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Sotatercept Safety and Effects on Hemoglobin, Bone, and Vascular Calcification

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Introduction: Patients with end-stage kidney disease (ESKD) exhibit anemia, chronic kidney disease–mineral bone disorder (CKD–MBD), and cardiovascular disease. The REN-001 and REN-002 phase II, multicenter, randomized studies examined safety, tolerability, and effects of sotatercept, an ActRIIA-IgG1 fusion protein trap, on hemoglobin concentration; REN-001 also explored effects on bone mineral density (BMD) and abdominal aortic vascular calcification.

Methods: Forty-three patients were treated in REN-001 (dose range: sotatercept 0.3–0.7 mg/kg or placebo subcutaneously [s.c.] for 200 days) and 50 in REN-002 (dose range: 0.1–0.4 mg/kg i.v. and 0.13–0.5 mg/kg s.c. for 99 days).

Results: In REN-001, frequency of achieving target hemoglobin response (>10 g/dl [6.21 mmol/l]) with sotatercept was dose-related and greater than placebo (0.3 mg/kg: 33.3%; 0.5 mg/kg: 62.5%; 0.7 mg/kg: 77.8%; 0.7 mg/kg [doses 1 and 2]/0.4 mg/kg [doses 3–15]: 33.3%; placebo: 27.3%). REN-002 hemoglobin findings were similar (i.v.: 16.7%–57.1%; s.c.: 11.1%–42.9%). Dose-related achievement of ≥2% increase in femoral neck cortical BMD was seen among only REN-001 patients receiving sotatercept (0.3–0.7 mg/kg: 20.0%–57.1%; placebo: 0.0%). Abdominal aortic vascular calcification was slowed in a dose-related manner, with a ≥15% increase in Agatston score achieved by more REN-001 sotatercept versus placebo patients (60%–100% vs. 16.7%). The most common adverse events during treatment were hypertension, muscle spasm, headache, arteriovenous fistula site complication, and influenza observed in both treatment and placebo groups.

Conclusion: In patients with ESKD, sotatercept exhibited a favorable safety profile and was associated with trends in dose-related slowing of vascular calcification. Less-consistent trends in improved hemoglobin concentration and BMD were observed.

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KEYWORDS: bone mineral density; end-stage kidney disease; hemoglobin; pharmacodynamics; sotatercept; vascular calcification

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osteodystrophy with low bone volume, and disordered mineral metabolism. In CKD, activin receptors are stimulated in skeletal, vascular, and heart tissues, implicating a possible role for sotatercept in ameliorating CKD-related cardiovascular disease and osteodystrophy. A murine analog of sotatercept increased bone formation, leading to increased bone density and strength and decreased atherosclerotic vascular calcification in a preclinical CKD model.

We report findings from 2 phase II, multicenter, randomized studies (REN-001 and REN-002) of ESKD patients undergoing hemodialysis and with anemia. Both studies evaluated the multiple-dose safety, pharmacokinetic, and pharmacodynamic effects of sotatercept on serum Hb concentration. REN-001 also explored effects on BMD and vascular calcification. REN-001 was placebo-controlled and evaluated sotatercept for the correction of anemia after ESA washout; REN-002 was an open-label study that evaluated Hb maintenance in ESKD patients after switching from a prior ESA. These studies shared an objective of exploring dosing strategies that would safely impact pharmacodynamic parameters, primarily Hb, and might translate into clinical benefit in larger clinical trials.

**METHODS**

**Patients**

For either study, patients had to be aged ≥18 years with ESKD, on hemodialysis (≥3 hours of high-flux hemodialysis at each session for ≥12 weeks before screening), and on a stable ESA dose for ≥6 weeks before screening. Proven ESA responsiveness was required (mean Hb values: 10–12 g/dl [6.21–7.45 mmol/l]). Patients were excluded if they had anemia due to non-renal causes, were receiving peritoneal dialysis, had systemic hemato logic disease, were medically unstable, or had uncon trolled diabetes mellitus (HbA1c >9%), hypertension (home systolic blood pressure [BP] >160 mm Hg, or home diastolic BP >90 mm Hg), or heart failure (New York Heart Association classification ≥3).

**Study Design**

ACE-011–REN-001 (REN-001; NCT01146574) Part 1 was a double-blind, placebo-controlled study evaluating pharmacokinetics, dialysis clearance, and safety of sotatercept following a single s.c. dose (0.1 mg/kg). REN-001 Part 2 was a randomized, single-blind, placebo-controlled study of s.c. sotatercept administration in doses ranging from 0.3 to 0.7 mg/kg, evaluating for the correction of anemia after ESA washout. Patients could receive treatment over 200 days if they did not require rescue or if the Hb threshold was not exceeded; the sotatercept 0.3, 0.5, and 0.7 mg/kg dose groups received up to 8 doses, given every 28 days, and the 0.7/0.4 mg/kg dose group received up to 15 doses (doses 1 and 2: 0.7 mg/kg; doses 3–15: 0.4 mg/kg), given every 14 days.

ACE-011 REN-002 (REN-002; NCT01999582) was an open-label, randomized study evaluating i.v. and s.c. sotatercept administration routes in doses ranging from 0.1 to 0.4 mg/kg (i.v.) and 0.13 to 0.5 mg/kg (s.c.) evaluating Hb maintenance after switching from a prior ESA. Patients could receive up to 8 doses given every 14 days over 99 days.

Study designs for REN-001 and REN-002 are illustrated in Figure 1. In both studies, if Hb fell below 9 g/dl (5.59 mmol/l), patients received rescue ESA treatment and discontinued sotatercept dosing. In REN-002, dose escalation in increments of 0.1 mg/kg was permitted in dose group 3 if an Hb reduction ≥1 g/dl (0.62 mmol/l) occurred or absolute Hb was <10 g/dl (6.21 mmol/l). Both studies followed patients for 112 days after their last sotatercept dose.

**Dosing Rules Based on Hb Concentration**

Sotatercept doses were delayed if absolute Hb concentration exceeded defined thresholds (REN-001: ≥11 g/dl [6.83–8.07 mmol/l]; failed to decrease to <11 g/dl [6.83 mmol/l] by day 36 [day 29 + 7 days = window for groups 1–3] or by day 19 [day 15 + 4 days for group 3a]; REN-002: >12 to <13 g/dl [7.45–8.07 mmol/l]). Doses were also delayed if the Hb rate of rise was ≥1 g/dl (0.62 mmol/l) at any time since the last dose (REN-002: over 14 days). In REN-001, a half-dose reduction of sotatercept occurred when Hb was <11 g/dl (6.83 mmol/l), but the rate of rise was >2 g/dl (1.24 mmol/l) (over 28 days, groups 1–3) or >1 g/dl (0.62 mmol/l) (over 14 days, group 3a). Sotatercept was re-dosed when the Hb concentration returned to <11 g/dl (6.83 mmol/l) (REN-001: resumed at half the previous dose; REN-002: resumed at the full assigned dose). Sotatercept was discontinued if the absolute Hb was ≥13 g/dl (8.07 mmol/l) (REN-002 only; if Hb was <14 g/dl [8.69 mmol/l], it could be reconfirmed within 7 days) or Hb was >12 g/dl (7.45 mmol/l) to <13 g/dl (8.07 mmol/l) for 2 consecutive weeks (REN-001 only).

**Dosing Rules Based on Home BP**

In addition to recording predialysis and postdialysis seated BP, home BP monitoring was used to evaluate safety because of a patient who experienced progressive hypertension due to a rapid rise in her Hb level in a study of healthy postmenopausal women. Patients were assigned a home BP monitor and trained in its use. Sotatercept dosing could be modified, interrupted, or discontinued based on BP increases. Sotatercept was...
REN-001

All randomized patients will continue treatment with sotatercept 0.3 mg/kg/placebo for up to 8 doses unless rescued or discontinued early

28 days after 6th patient is dosed with sotatercept 0.3 mg/kg, evaluate PK and safety

Placebo (n~3)
q28d, up to 8 doses

28 days after 6th patient is dosed with sotatercept 0.5 mg/kg, evaluate PK and safety

All randomized patients will continue treatment with sotatercept 0.5 mg/kg/placebo for up to 8 doses unless rescued or discontinued early

28 days after 6th patient is dosed with sotatercept 0.5 mg/kg, evaluate PK and safety

Placebo (n~3)
q28d, up to 8 doses

Sotatercept 0.7 mg/kg s.c. (n~9)
q28d, up to 8 doses

All randomized patients will continue treatment with sotatercept 0.7 mg/kg/placebo for up to 8 doses unless rescued or discontinued early

14 days after 6th patient is dosed with sotatercept, evaluate PK and safety

Placebo (n~3)
q14d, up to 15 doses

REN-002

Screening and ESA washout (Day −90 to Day −1)

Screening and ESA washout (Day −90 to Day −1)

Screening and ESA washout (Day −90 to Day −1)

Figure 1. Study designs for REN-001 (a) and REN-002 (b).  *If hemoglobin (Hb) levels are >11 g/dl (6.83 mmol/l) and have not returned to <11 g/dl by day 36 (window is day 29 + 7 days) of a dosing cycle, sotatercept/placebo doses 2 to 8 may be delayed until Hb is <11 g/dl. Patients will be dosed when Hb is <11 g/dl.  †If Hb levels are >11 g/dl and have not returned to <11 g/dl by day 19 (window is day 15 + 4 days) of a dosing cycle, sotatercept/placebo doses 2 to 15 may be delayed until Hb is <11 g/dl. Patient will be dosed when Hb is <11 g/dl. BMD, bone mineral density; ESA, erythropoiesis-stimulating agent; ESKD, end-stage kidney disease; PK, pharmacokinetic; qCT, quantitative computed tomography; s.c., subcutaneous.
discontinued if mean systolic BP was >200 mm Hg or mean diastolic BP was >110 mm Hg at any time (REN-002 only), or if mean pre-dose home systolic BP was >160 mm Hg and there was a >20 mm Hg systolic BP increase or a >10 mm Hg diastolic BP increase from baseline. In response to increased BP, dialysis and/or antihypertensive medications could be modified at the investigator’s discretion, with mean home BP reassessed before the next dosing visit. In REN-002, post-dose home BP values were evaluated for 2 days following each dose.

Quantitative Computed Tomography
A quantitative computed tomography (qCT) scan of the hip, lumbar spine, and abdominal aorta was obtained at baseline and after the 225-day treatment phase. Trabecular volumetric BMD (mg/cm³) was determined with a 0.1 increase or a 0.1 increase to baseline for analysis]. Placebo arms were combined for all efficacy and safety analyses. Efficacy endpoints included proportions of patients achieving an absolute Hb concentration >10 g/dl (6.21 mmol/l) at any time before rescue during the treatment period, and those requiring rescue therapy during the treatment period. Time to target Hb concentration and time to receiving rescue treatment were summarized. Exploratory endpoints based on qCT included proportions of patients with a >2% increase from baseline in BMD assessments of femoral neck, lumbar spine, and hip, and change from baseline in Agatston scores for abdominal aorta vascular calcification. No formal hypothesis testing or treatment comparison was performed for the exploratory endpoints.

REN-002
Primary endpoints were sotatercept serum pharmacokinetic parameters. Secondary endpoints included proportions of patients maintaining a mean Hb concentration of ≥10 to ≤12 g/dl (6.21–7.45 mmol/l) between days 98 and 113 and requiring rescue therapy (Hb <9 g/dl [5.59 mmol/l]) during the treatment period. Efficacy measures were analyzed using descriptive statistics among the full analysis set; safety was examined in the safety population (i.e., all randomized patients who received ≥1 dose of study treatment).

RESULTS
Patient Disposition

REN-001
In Part 1, a total of 7 patients from 4 US sites were enrolled (placebo: n = 1; sotatercept 0.1 mg/kg s.c.: n = 6). In Part 2, a total of 43 patients from 13 US sites were enrolled and received ≥1 dose of study medication by s.c. injection (placebo: n = 11; sotatercept 0.3 mg/kg: n = 9 [group 1]; 0.5 mg/kg: n = 8 [group 2]; 0.7 mg/kg: n = 9 [group 3]; 0.7/0.4 mg/kg: n = 6 [group 3a]). In the placebo group, 1 of 11 (9.1%) patients completed the study treatment (i.e., received assigned study treatment throughout the 200-day treatment phase); among the treatment groups, the sotatercept 0.3 mg/kg group had the lowest proportion of completers (2 of 9 patients [22.2%]), and the sotatercept 0.7 mg/kg group had the highest proportion of completers (4 of 9 patients [44.4%]). Rescue ESA administration due to Hb concentration <9 g/dl (5.59 mmol/l) was the primary reason for discontinuation across all treatment groups (Figure 2).
REN-002

Fifty patients from 16 European Union sites were randomized and received ≥1 dose of sotatercept (i.v. doses 0.1 mg/kg, n = 7; 0.2 mg/kg, n = 9; 0.1–0.4 mg/kg, n = 12; s.c. doses 0.13 mg/kg, n = 7; 0.26 mg/kg, n = 9; 0.4–0.5 mg/kg, n = 6). Thirty (60%) patients completed study treatment throughout the 99-day treatment phase; 20 (40%) patients discontinued. Among those receiving sotatercept, the s.c. 0.4 to 0.5 mg/kg dose group had the lowest proportion of completers (3 of 6 patients [50.0%]), and the i.v. 0.1 to 0.4 mg/kg dose group had the highest proportion of
completers (10 of 12 patients [83.3%]). The most common reasons for discontinuation were lack of efficacy (n = 5) and adverse event (AE; n = 4) across all the treatment groups; 8 patients discontinued for other reasons unrelated to safety (Figure 2).

Dialysis Prescription
Patients in both studies were on a fixed dialysis protocol, and there were no changes in dialysis prescriptions during the study period. Baseline demographics, dialysis treatment history, and concomitant phosphate-binder use are reported in Supplementary Tables S1 and S2.

Primary Endpoint: Pharmacokinetics

**REN-001**
In the Part 1 noncompartmental pharmacokinetic analysis, sotatercept 0.1 mg/kg s.c. single dose was slowly absorbed into systemic circulation (median time to maximum plasma concentration, approximately 6 days), exhibiting a mean terminal half-life (t1/2.z) of 21.1 days (n = 6; Table 1). Serum sotatercept concentration showed no changes during dialysis, indicating that the drug is nondialyzable. In the Part 2 noncompartmental analysis, sotatercept mean 28-day exposure [area under the concentration-time curve from 0 to 28 days (AUC0–28days)] and maximum serum concentration (Cmax) increased in an approximate dose-proportional manner from a dose of 0.3 mg/kg to 0.7 mg/kg. The 14-day dosing regimen, with loading dose in the first month (dose group 3a), led to increased AUC and Cmax levels during the study period. Baseline demographics, dialysis prescription, sotatercept displayed elimination rates across all dose groups ranging from 20–32 days.

**REN-002**
Increases in AUC0–28days and Cmax were approximately dose-proportional, from 0.1 to 0.2 mg/kg for the i.v. sotatercept dosing (Table 1). A dose-dependent increase in AUC0–28days and Cmax was not obvious for s.c. sotatercept dosing from 0.4 to 0.5 mg/kg, likely due to the small sample size and higher interpatient variability. Regardless of administration route, sotatercept displayed elimination rates ranging from 18 to 26 days.

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**Table 1.** PK parameters\(^{a}\) of sotatercept in REN-001 and REN-002 (noncompartmental analysis)

| PK parameter, mean (CV%) | REN-001 Part 1 | REN-002 | REN-000 Part 2 |
|--------------------------|---------------|---------|---------------|
|                         | Sotatercept dose: 0.1 mg/kg s.c. | Sotatercept administration route and dose | Sotatercept dose (s.c.) |
|                         | n = 6 | l.v. (n = 4) | i.v. (n = 3) | i.v. (n = 4) | s.c. (n = 5) | s.c. (n = 4) | s.c. (n = 4) |
| Cmax, µg/ml | 2.40 (40.0) | 3.66 (18.3) | 3.97 (41.3) | 7.71 (25.6) |
| T \(_{\text{max}, 0}\) | 11.94 (20.0, 14.0) | 6.96 (0.02, 14.0) | 12.00 (5.0, 16.0) | 18.50 (15.0, 21.0) |
| AUC0–28days, µg/ml | 50.64 (34.9) | 78.03 (17.1) | 87.51 (41.9) | 126.96 (16.4) |
| t1/2,z | 24.31 (13.5) | 32.07 (61.9) | 22.16 (31.6) | 19.61 (14.8) |

\(\text{AUC0–28days}\), area under the curve during a 28-day exposure period; \(\text{Cmax}\), maximum plasma concentration during a 28-day exposure period; CV%, coefficient of variance; PK, pharmacokinetic; s.c., subcutaneous; \(\text{t1/2,z}\), terminal half-life; \(\text{T}_{\text{max, 0}}\), time to \(\text{Cmax}\) during a 28-day exposure period.

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**References**

1. Coyne DW et al.: Sotatercept in End-Stage Kidney Disease. Kidney International Reports (2019) 4, 1585–1597

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**Supplementary Material**

- Supplementary Tables S1 and S2
- Discussion on the pharmacokinetic analysis and clinical implications
- Additional data on the study design and patient population

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**Acknowledgments**

- Acknowledgment to the research team and funding sources
- Declaration of authorship and conflicts of interest

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**Appendix**

- Additional details on the study methodology and results
- Further analysis of the data

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**Correspondence**

- Contact information for the lead author
- Address for inquiries and supplementary materials

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**Literature Cited**

- Relevant studies cited for the current investigation
- Other references for further reading and context

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**Clinical Research**

- Clinical relevance and implications of the study findings
Secondary Endpoints: Target Hb

*REN-001*

In dose groups 1–3 for up to 200 days of treatment, a general trend toward increase in mean Hb concentration and mean change from baseline in Hb concentration over time was observed across treatment groups. No consistent trend was observed in mean Hb concentration or mean change from baseline in Hb concentration over time in dose group 3a. Figure 3a summarizes the proportions of patients achieving predefined target Hb for REN-001 (Hb >10 g/dl [6.21 mmol/l] any time during the treatment period). There were no consistent trends in time to achieve target Hb across the placebo and sotatercept dose groups (range median time to target, Hb censored for rescue: 1.0–18.5 days).

Fewer patients were rescued in the sotatercept 0.5 and 0.7 mg/kg treatment groups compared with the sotatercept 0.3 mg/kg and placebo groups (Figure 3c). Because of the small group size, the chance that differences between groups existed by chance could not be excluded. All 6 sotatercept 0.7/0.4 mg/kg patients required rescue during the treatment period. Mean time to rescue was longest with sotatercept 0.7 mg/kg (100.4 days) and 0.7/0.4 mg/kg (117.5 days) and shortest with placebo (44.8 days).

*REN-002*

Sixteen (32%) patients maintained predefined target Hb (≥10.0 [6.21 mmol/l] and ≤12.0 g/dl [7.45 mmol/l] for visits 14–17) without rescue medication. Proportionately more patients in s.c. groups 2 (33%) and 3 (50%) met this criterion, versus i.v. dose groups 2 (11%) and 3 (25%), although the small sample size in each dose group makes comparisons difficult (Figure 3b).

Overall, during the treatment period, similar proportions of patients used rescue therapy in the i.v. (8 of 28 patients [28.6%]) and s.c. (6 of 22 patients [27.3%]) dose groups. A trend toward lower rescue therapy use was observed with higher i.v. doses (Figure 3d).

Exploratory Endpoints: Effects on Bone Endpoints (REN-001)

In 27 patients with paired qCT measurements at baseline and day 225, there were no consistent trends in the mean percent changes from baseline in lumbar spine or total hip BMD. One patient (sotatercept 0.7 mg/kg) had a ≥2% increase from baseline in total hip cortical BMD. No placebo or sotatercept 0.7/0.4 mg/kg patients had a ≥2% increase from baseline in femoral neck cortical BMD; the proportions of patients achieving a ≥2% increase from baseline in femoral neck cortical BMD increased with sotatercept dose (Figure 4). Mean percent changes from baseline in femoral neck cortical BMD were −1.2% (placebo), −1.4% (0.3 mg/kg), 1.6% (0.5 mg/kg), 1.0% (0.7 mg/kg), and −2.4% (0.7/0.4 mg/kg). Median (minimum, maximum) BMD values and other bone remodeling outcomes are presented in Supplementary Table S3.

Change in Vascular Calcification of the Abdominal Aorta (REN-001)

The highest mean percentage increase from baseline in Agatston score (48.6%) was observed with placebo (mean Agatston score: 5216 at day 225) and the smallest (7.6%) was observed with sotatercept 0.7 mg/kg (mean Agatston score: 4411 at day 225). Similar results were observed for volumetric score and square root of volumetric score. Among patients with paired assessments at baseline and day 225, proportions with a ≤15% increase from baseline in Agatston score were higher in all sotatercept treatment groups versus the placebo group. All sotatercept 0.7 mg/kg patients had a ≤15% increase from baseline in Agatston score at day 225 (Figure 5). Among patients with paired assessments of volumetric score and square root of volumetric score, the smallest mean percentage increases from baseline (9.5% and 4.6%, respectively) were observed with sotatercept 0.7 mg/kg treatment (Figure 5). Among patients with assessments of square root of volumetric score at baseline and day 225, the proportion with a ≤2.5-mm increase from baseline in square root of volume score was higher with sotatercept 0.5 mg/kg (5 of 5) and 0.7 mg/kg (6 of 8) versus placebo (4 of 6). Median (minimum, maximum) Agatston scores are presented in Supplementary Table S3.

Safety

*REN-001*

No dose-related increase was observed in incidence of treatment-emergent AEs (TEAEs) with sotatercept treatment. The most common TEAEs in these patients were hypertension, nausea, and fatigue (Table 2). Two deaths occurred in the placebo group: One female died on study day 148 due to cardiomyopathy and 1 male died on day 186 due to worsening coronary artery disease. There were no deaths in the sotatercept treatment groups. No association between TEAE occurrence and sotatercept mean AUC0–28days or Cmax was observed.

Serious AEs (SAEs) were reported in 13 patients (Table 2). The SAEs reported by >1 sotatercept patient were gastroenteritis and hypertensive crisis. Two SAEs were considered treatment-related (atrial fibrillation: n = 1 [sotatercept 0.3 mg/kg]; anemia [reported by the investigator as an SAE instead of lack of efficacy, per protocol]: n = 1 [sotatercept 0.3 mg/kg]).

BP assessments at clinic visits or periodic interdialytic ambulatory home monitoring showed no dose-related trends versus placebo. Hypertension events...
Figure 3. Hemoglobin endpoints are shown for REN-001 (a) and REN-002 (b), and rescue treatment is shown for REN-001 (c) and REN-002 (d). For REN-001, the target Hb was >10 g/dl (6.21 mmol/l) at any time before rescue during the treatment period; for REN-002, the target Hb was ≥10 (6.21 mmol/l) to ≤12 g/dl (7.45 mmol/l) at any time before rescue between days 98 and 115. If Hb was <9 g/dl (5.59 mmol/l), or at the discretion of the investigator if deemed necessary for the safety and well-being of the patient, a blood transfusion or erythropoietin-stimulating agent therapy was given. Because of the small group size, the chance that differences between groups existed because of chance could not be excluded.
were the most frequently reported TEAEs in sotatercept patients. All hypertension TEAEs were mild/moderate in severity; none were considered treatment-related.

One patient (sotatercept 0.7 mg/kg) had at least 1 Hb measurement >12 g/dl (7.45 mmol/l), and 1 patient (sotatercept 0.5 mg/kg) had a rise in Hb concentration >2 g/dl (1.24 mmol/l) during any 4-week treatment period. Patients with these Hb increases did not experience AEs of hypertension or increased BP.

No persistent or dose-related changes were noted in laboratory parameters (including chemistries, lipids, HbA1c, sex steroids, and non–red blood cell–related hematology parameters) or electrocardiographic parameters.

**REN-002**

Forty-one patients experienced ≥1 TEAE; <10% had treatment-related AEs or a TEAE leading to treatment discontinuation. Approximately one-fourth experienced SAEs (Table 2). The most commonly reported TEAEs were hypertension, muscle spasms, headache, arteriovenous fistula site complication, and influenza (Table 2). No association between TEAE occurrence and sotatercept AUC0–28days or Cmax was observed.

Although 40% of patients had Hb >12 g/dl (7.45 mmol/l) after the first dose, and 44% had a change from baseline in Hb >1.0 g/dl (0.62 mmol/l), neither occurrence appeared to be dose-related; 8% had Hb >13 g/dl (8.07 mmol/l) without discontinuation of study medication, and 2% had Hb >13 g/dl (8.07 mmol/l), leading to treatment discontinuation. These increases in Hb >12 g/dl (7.45 mmol/l) or >13 g/dl (8.07 mmol/l) were not accompanied by hypertension or increased BP AEs. Mean changes from baseline in home systolic and diastolic BP values across all patients showed considerable variability within and across dose groups, with no clear trend.

One death occurred. A 70-year-old male with a history of hypertension, myocardial infarction, and mitral valve incompetence died within 115 days of the last dose (s.c. sotatercept 0.4–0.5 mg/kg). Cause of death (severe cardiac failure) was not considered by the investigator to be treatment-related.

**Anti-Sotatercept Antibodies**

Anti-sotatercept antibodies were detected in 3 patients during Part 2 (Supplementary Table S4). One patient (sotatercept 0.7 mg/kg) tested positive on day 1 of dose cycle 1 and remained positive through day 309 and at 3 unscheduled follow-up visits. One patient (sotatercept 0.7/0.4 mg/kg) tested positive on day 1 of dose cycle 2 and then tested negative through day 112; another receiving the same dose tested positive on day 1 of dose cycle 2 and through day 15. No TEAEs of hypersensitivity were reported in any patient positive for anti-sotatercept antibodies. Anti-sotatercept antibodies were not factors in the decisions related to repeated dosing. The anti-sotatercept antibodies did not have an impact on safety or efficacy, and the Hb response did not differ in these patients.

**REN-002**

Anti-sotatercept antibodies were detected in 7 patients (Supplementary Table S4); among these, 5 were in the i.v. dosing groups and 2 were in the s.c. sotatercept 0.13 mg/kg dosing group. In all antidrug antibody-positive patients, the first confirmed positive sample was observed ≈28 days after the first dose. Antidrug antibody titer tended to decrease over time, and most antidrug antibody-positive patients were antibody-negative.
at study end (6 of 7 patients [85.7%]). Antidrug antibody positivity was not related to hypersensitivity AEs or other safety concerns.

**DISCUSSION**

Sotatercept, a ligand trap based on the ActRIIA receptor for selected proteins of the TGF-β superfamily, including activin A, was originally conceived as a potential treatment for CKD-related anemia because of effects on late-stage erythropoiesis observed in preclinical models and phase I healthy volunteers. However, preclinical models demonstrated that the ActRIIA receptor is activated in skeletal, vascular, and heart tissue in CKD. Therefore, in REN-001, we also explored the impact of sotatercept on bone and vascular calcification endpoints. Targeting ActRIIA activity with sotatercept treatment in ESKD patients in two phase 2 studies demonstrated an acceptable safety
profile and dose-related slowing of vascular calcification progression, consistent with previously reported results in CKD-MBD models using sotatercept’s murine analog RAP-011. Improvements were seen in serum Hb concentration and BMD endpoints, although less consistently.

In both studies, sotatercept was nondialyzable and was eliminated slowly, regardless of administration route. Sotatercept demonstrated an acceptable safety profile and was well tolerated up to 225 days (up to eight 28-day or fifteen 14-day dose cycles). Across both studies, no increase in TEAE incidence was observed with sotatercept related to dose or administration route. TEAE occurrence was not associated with sotatercept mean AUC$_{0–28days}$ or C$_{max}$. Interdialytic ambulatory home BP monitoring, repeated at regular intervals, did not reveal dose-dependent changes over time. A higher proportion of all REN-001 sotatercept treatment groups achieved the target Hb increase versus the placebo group; Hb response was dose-related when doses were given monthly. This dose effect was lost with administration every 2 weeks. REN-002 Hb findings were similar, with generally better responses seen among the s.c. versus i.v. dose groups. No increase in Hb response or maintenance of Hb response was apparent with sotatercept when given in higher and/or more frequent doses, suggesting that sotatercept’s Hb-stimulatory effect may be limited in ESKD patients.

REN-001 results from the placebo group were as expected for CKD-MBD, with increasing trabecular bone (e.g., increase in lumbar spine BMD), decreasing cortical BMD (e.g., decrease in femoral neck cortical BMD), and progressive vascular calcification. Sotatercept demonstrated a ≥2% increase from baseline in femoral neck cortical BMD in a dose-dependent manner when administered monthly; no treatment

### Table 2. Overview of TEAEs in patients receiving sotatercept in REN-001 and REN-002

| Patients, n (%) | Placebo | Sotatercept dose (s.c.) | Any TEAE | TEAE related to study drug | Serious TEAE | Any TEAE leading to discontinuation | Death |
|----------------|---------|-------------------------|----------|---------------------------|-------------|-----------------------------------|-------|
| n = 11         | 0.3 mg/kg | 0.5 mg/kg | 0.7 mg/kg | 0.7/0.4 mg/kg | N = 32      | n = 9 | n = 8 | n = 9 | n = 6 | All sotatercept |
| Any TEAE       | 7 (63.6) | 8 (88.9) | 6 (75.0) | 8 (88.9) | 4 (66.7) | 26 (81.3) |
| TEAE related to study drug | 3 (27.3) | 2 (22.2) | 0 (0.0) | 3 (33.3) | 1 (16.7) | 6 (18.8) |
| Serious TEAE   | 2 (18.2) | 4 (44.4) | 0 (0.0) | 4 (44.4) | 1 (16.7) | 9 (28.1) |
| Any TEAE leading to discontinuation | 1 (9.1) | 0 (0.0) | 0 (0.0) | 2 (22.2) | 1 (16.7) | 3 (9.4) |
| Death          | 2 (18.2) | 0 (0.0) | 0 (0.0) | 0 (0.0) | 0 (0.0) | 0 (0.0) |

**TEAEs in ≥3 patients in any treatment group**

- Hypertension: 1 (9.1) in Placebo, 4 (44.4) in Sotatercept 0.3 mg/kg, 0 (0.0) in Sotatercept 0.5 mg/kg, 4 (44.4) in Sotatercept 0.7 mg/kg, and 0 (0.0) in Sotatercept 0.7/0.4 mg/kg. Total: 8 (25.0%
- Nausea: 1 (9.1) in Placebo, 1 (11.1) in Sotatercept 0.3 mg/kg, 1 (12.5) in Sotatercept 0.5 mg/kg, 4 (44.4) in Sotatercept 0.7 mg/kg, and 0 (0.0) in Sotatercept 0.7/0.4 mg/kg. Total: 6 (18.8%
- Fatigue: 2 (18.2) in Placebo, 2 (22.2) in Sotatercept 0.3 mg/kg, 0 (0.0) in Sotatercept 0.5 mg/kg, 1 (11.1) in Sotatercept 0.7 mg/kg, and 2 (33.3) in Sotatercept 0.7/0.4 mg/kg. Total: 5 (15.6%

**TEAE, treatment-emergent adverse event.**

*In REN-001, 2 deaths occurred in the placebo group. A 53-year-old male died on day 186 of coronary artery disease, and a 76-year-old female died on day 148 of cardiomyopathy. Both patients had a history of cardiovascular disease.*

*In REN-002, a 70-year-old male died in the s.c. sotatercept 0.4 mg/kg group on day 132, of cardiac failure. The patient had a history of cardiovascular disease and the event was not considered related to study treatment.*

### Table 2. Overview of TEAEs in patients receiving sotatercept in REN-001 and REN-002 (continued)

| Sotatercept administration route and dose | i.v. | i.v. | i.v. | i.v. | s.c. | s.c. | s.c. | All sotatercept |
|-------------------------------------------|-----|-----|-----|-----|-----|-----|-----|----------------|
| n = 7 | n = 9 | n = 12 | n = 7 | n = 9 | n = 6 | N = 50 |
| Any TEAE | 7 (100.0) | 9 (100.0) | 10 (83.3) | 3 (42.9) | 6 (88.7) | 6 (100.0) | 41 (82.0) |
| TEAE related to study drug | 1 (14.3) | 1 (11.1) | 0 (0.0) | 1 (14.3) | 0 (0.0) | 1 (16.7) | 4 (8.0) |
| Serious TEAE | 3 (42.9) | 3 (33.3) | 3 (25.0) | 0 (0.0) | 1 (11.1) | 3 (50.0) | 13 (26.0) |
| Any TEAE leading to discontinuation | 0 (0.0) | 3 (33.3) | 1 (8.3) | 0 (0.0) | 0 (0.0) | 0 (0.0) | 4 (8.0) |
| Death | 0 (0.0) | 0 (0.0) | 0 (0.0) | 0 (0.0) | 0 (0.0) | 1 (16.7) | 1 (2.0) |

**TEAE in ≥3 patients in any treatment group**

- Hypertension: 1 (14.3) in i.v. Sotatercept 0.1-0.4 mg/kg, 2 (22.2) in i.v. Sotatercept 0.13 mg/kg, 2 (28.6) in i.v. Sotatercept 0.26 mg/kg, and 1 (11.1) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 9 (18.0%
- Muscle spasms: 0 (0.0) in i.v. Sotatercept 0.1-0.4 mg/kg, 0 (0.0) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 0 (0.0%
- Arteriovenous fistula site complication: 2 (28.6) in i.v. Sotatercept 0.1-0.4 mg/kg, 0 (0.0) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 2 (28.6%
- Headache: 0 (0.0) in i.v. Sotatercept 0.1-0.4 mg/kg, 1 (11.1) in i.v. Sotatercept 0.13 mg/kg, 1 (8.3) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 1 (11.1%
- Influenza: 1 (14.3) in i.v. Sotatercept 0.1-0.4 mg/kg, 1 (11.1) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 1 (11.1%
- Epistaxis: 1 (14.3) in i.v. Sotatercept 0.1-0.4 mg/kg, 2 (22.2) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 1 (14.3%
- Hematuria: 2 (28.6) in i.v. Sotatercept 0.1-0.4 mg/kg, 0 (0.0) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 2 (28.6%
- Nausea: 0 (0.0) in i.v. Sotatercept 0.1-0.4 mg/kg, 0 (0.0) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 0 (0.0%
- Urinary tract infection: 2 (28.6) in i.v. Sotatercept 0.1-0.4 mg/kg, 0 (0.0) in i.v. Sotatercept 0.13 mg/kg, 0 (0.0) in i.v. Sotatercept 0.26 mg/kg, and 0 (0.0) in s.c. Sotatercept 0.4-0.5 mg/kg. Total: 2 (28.6%
effects on total hip or lumbar spine BMD were apparent. Mixed findings in the assessed skeletal endpoints indicate that sotatercept’s effects on bone volume in the CKD-MBD setting are not fully understood. Furthermore, despite recent progress, BMD is not a well-established marker of bone disease in patients with ESKD.

Sotatercept showed a dose-dependent trend toward slowing progression of abdominal aortic vascular calcification. The highest mean percentage increase from baseline in Agatston score (48.6%) was observed with placebo; the smallest (7.6%) was observed with sotatercept 0.7 mg/kg. Similar results were observed for volumetric score and square root of volumetric score.

REN-001 parameters measured to determine sotatercept’s pharmacodynamic effects (e.g., Hb, BMD, Agatston score) generally showed dose-dependency when it was administered monthly (0.3–0.7 mg/kg). Paradoxically, this effect was lost when sotatercept was administered with higher and/or more frequent doses (every 2 weeks). A ligand and receptor pair within the TGF-β superfamily can have opposing effects, depending on the tissue and biologic context. Therefore, it is plausible that opposing effects could be observed when the ActRIIA receptor is highly presented with sotatercept administration, possibly by changing the relative inhibition of various ligands in the circulation or at the tissue level (e.g., changing their signaling profile through various native TGF-β superfamily receptors).

Interpretation of our findings is limited by the small number of patients in each dose group, differences in baseline characteristics, unmeasured variables (e.g., dialysate calcium), relatively short treatment duration, and background co-medication patterns. Patient selection criteria were based on presence of ESA-responsive anemia, not CKD-MBD. Selected sotatercept dose levels were based on Hb dynamics and its predicted effects on Hb. Overall, our findings may have been influenced by high variability, curtailting our ability to detect “signal” versus “noise.”

In summary, although highly preliminary and derived from a small number of patients, current vascular and bone findings with sotatercept treatment, along with preclinical findings of activin’s role in vascular and bone changes and RAP-011 in decreasing vascular calcification in CKD, suggest that targeting ActRIIA activity may be valuable in slowing vascular disease progression in CKD patients. We believe that these highly preliminary data hold promise for modulating activin biology in CKD. Further preclinical and clinical studies targeting ActRIIA activity in CKD may be warranted.

DISCLOSURE
DWC is a consultant and speaker for Fresenius Medical Care North America and a consultant for GlaxoSmithKline and MediBeacon. HNS, ACG, and JNC are employees of Celgene Corporation. WTS was an employee of Celgene Corporation at the time the study was conducted. MLS is an employee of Acceleron Pharma Inc. FD has served as an advisor for Sandoz and an investigator for Hexal AG. HHM and KAH have been Celgene Corporation consultants.

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DATA SHARING
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SUPPLEMENTARY MATERIAL
Supplementary File (PDF)
Table S1. Baseline demographic characteristics and dialysis treatment history in REN-001 and REN-002.
Table S2. Concomitant phosphate binding use at baseline.
Table S3. Vascular calcification and bone modeling outcomes.
Table S4. Summary of patients who developed anti-sotatercept antibodies.
CONSORT Statement.

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