.028$). Key measures of disease status, including functional class, Borg dyspnea score, and N-terminal pro–brain natriuretic peptide, all favored oral treprostinil treatment at Week 24 and beyond. A noninvasive risk stratification analysis demonstrated that oral treprostinil–assigned participants had a substantially higher mortality risk at baseline but achieved a lower risk profile from Study Weeks 12–60. The most common adverse events in the oral treprostinil group were headache, diarrhea, flushing, nausea, and vomiting.

Conclusions: In participants with PAH, addition of oral treprostinil to approved oral monotherapy reduced the risk of clinical worsening.

Clinical trial registered with www.clinicaltrials.gov (NCT01560624).

Keywords: pulmonary arterial hypertension; oral treprostinil; clinical study; combination therapy; sequential therapy

(Received in original form August 21, 2019; accepted in final form November 22, 2019)

A complete list of the FREEDOM-EV Investigators may be found before the beginning of the REFERENCES.

Supported by United Therapeutics Corporation.

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This article has a related editorial.

This article has an online supplement, which is accessible from this issue's table of contents at www.atsjournals.org.

Am J Respir Crit Care Med Vol 201, Iss 6, pp 707–717, Mar 15, 2020

Originally Published in Press as DOI: 10.1164/rccm.201908-1640OC on November 25, 2019
Internet address: www.atsjournals.org

At a Glance Commentary

Scientific Knowledge on the Subject: Oral treprostinil improved exercise capacity in treatment-naive patients with pulmonary arterial hypertension (PAH) and substituted for parenteral treprostinil in a carefully selected group of participants, but the effect on clinical outcomes was unknown.

What This Study Adds to the Field: This multicenter, randomized, double-blind placebo-controlled trial demonstrates that initiation of oral treprostinil reduces the risk of clinical worsening events in participants who had recently (median, 5.4 mo) started oral monotherapy for PAH. Secondary endpoints, including N-terminal pro–brain natriuretic peptide and a multifaceted noninvasive risk assessment, improved in oral treprostinil–assigned participants beginning at Week 12 and continuing through Week 60.

Pulmonary arterial hypertension (PAH) is a rare, but progressive and often fatal, pulmonary vascular disease. Treatment options have expanded greatly in the past 20 years (1), and two event-driven studies of sequential combination therapy have established the durable benefit of the endothelin receptor antagonist (ERA) macitentan (2) and the prostacyclin receptor agonist selexipag (3). Epoprostenol, the endogenous agonist for the prostacyclin receptor, is highly effective in PAH, but it is short acting and requires continuous intravenous infusion (4). Selexipag was thus a significant addition to treatment options as a long-acting and orally available, selective prostacyclin IP receptor agonist. Oral extended-release treprostinil diolamine tablets improved exercise capacity when dosed twice daily in treatment-naive patients with PAH (5). Oral treprostinil dosed three times daily had a better pharmacokinetic profile, allowed participants to achieve a higher total daily dose, and substituted for parenteral treprostinil in a cohort of carefully selected participants with PAH (6). Therefore, the FREEDOM-EV study hypothesized that combination therapy with oral treprostinil would reduce the risk of clinical worsening events in patients who had recently started oral monotherapy for PAH. Preliminary results of this study have been previously reported in the form of conference abstracts (7–9).

Methods

Study Design

The FREEDOM-EV trial was a multicenter, randomized, double-blind, placebo-controlled, event-driven study. Investigators from 152 centers across 23 countries conducted the study between June 2012 and June 2018. The steering committee, in collaboration with the sponsor, designed the study protocol (*see* the online supplement), and the institutional review board at each center approved the protocol. The sponsor collected and analyzed the data according to a prespecified statistical analysis plan. An independent data monitoring committee supervised the study, and all authors had access to the source-verified data and attest to the accuracy and completeness of this report.

Selection of Participants

Participants were 18–75 years of age, met the 2013 consensus definition of World Health Organization (WHO) Group 1 pulmonary hypertension (10), and had a 6-minute-walk distance (6MWD) 150 m or greater at the screening visit. Historical right heart catheterization within 3 years (or during the screening period) must have demonstrated a mean pulmonary artery pressure of 25 mm Hg or greater and a pulmonary artery wedge pressure of 15 mm Hg or less. Based on the AMBITION study (11), protocol amendment 5 excluded participants who had three or more of the following risk factors for heart failure with preserved ejection fraction: *1*) body mass index of 30 kg/m^2 or greater; *2*) essential hypertension; *3*) diabetes mellitus; or *4*) clinically significant coronary artery disease. The initial protocol sought to enroll participants soon after they began oral monotherapy (between 30 and 90 d of beginning an approved dose and schedule of sildenafil, tadalafil, bosentan, ambrisentan, macitentan, or riociguat). Subsequent amendments expanded the monotherapy treatment window to address slow enrollment. The full set of protocol entry criteria are provided in the online supplement. All the participants provided written informed consent.

Trial Procedures

Randomization (1:1) was stratified by type of background therapy (i.e., phosphodiesterase type 5 [PDE5] inhibitor or soluble guanylate cyclase [SGC] stimulator vs. ERA) and by baseline 6MWD (breakpoint ⩽350 m). Participants initially took oral treprostinil or matching placebo 0.125 mg three times daily (spaced carefully every 6–8 h with food). The protocol allowed daily up-titration in 0.125 mg increments for the first 4 weeks and 0.25-mg daily titration thereafter to a maximum dose of 12 mg three times daily. We instructed investigators to increase doses steadily and to assess the need for dose adjustment during weekly telephone calls, attempting to balance the expected adverse drug effects with the apparent clinical benefits (i.e., a reduction in the signs and symptoms of PAH).

Outcome Measures

The primary endpoint was the time to first adjudicated clinical worsening event, which was defined as death from any cause, hospitalization for worsening PAH, disease progression, initiation of inhaled or infused prostacyclin therapy, or unsatisfactory

Author Contributions: R.J.W. is the Principal Investigator of the study and contributed substantially to the protocol, beginning with amendment 2; actively recruited and treated participants in the study; served as the academic lead for analysis and interpretation of the data; and wrote the initial manuscript draft. C.J.-S., G.M.B.M., T.P., P.S., K.Y.W., E.G., S.H., Z.Y., Z.G., W.L.J.Y., S.Z., and A.K. are investigators in the study and actively recruited and treated participants in the study and made revisions to the manuscript. V.F.T. shared leadership responsibility with R.J.W. in the analysis and interpretation of data and early revisions of the manuscript. R.G. served as medical monitor for the study and provided critical input to data analysis and manuscript revision. C.Q.D. managed the study database, performed and directed all the statistical analyses per the statistical analysis plan, helped with interpretation of the statistics and their inclusion in the manuscript, supported additional analyses requested by the other authors, and revised the manuscript throughout its development. All authors approved the decision to submit the manuscript for publication.

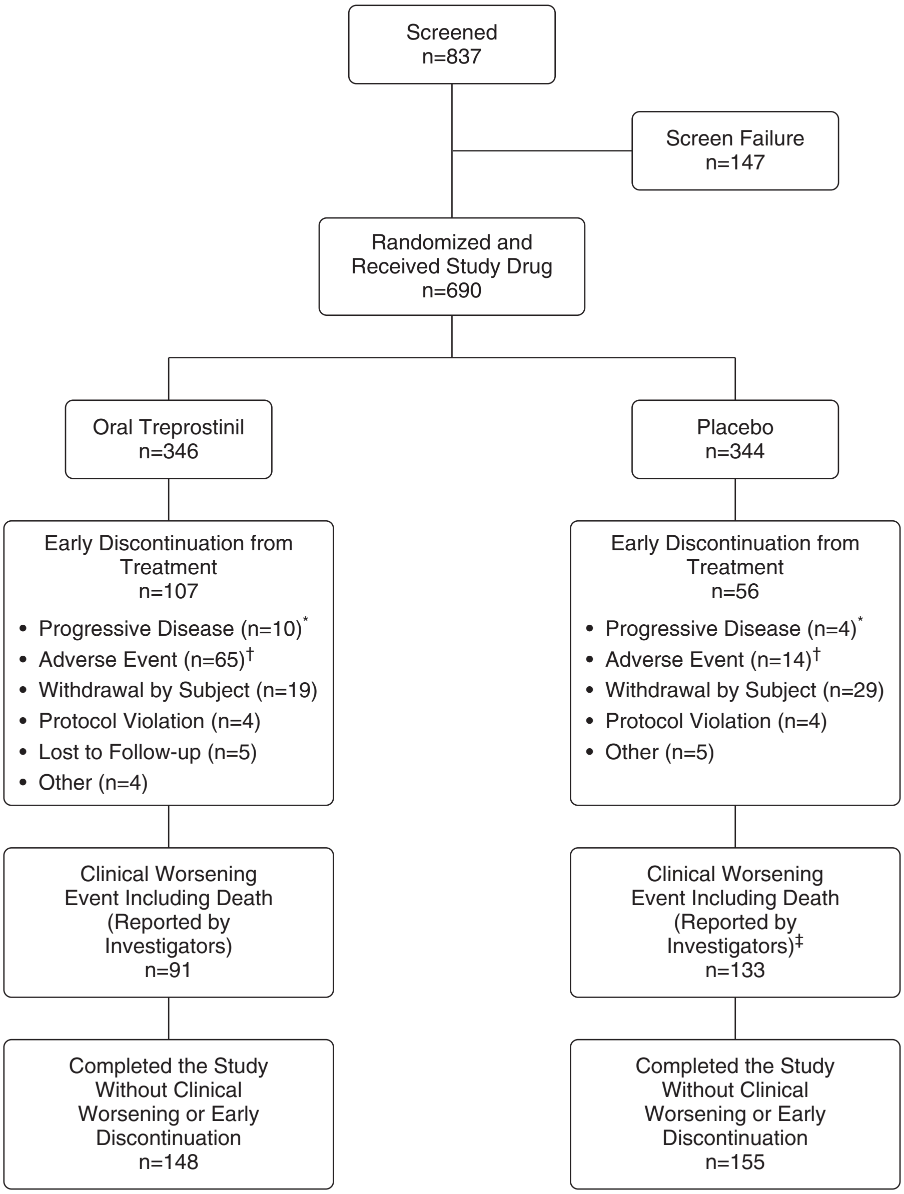

Figure 1. Patient disposition. *Includes one subject in the oral treprostinil group and one subject in the placebo group who experienced clinical worsening events due to urgent hospitalization for treatment of worsening pulmonary arterial hypertension. †Includes one subject in the oral treprostinil group and one subject in the placebo group who experienced clinical worsening events due to fatal serious adverse events, and one subject in the oral treprostinil group who discontinued treatment due to an adverse event, but remained in the study until death (which did not qualify as a clinical worsening event). ‡Includes one subject in the placebo group who died after discontinuation of study treatment due to clinical worsening.

long-term clinical response (definitions provided in the online supplement). Three disease experts (not otherwise participating in the study) formed a blinded, independent clinical event committee, which adjudicated all clinical worsening events using a narrative that was stripped of information about adverse events or dosing that might cue them to treatment assignment.

Investigator teams met participants at Weeks 4, 8, and 12, and then at 12-week intervals throughout the study to conduct efficacy assessments, including 6MWD, Borg dyspnea score, plasma N-terminal pro–brain natriuretic peptide (NT-proBNP) levels, and WHO functional class. Before the final statistical analysis plan was submitted to the U.S. Food and Drug Administration and before unblinding, we planned a risk analysis using three noninvasive variables as previously proposed (12) and validated (13) (e.g., 6MWD, NT-proBNP, and WHO functional class). Safety assessments included evaluation of adverse events and clinical laboratory parameters. Beginning in 2015, with protocol amendment 6, we collected vital status by phone every 6 months for those who discontinued the study; survival analysis was prespecified in the statistical plan submitted to the Food and Drug Administration.

Statistical Analysis

The final power calculation estimated that 205 adjudicated events would provide at least 90% power (type I error rate, 0.05; two tailed) to detect a difference in the time to adjudicated clinical worsening event between treatment groups, assuming exponential distributions and an underlying hazard ratio of 0.62. We assumed a placebo event rate of 23% at Month 12 and accrual of subjects over 3 years with 10% attrition. These assumptions indicated a sufficient sample size would be 610–850 participants; we closed enrollment at 690 participants when we approached the required 205 events. The primary efficacy endpoint had been tested at an interim analysis when approximately 75% of the total adjudicated events had occurred with a prespecified decision to stop if the interim type I error was less than 0.02; this required that the final analysis have an α of less than 0.044 for an overall type I error rate at 0.05. The main analyses for the primary and secondary endpoints were performed in the entire population. For the primary efficacy analysis of time to adjudicated clinical worsening event, data were summarized by treatment group using product-limit estimates calculated by the Kaplan-Meier method. The log-rank test adjusted for the type of background PAH therapy (PDE5 inhibitor or SGC stimulator vs. ERA), and the baseline 6MWD (breakpoint $\leqslant$350 m) was used to calculate significance for treatment differences in the intention-to-treat population. The risk of clinical worsening was also compared between treatment groups using a Cox proportional hazards regression model to estimate a hazard ratio and its 95% confidence interval (CI), also adjusting for background PAH therapy and baseline 6MWD. All safety analyses were also performed in the entire population.

Table 1. Baseline Characteristics*

Characteristic	Oral Treprostinil (*n* = 346)	Placebo (*n* = 344)	Overall (*n* = 690)
Age, yr	45.6 ± 15.7	44.8 ± 15.4	45.2 ± 15.5
Sex, F, *n* (%)	275 (79.5)	269 (78.2)	544 (78.8)
Race, *n* (%)			
White	187 (54.0)	173 (50.3)	360 (52.2)
Black or African American	8 (2.3)	13 (3.8)	21 (3.0)
Asian	150 (43.4)	156 (45.3)	306 (44.3)
Unknown	1 (0.3)	2 (0.6)	3 (0.4)
Region, *n* (%)			
North America	39 (11.3)	54 (15.7)	93 (13.5)
Asia-Pacific	162 (46.8)	160 (46.5)	322 (46.7)
Europe	55 (15.9)	44 (12.8)	99 (14.3)
Latin America	90 (26.0)	86 (25.0)	176 (25.5)
Median time since diagnosis (IQR), mo	6.2 (2.4–13.3)	6.5 (2.28–13.2)	6.4 (2.3–13.3)
Etiology of PAH, *n* (%)			
Idiopathic or heritable PAH	219 (63.3)	216 (62.8)	435 (63.0)
Connective tissue disease	94 (27.2)	84 (24.4)	178 (25.8)
HIV infection	2 (0.6)	7 (2.0)	9 (1.3)
Congenital heart defect	20 (5.8)	27 (7.8)	47 (6.8)
Other	11 (3.2)	10 (2.9)	21 (3.0)
6MWD, *n* (%)			
⩽350 m	95 (27.5)	93 (27.0)	188 (27.2)
>350 m	251 (72.5)	251 (73.0)	502 (72.8)
6MWD, m	392.9 ± 92.5	398.5 ± 100.0	395.7 ± 96.3
WHO functional class at baseline, *n* (%)			
I	9 (2.6)	13 (3.8)	22 (3.2)
II	205 (59.2)	228 (66.3)	433 (62.8)
III	131 (37.9)	103 (29.9)	234 (33.9)
IV	1 (0.3)	0	1 (0.1)
Background PAH therapy at baseline, *n* (%)			
PDE5 inhibitor or SGC stimulator alone	248 (71.7)	246 (71.5)	494 (71.6)
ERA alone	98 (28.3)	98 (28.5)	196 (28.4)
Median time on background PAH therapy at baseline (IQR), mo	5.3 (2.3–10.7)	5.5 (2.4–10.6)	5.4 (2.4–10.7)
Risk stratification by number of low-risk criteria met[†‡], *n* (%)			—
0	85 (25.2)	59 (17.7)	
1	112 (33.2)	110 (32.9)	
2	102 (30.3)	94 (28.1)	
3	38 (11.3)	71 (21.3)	

Definition of abbreviations: 6MWD = 6-minute-walk distance; ERA = endothelin receptor antagonist; IQR = interquartile range; PAH = pulmonary arterial hypertension; PDE5 = phosphodiesterase type 5; SGC = soluble guanylate cyclase; WHO = World Health Organization.

*Plus/minus values are means ± SD. Testing of baseline characteristics showed that there were no significant between-group differences at baseline, except regarding risk stratification by number of low-risk criteria.

†Low-risk criteria defined as WHO functional class I or II, 6MWD greater than 440 m, and/or N-terminal pro–brain natriuretic peptide less than 300 pg/ml. Low-risk criteria met were only counted for subjects with all three measures available; *n* = 337 oral treprostinil, *n* = 334 placebo.

‡$P = 0.002$; *P* value was obtained from Fisher's exact test.

Results

Participants

We randomly allocated 690 participants to oral treprostinil (346 participants) or placebo (344 participants) treatment groups (Figure 1). Table 1 shows the demographic and clinical characteristics of participants; individual characteristics were largely balanced at baseline. We enrolled participants after beginning initial monotherapy (median time, 5.4 mo). Participants were predominantly female; 63% had WHO functional class II symptoms, and 72% were taking a PDE5 inhibitor or SGC stimulator. Median dose of oral treprostinil achieved at Week 24 was 3.56 mg three times daily, which corresponds to titration by approximately 0.125 mg once weekly (288 oral treprostinil participants; *see* Figure E1 in the online supplement). Median dose of placebo at Week 24 was 6 mg three times daily (289 placebo participants).

Primary Efficacy Endpoint

Overall, 90 (26%) participants in the oral treprostinil group experienced an adjudicated clinical worsening event compared with 124 (36%) placebo participants. Kaplan-Meier estimates of the time to adjudicated clinical worsening event suggested group separation before Week 24 (Figure 2A, log-rank test, $P = 0.039$); the hazard ratio adjusted for background therapy and baseline 6MWD as a continuous variable was 0.74 (95% CI, 0.56–0.97; $P = 0.028$). When adjusted for baseline 6MWD as a categorical variable (breakpoint ⩽350 m), the hazard ratio was 0.75 (95% CI, 0.57–0.99; $P = 0.040$). The median time to clinical worsening was 46 weeks with oral treprostinil and 37 weeks with placebo. The treatment-attributable difference in clinical worsening was driven by a reduced incidence of disease progression in the oral treprostinil group (hazard ratio, 0.39; 95% CI, 0.23–0.66; $P < 0.001$). Deaths and hospitalizations were balanced. Subgroup analyses of the primary endpoint, based on age, sex, baseline 6MWD, WHO functional class, PAH etiology, geographic region, and background oral PAH therapy did not show any significant interactions between subgroup and treatment (*see* Figure E2).

Individual components of the demographics suggested balanced participant characteristics at baseline; however, a prespecified (before unblinding), noninvasive risk stratification (12) indicated that the oral treprostinil–assigned group had a higher mortality risk at baseline. Placebo-assigned participants had more low-risk criteria (e.g., WHO functional class I or II symptoms, 6MWD >440 m, and NT-proBNP <300 pg/ml) compared with the oral treprostinil group (Fisher's exact test, $P = 0.002$, Table 1). We thus conducted a *post hoc* analysis accounting for baseline risk profile (number of low-risk factors, 0–3); the hazard ratio for a clinical worsening event dropped further to 0.61 (95% CI, 0.46–0.81; $P < 0.001$). Arbitrarily classifying those with two to three low-risk

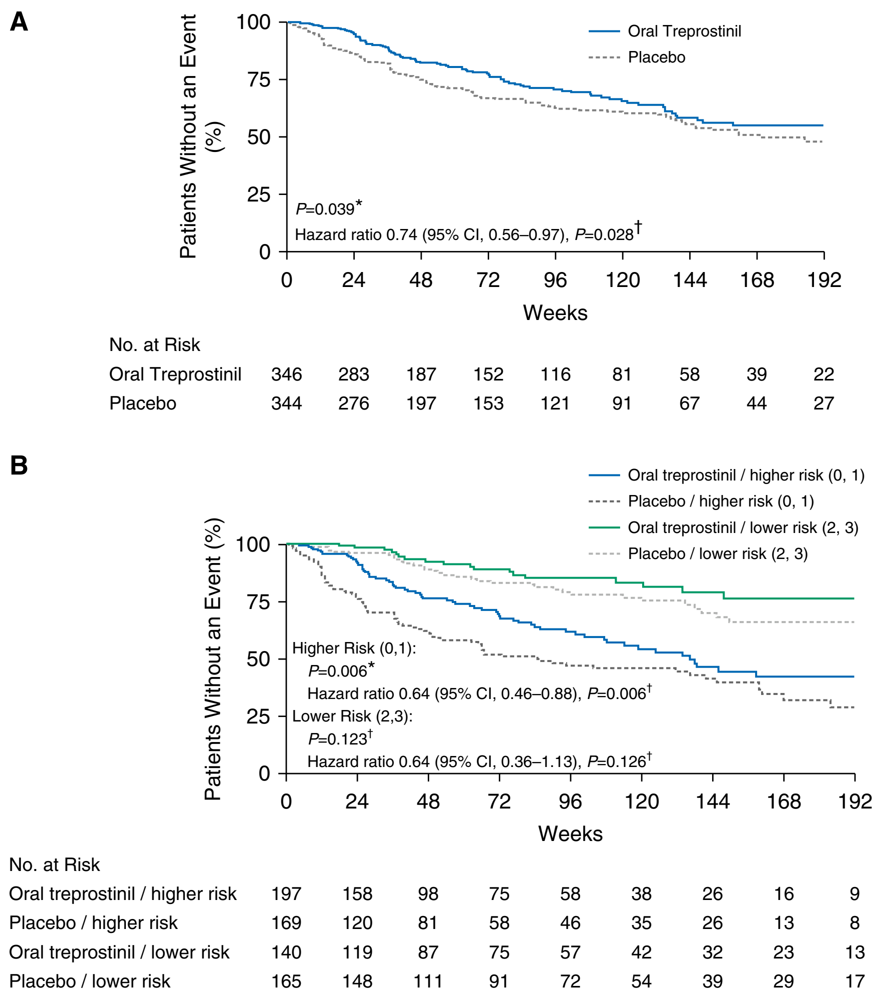

Figure 2. Kaplan-Meier plots of primary endpoint and primary endpoint by baseline risk stratification. (*A*) Time to adjudicated clinical worsening events. (*B*) Time to adjudicated clinical worsening events by baseline risk stratification. "Lower risk" is defined as subjects with two or three low-risk criteria met; "higher risk" is defined as subjects with zero or one low-risk criterion met. **P* values were calculated with log-rank test stratified by background pulmonary arterial hypertension (PAH) therapy and baseline 6-minute-walk distance (6MWD) category. †Hazard ratios, 95% confidence intervals (CIs), and *P* values were calculated with proportional hazard model with explanatory variables of treatment, background PAH therapy, and baseline 6MWD as a continuous variable.

factors as "lower risk" and those with zero to one low-risk factors as "higher risk" resulted in two groups of similar size ($n = 366$ vs. 305). We re-estimated Kaplan-Meier time-to-event curves for these two groups, finding that oral treprostinil protected higher-risk participants from clinical worsening events (log-rank, $P = 0.006$; Figure 2B).

Secondary and Exploratory Efficacy Endpoints

Plasma NT-proBNP levels decreased in the oral treprostinil group beginning at Week 12 (Figure 3). WHO functional class improved significantly for participants in the oral treprostinil group at all visits from Week 12 to Week 48 when compared with the placebo group (Figure 4A). Improvement was observed as both a higher proportion of favorable ("improved") and a lower proportion of worsening ("deteriorated") categorical change from baseline. At Week 24, oral treprostinil participants increased their 6MWD 16 m (least squares mean) compared with 8 m in the placebo group (mixed-model repeated measurement [MMRM] estimate of treatment effect, 8 m [95% CI, −2 to 18; $P = 0.12$], Table 2). By Week 36, treatment difference in 6MWD was clear (MMRM = 13 m [95% CI, 1–25]; $P = 0.04$), and this increased further at Week 48 (MMRM = 22 m [95% CI, 8–35; $P = 0.002$]; *see* Figure E3). Hodges-Lehmann estimate of treatment effect yielded similar results (*see* Figure E4). Although the change in 6MWD was not statistically different between the treatment groups at Weeks 12 or 24, categorical changes in Borg dyspnea score measured at the end of each walk test favored oral treprostinil at assessments from Week 12 to Week 48 (Figure 4B). Similarly, the combined 6MWD/Borg dyspnea score ranking, a statistical method for analyzing changes in walk distance and associated changes in Borg dyspnea score, favored the oral treprostinil treatment group at Week 24 (*see* Figure E5).

We hypothesized *a priori* (before unblinding) that oral treprostinil applied as sequential combination therapy would improve risk assessments at follow-up. We obtained the necessary variables to define the recently proposed, noninvasive risk assessment at Weeks 12, 24, 36, and 60. At each assessment, the Fisher's exact analysis of those having categorical change was highly significant ($P < 0.002$), with more oral treprostinil participants having an improved risk profile and fewer having a deteriorated risk profile (Figure 4C). A *post hoc* analysis using the Reveal 2.0 risk score (14) yielded a similar result beginning at Week 12 (*see* Table E1).

The initial data collection plan stopped following participants 30 days after discontinuing randomized treatment unless they consented to participate in an open-label follow-up study. An amended protocol issued in 2015 collected vital status every 6 months for consenting participants until final study closure in October 2018. As of October 2018, 38 (11%) participants initially assigned to oral treprostinil were confirmed dead compared with 60 (17.4%) in the placebo group (hazard ratio, 0.63; 95% CI, 0.42–0.95; $P = 0.026$; Table 2). Because we did not begin collecting vital status until some participants had exited the study (and some investigative sites had closed), survival could not be confirmed for 74 (11%) participants. A sensitivity analysis assuming the observed mortality rate in those with unknown vital status still favored oral treprostinil (*see* Tables E2 and E3).

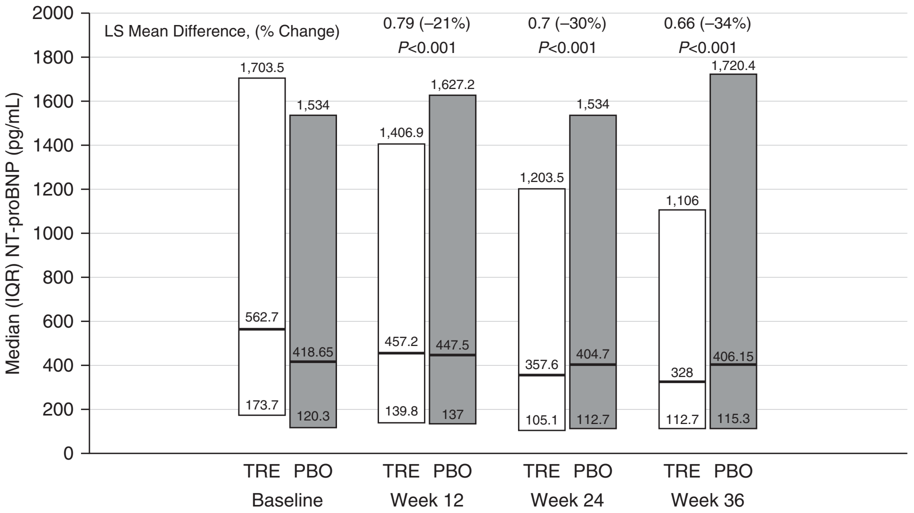

Figure 3. Plasma N-terminal pro–brain natriuretic peptide (NT-proBNP) results by study visit. Per protocol, NT-proBNP values were not measured at Week 48. *P* value was obtained from the analysis of covariance with change from baseline in log-transformed data in NT-proBNP as the dependent variable, treatment as fixed effect, and log-transformed baseline NT-proBNP as a covariate. NT-proBNP assay centrally performed by Covance via the Immulite 2000 on a Seimens platform. The normal range for both sexes less than 75 years of age is less than 125 pg/ml. The normal range for both sexes over 75 years of age is less than 450 pg/ml. IQR = interquartile range; LS = least squares; PBO = placebo; TRE = oral treprostinil.

Safety

A total of 334 (96.5%) participants in the oral treprostinil group and 219 (63.7%) participants in the placebo group reported at least one adverse event attributable to study drug (Table 3). Headache, diarrhea, flushing, nausea, and vomiting were more commonly attributed to oral treprostinil and were more often severe compared with events attributed to placebo. Study drug discontinuation because of adverse events was substantially more common in oral treprostinil–assigned participants (18.8%) than in placebo participants (4.1%). Discontinuation because of an adverse event was more common before Week 24 (*see* Figure E6) and occurred at a median (interquartile range) oral treprostinil dose of 1.4 (0.4–3.0) mg three times daily.

Discussion

In the present study, oral treprostinil dosed three times daily delayed a composite clinical endpoint of time to first adjudicated clinical worsening event by reducing the likelihood of disease progression in participants, all of whom were taking an approved oral monotherapy for PAH. Hospitalizations and deaths were balanced between groups as components of the primary endpoint. This study differs from previous sequential combination studies (2, 3) in that participants had a younger age, more recent diagnosis, less severe symptoms, and better baseline exercise capacity. Although prostacyclin-class adverse events were common and 18.8% of oral treprostinil participants discontinued therapy because of adverse events, active treatment facilitated steady reductions in plasma NT-proBNP, improved WHO functional class, and reduced Borg dyspnea score after 6MWT, all beginning at Week 12. Actual 6MWD was improved at Weeks 36 and 48 in an analysis that does not require imputation. Total daily dose among actively treated participants at Week 24 was 50% higher than that at Week 16 in the previous combination studies of oral treprostinil (15, 16), and we postulate that higher doses were possible, because three times daily dosing reduced peak–trough excursions in plasma concentrations of treprostinil (6, 17).

Functional improvements, measured as part of a multifaceted risk assessment, have been repeatedly associated with improved outcomes (12, 13, 18, 19). We prespecified (before submission of the final statistical analysis plan) use of the French risk assessment, because we had collected the three required noninvasive variables at nearly all of the quarterly follow-up visits. For those who remained on therapy, participants taking oral treprostinil had a favorable shift in this noninvasive risk at Week 12, and the measured treatment benefit in risk reduction persisted at Week 60. This shift reflected an improvement in risk profile for 39% of oral treprostinil participants at Week 60 and was independent of the differences in the primary event of clinical worsening (because those participants had been censored). Our data support the recently suggested "net clinical benefit" strategy for clinical studies of novel therapies in PAH (20).

The balanced appearance of baseline characteristics in our study was deceiving and revealed the need for a multifaceted assessment of prognosis to ensure a reliable assessment of subsequent treatment efficacy. The unexpected imbalance in risk profiles at baseline indicates that our randomization strategy failed to create comparable baseline groups. This may be because the 350 m or lower breakpoint for 6MWD included less than 30% of the baseline walks and/or because this 350-m value is not a recognized transition point for prognosis (21). The *post hoc*, risk-adjusted analysis of the primary endpoint demonstrating a greater treatment effect indicates that future studies should consider stratifying randomization based upon background therapy and a validated risk score to create cohorts that have a similar prognosis at baseline (22). A failure in this regard could lead to under- or overestimation of the treatment effect.

Participants initially assigned placebo had a similar rate of death at the end of randomized treatment. A total of 108 of the 117 participants with an investigator-reported, nonfatal clinical worsening event in the primary study began therapy with oral treprostinil in the extension study. An apparent increase in survival for those initially assigned oral treprostinil emerged late in the study, but this observation must be treated cautiously, because vital status was unknown for 74 participants (11%). The results still favored oral treprostinil, assuming a proportional mortality among those with unknown vital status (Tables E2 and E3). We know very little about participants who discontinued the study. Only vital status was collected via phone call; we do not know the causes of death. Deaths were distributed relatively uniformly throughout the world with the exception of India, which had a death rate of approximately 20%. However, other countries with less access to expensive,

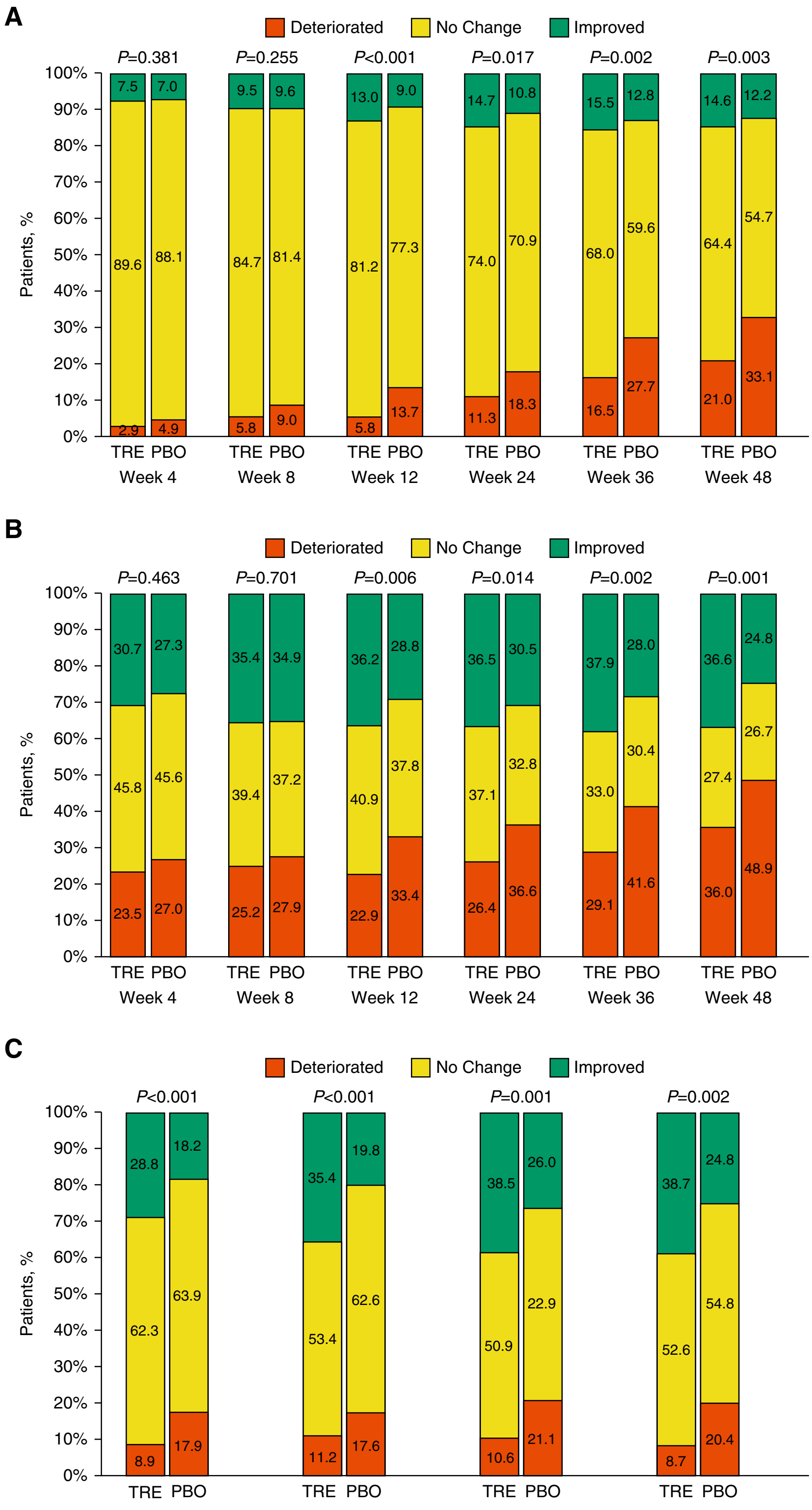

Figure 4. Categorical changes from baseline in World Health Organization (WHO) functional class, Borg dyspnea score, and risk stratification criteria. (*A*) WHO functional class categorical change from baseline by study visit; participants who had a missing assessment at Week 24 and had deteriorated were assigned functional class IV; *P* value was obtained from Fisher's exact test. (*B*) Borg dyspnea score categorical change from baseline by study visit; participants who had a missing assessment at Week 24 and had deteriorated were assigned worst case of 10; *P* value was obtained from Fisher's

approved PAH therapies (e.g., Mexico and China) did not have excess deaths relative to countries with more ready access. We know nothing about treatment status for those who died after discontinuing the study, and treatment differences between the groups might be an important confounder. Thus, this apparent difference in mortality (using the strategy prescribed in the final statistical analysis plan) is intriguing, but must be interpreted with appropriate context due to the amount of missing data. In a recent meta-analysis of 17 randomized, controlled therapeutic trials in PAH, sequential therapy was associated with a significant risk reduction for clinical worsening (−35%; $P < 0.001$), but not mortality (−14%; $P = 0.09$) (23). Macitentan was associated with a trend toward improved survival (2) in a prespecified analysis, and initial combination therapy improved survival (as compared with initial monotherapy) in a *post hoc* analysis (24). Although selexipag prevented clinical worsening events overall (3), death was numerically greater at the end of randomized treatment and similar to placebo through the end of the study.

Our study has important limitations. Adverse effects typical for prostacyclin-class medications were common, and the 18.8% discontinuation rate was higher than for a previous study of selexipag (14.3%). It is conceivable that some of the oral treprostinil–assigned participants who stopped taking the drug because of adverse events might have later had clinical worsening, but we used standard censoring methodology in generating the primary outcome analysis. The protocol was launched in 2013 when sequential combination therapy was standard, but initial combination therapy is becoming increasingly common. It is unknown whether the present results are generalizable to patients in clinical practice who are already taking two approved therapies.

In conclusion, oral treprostinil administered three times daily to a relatively homogenous group of participants with PAH who were taking oral monotherapy reduced the likelihood of clinical worsening due to disease progression. Plasma levels of NT-proBNP dropped markedly with oral treprostinil, and we also observed improvements in investigator-assessed WHO functional class and participant-reported Borg dyspnea score after hallway walking. Serial, noninvasive risk score

Table 2. Primary and Secondary Efficacy Endpoints

Endpoint	Oral Treprostinil (*n* = *346*)	Placebo (*n* = *344*)	Treatment Effect (95% CI)
Primary endpoint: adjudicated clinical worsening event, *n* (%)			
All events	90 (26.0)	124 (36.0)	HR, 0.74 (0.56 to 0.97); $P = 0.028$*; $P = 0.039$†
Death (all causes)	15 (4.3)	14 (4.1)	
Hospitalization due to PAH and/or right heart failure	35 (10.1)	35 (10.2)	
Initiation of inhaled or infused prostacyclin	2 (0.6)	5 (1.5)	
Disease progression	19 (5.5)	50 (14.5)	
Unsatisfactory long-term clinical response	19 (5.5)	20 (5.8)	
Secondary endpoints (at Week 24)			
6MWD, LS mean change, m	16	8.03	7.96 (−2 to 17.92); $P = 0.117$‡
NT-proBNP, concentration ratio to baseline, LS mean change	0.82	1.16	0.71 (0.61 to 0.82); $P < 0.001$§
Borg dyspnea score, shift from baseline, *n* (%)			$P = 0.014$‖
Improved	126 (36.5)	105 (30.5)	
No change	128 (37.1)	113 (32.8)	
Deteriorated	91 (26.4)	126 (36.6)	
Combined ranking of 6MWD and Borg dyspnea score	—	—	$P = 0.006$¶
WHO functional class, shift from baseline, *n* (%)			$P = 0.017$‖
Improved	51 (14.7)	37 (10.8)	
No change	256 (74)	244 (70.9)	
Deteriorated	39 (11.3)	63 (18.3)	
Deaths (all causes), *n* (%)			
Deaths during study	17 (4.9)	18 (5.2)	HR, 1.00 (0.52 to 1.95); $P = 0.992$*; $P = 0.978$†
Deaths at closure of study**	38 (11.0)	60 (17.4)	HR, 0.63 (0.42 to 0.95); $P = 0.026$*; $P = 0.032$†

Definition of abbreviations: 6MWD = 6-minute-walk distance; CI = confidence interval; HR = hazard ratio; LS = least squares; MMRM = mixed-model repeated measurement; NT-proBNP = N-terminal pro–brain natriuretic peptide; PAH = pulmonary arterial hypertension; WHO = World Health Organization.
*Hazard ratio, 95% CI, and *P* value were calculated with proportional hazard model with explanatory variables of treatment, background PAH therapy, and baseline 6MWD as a continuous variable.
†*P* value was obtained from log-rank test stratified by background PAH therapy and baseline 6MWD category.
‡LS mean, *P* value, estimated difference, and its 95% CI were from the MMRM with the change from baseline in 6MWD as the dependent variable, treatment, week, treatment-by-week interaction, and background PAH therapy as the fixed effects, and baseline 6MWD as the covariate. An unstructured variance/covariance structure shared across treatment groups was used to model the within-subject errors.
§LS mean, *P* value, estimated difference, and its 95% CI were from the MMRM with the change from baseline in log-transformed data in NT-proBNP as the dependent variable, treatment, week, and treatment-by-week interaction as the fixed effects, and log-transformed baseline NT-proBNP as the covariate. An unstructured variance/covariance structure shared across treatment groups was used to model the within-subject errors.
‖*P* value was obtained from Fisher's exact test.
¶*P* value obtained from nonparametric analysis of covariance.
**Vital status was collected at the study closure for all subjects including subjects who rolled over to extension study and who discontinued early from the study. For subjects whose vital status was not available at the study closure, their time to death was censored at the subjects' last known date to be alive. Subjects who were alive at the study closure have their time to death censored at the last contact date.

measurements appeared useful to document treatment-related benefits, and a prognostic score should be considered for future outcome studies to balance baseline risk profiles between the randomized treatment groups. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

Acknowledgment: The authors thank Aliou Ousmanou, Pharm.D. (United Therapeutics), for successfully leading the global operation throughout the project. Andrew Nelsen, Pharm.D., and Derek Solum, Ph.D. (United Therapeutics), provided critical support to the data analysis and the development of figures and tables. Erick Borg, Pharm.D. (United Therapeutics), and Tina Lin, Pharm.D. (Write Science), provided excellent editorial support; the latter was funded by United Therapeutics.

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Figure 4. (Continued). exact test. (*C*) Risk categorical change from baseline through Week 60. Percentages are calculated based on the number of participants at each visit within each treatment group. Low-risk criteria are defined as WHO functional class I or II, 6-minute-walk distance >440 m, or N-terminal pro–brain natriuretic peptide <300 pg/ml. Low-risk criteria met were only counted for subjects with all three measures. "Improved" indicates any increase in the number of low-risk criteria met; "no change" indicates the same number of low-risk criteria met; and "deteriorated" indicates any decrease in the number of low-risk criteria met. *P* values were obtained from Fisher's exact test. PBO = placebo; TRE = oral treprostinil.

Table 3. Most Frequent Adverse Events

Variable	Oral Treprostinil (*n* = *346*) [*n (%)*]	Placebo (*n* = *344*) [*n (%)*]
Any event reported	342 (98.8)	328 (95.3)
Any event probably or possibly related to study drug	334 (96.5)	219 (63.7)
Study drug–related serious adverse event	27 (7.8)	18 (5.2)
Study drug–related severe adverse event	78 (22.5)	27 (7.8)
Adverse events*		
Headache	242 (69.9)	102 (29.7)
Diarrhea	227 (65.6)	68 (19.8)
Flushing	151 (43.6)	26 (7.6)
Nausea	128 (37.0)	58 (16.9)
Vomiting	111 (32.1)	26 (7.6)
Pain in jaw	60 (17.3)	8 (2.3)
Dizziness	52 (15.0)	45 (13.1)
Pain in extremity	48 (13.9)	11 (3.2)
Myalgia	44 (12.7)	23 (6.7)

*Adverse events listed are those probably or possibly related to study drug that occurred in more than 10% of participants in either study group.

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