

Original Article

An exploratory analysis of alkaline phosphatase, lactate dehydrogenase, and prostate-specific antigen dynamics in the phase 3 ALSYMPCA trial with radium-223

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Running title: ALP, LDH, and PSA in radium-223–treated CRPC patients

ABSTRACT

Background: Baseline clinical variables are prognostic for overall survival (OS) in patients with castration-resistant prostate cancer (CRPC). Their prognostic and predictive value with agents targeting bone metastases, such as radium-223, is not established.

Patients and methods: The radium-223 ALSYMPCA trial enrolled patients with CRPC and symptomatic bone metastases. Prognostic potential of baseline variables was assessed using Cox models. Percentage changes in biomarker levels from baseline were evaluated during the trial period; changes from baseline to week 12 were evaluated for association with OS and surrogacy.

Results: Eastern Cooperative Oncology Group performance status, total alkaline phosphatase (tALP), lactate dehydrogenase (LDH), and prostate-specific antigen (PSA) at baseline were associated with OS ($P \leq 0.0003$) in the intent-to-treat population (radium-223, $N=614$; placebo, $N=307$). tALP declined from baseline within 4 weeks after beginning radium-223, by week 12 declining in 87% of radium-223 and 23% of placebo patients ($P < 0.001$). LDH declined in 51% and 34% ($P=0.003$), whereas PSA declined in 27% and 14% ($P=0.160$). Mean tALP change from baseline was 32.2% decrease with radium-223 and 37.2% increase with placebo. Radium-223 patients with tALP decline from baseline to week 12 (confirmed ≥ 3 weeks from week 12) had 55% lower risk of death (hazard ratio=0.45; 95% CI 0.34-0.61) versus those with no confirmed tALP decline. Proportional treatment effect (PTE) values for tALP, LDH, and PSA changes from baseline at week 12 as OS surrogate markers were 0.34 (95% CI: 0-0.746), 0.07 (95% CI: 0-0.211), and 0 (95% CI: 0-0.082), respectively.

Conclusions: Significant tALP declines (versus placebo) occurred as early as 4 weeks after beginning radium-223 therapy. tALP or LDH declines at 12 weeks correlated with longer OS,

but did not meet statistical surrogacy requirements. Dynamic changes in tALP and LDH during radium-223 treatments may be useful to monitor, but do not serve as surrogates for survival.

Key message

In an exploratory analysis of patients with CRPC and bone metastases enrolled in the phase 3 ALSYMPCA trial, tALP was an early pharmacodynamic marker with declines significantly associated with longer survival. Monitoring biomarker levels during treatment may be useful in managing radium-223 therapy, but changes in tALP do not meet statistical requirements as a surrogate for survival.

INTRODUCTION

For individual patients with metastatic castration-resistant prostate cancer (mCRPC), prognostic models based on baseline clinical characteristics may be used to predict survival but are not currently used to monitor responses to therapy [1-5]. Serial bone scans [6] and advanced imaging methods [7] may serve this purpose, but simpler, less invasive, less expensive methods are needed to dynamically monitor therapy and inform decisions regarding treatment modification [8]. A surrogate marker that predicted overall survival (OS) in individual patients would be particularly useful in decisions regarding treatment modification [9].

Surrogacy requirements for OS in advanced prostate cancer were met for patients receiving docetaxel therapy by prostate-specific antigen (PSA) decreases $\geq 30\%$ after 3 weeks of treatment in the SWOG 99-16 [10] and TAX327 [3] trials, and for patients receiving abiraterone acetate plus prednisone therapy or prednisone alone by the number of circulating tumor cells (CTC) and lactate dehydrogenase (LDH) levels after 12 weeks of treatment [11]. These surrogates may eventually aid in monitoring therapy with these agents, but further clinical investigation and validation are required [10, 12]. For approximately 70% of advanced prostate cancer patients with bone metastases [8], bone-related markers (eg, total alkaline phosphatase [tALP]) are prognostic for OS [13-15] and tALP changes may be an early indicator of bone progression [8]. Both PSA and tALP changes are closely associated with survival, but PSA levels do not provide accurate information regarding extent of skeletal metastases or treatment effects on disease progression in bone. Therefore, tALP changes may correlate better with OS than PSA [16, 17].

The phase 3 ALSYMPCA trial established radium-223 efficacy and safety in CRPC patients with bone metastases [18, 19]. With radium-223, versus placebo, OS improved significantly

(median 14.9 vs 11.3 mo; hazard ratio [HR]=0.70; 95% confidence interval [CI]: 0.58, 0.83).

Time to first symptomatic skeletal event was significantly prolonged (median 15.6 vs 9.8 mo; HR=0.66; 95% CI: 0.52-0.83), and secondary end points (including time to tALP increase, tALP response rate, and tALP normalization rate) favored radium-223 treatment [18, 19].

For mCRPC patients treated with radium-223, tALP changes properly established as a surrogate for survival could optimize treatment, allowing quick change of direction of therapies to patients most likely to benefit from such changes. Thus, exploratory analyses were conducted from ALSYMPCA to evaluate the treatment effect of radium-223 on changes in tALP, LDH, and PSA levels and assess their prognostic and predictive value.

METHODS

ALSYMPCA compared efficacy and safety of radium-223 versus placebo, each plus best standard of care, in CRPC patients with symptomatic bone metastases [18]. Randomized patients (2:1) received 6 intravenous injections of radium-223 (50 kBq/kg IV [55 kBq/kg IV following US National Institutes of Standards and Technology update]) [20] or matching placebo, 1 injection every 4 weeks. The primary end point was OS.

Univariate and multivariate analyses with Cox proportional hazards models assessed the potential prognostic value for survival of selected baseline variables in placebo patients, radium-223 patients, and the intent-to-treat (ITT) population. Selected variables included prior docetaxel, prior hormone therapy, hemoglobin, serum albumin, tALP, PSA, LDH, Eastern Cooperative Oncology Group performance status (ECOG PS), opiate use, and age at study entry [4]. Kaplan-Meier analysis, after tertile grouping using baseline values, further illustrated the association of baseline tALP, PSA, and LDH with OS for radium-223 and placebo patients.

Changes from baseline in tALP, PSA, and LDH were assessed as least-squares mean percentage change at week 12, the halfway point of treatment, allowing consistency in protocol-defined timing of tALP and PSA measurements. Waterfall plots of maximum percentage change in tALP, LDH, and PSA from baseline to week 12 for each patient illustrated the magnitude of treatment effect. Dynamics of mean percentage change from baseline in biomarker levels, at each treatment visit and follow-up visits 12 and 24 weeks after last study-drug dose, were evaluated. OS by confirmed tALP or LDH decline at week 12 (decline confirmed ≥ 3 weeks from week 12) was evaluated. The relationship of relative risk of death to percentage changes from baseline at week 12 (last observation carried forward) was assessed using Cox proportional hazards modeling, including all baseline covariates.

Changes in tALP, PSA, and LDH from baseline to week 12 were evaluated as potential measures of OS surrogacy, as defined by Prentice [9], and quantified as a proportional treatment effect (PTE) [12]. PTE describes how much of the treatment effect on OS is explained by biomarker changes. PTE was calculated as 1 minus the ratio of (a) HR in the Cox proportional hazards regression model for survival with treatment (radium-223) plus the surrogate marker (tALP, PSA, LDH) to (b) that with treatment alone. Perfect surrogacy would be indicated by PTE=1; no surrogacy, by PTE=0. CIs were calculated according to Lin et al [12], with a strong degree of surrogacy suggested if the 95% CI lower bound exceeded 0.5.

RESULTS

Baseline Prognostic Factors

Multivariate analysis of baseline prognostic values as continuous variables was performed for placebo and radium-223 patients separately and for the entire ITT population (**Table 1**). For

radium-223 patients, poor baseline ECOG PS and elevated baseline values for LDH, tALP, and PSA were associated with highest risk of death; for placebo patients, elevated baseline values for LDH and tALP were significantly associated with an increased risk of death. For the overall ITT population, opiate use was an additional significant baseline prognostic variable for OS. Kaplan-Meier analysis showed longer median survival among radium-223 patients in the lowest tALP tertile (≤ 131 U/L), versus those in the highest tertile (≥ 334 U/L) (23.9 vs 10.2 mo); no overlap in the 95% CIs indicated a consistent trend across subgroups (supplementary **Figure S1A**). Placebo patients in the lowest (≤ 153 U/L) versus highest (≥ 360 U/L) tALP tertile also survived longer (median 18.8 vs 7.5 mo) (supplementary **Figure S1B**). Similarly, longer survival was seen for radium-223 and placebo patients with lower versus higher baseline LDH (supplementary **Figure S1 C and D**, respectively) and PSA values (data not shown).

Posttreatment Changes From Baseline

Changes from baseline were assessed at week 12 for tALP, LDH, and PSA for patients with baseline and week 12 determinations (supplementary **Figure S2**). tALP decreased from baseline in 87% (433/497) of radium-223 patients versus 23% (49/211) of placebo patients ($P < 0.001$). For LDH, 51% (242/473) radium-223 and 34% (70/206) placebo patients showed a decrease ($P = 0.003$). PSA declined in 27% (135/493) of radium-223 and 14% (30/210) of placebo patients ($P = 0.160$) (supplementary **Table S1**). Waterfall plots, showing maximum percentage change in tALP and LDH at any time from baseline to week 12 for each patient in radium-223 and placebo groups, illustrated the between-group magnitude of difference in tALP response (supplementary **Figure S3A**) and a similarity in LDH response (supplementary **Figure S3B**), revealing a stronger association of tALP versus LDH declines with radium-223 treatment. No apparent

difference was seen in waterfall plots of PSA response for radium-223 versus placebo (not shown).

Mean percentage change from baseline in tALP and LDH for radium-223 and placebo patients through 24 weeks of radium-223 treatment and follow-up are shown in **Figure 1 A and B**. With radium-223, tALP decreases occurred as early as 4 weeks after treatment initiation, remained consistently low until treatment completion at 24 weeks, and remained significantly lower versus placebo patients at all time points to 46 weeks ($P<0.001$) (**Figure 1A**). With placebo, tALP increased continuously through treatment and posttreatment follow-up. LDH levels for radium-223 patients were significantly lower versus placebo patients throughout most of the 24-week treatment period, but remained above baseline and increased through posttreatment follow-up at a rate similar to the placebo group rate (**Figure 1B**).

Relationship of Posttreatment Changes to OS and Surrogacy

In an exploratory analysis, radium-223 patients with confirmed tALP or LDH decline from baseline at week 12 survived longer than those with no confirmed decline (**Figure 2 A and B**). Among 497 patients with tALP values determined at baseline and week 12, 400 patients with a confirmed tALP decline had a median survival of 17.8 months and 55% lower risk of death (HR=0.45; 95% CI: 0.34-0.61; $P<0.0001$) versus 97 patients with no confirmed tALP decline (median survival, 10.4 mo) (**Figure 2A**). Baseline characteristics were similar between patients with and those without confirmed decline. Although heavily weighted at the lower end by number of patients experiencing a tALP decrease, Cox regression modeling shows a near-linear relationship between percentage change in tALP from baseline (increase or decrease) at week 12 and risk of death, relative to no change in tALP (**Figure 3A**). Similarly, 196 radium-223 patients

with an LDH decline from baseline to week 12 survived a median of 19.5 months and had a 45% lower risk of death (HR=0.55; 95% CI: 0.42-0.73; $P<0.0001$) versus 277 patients with no LDH decline (median survival, 14.5 mo) (**Figure 2B**). Greater LDH increases, however, were associated with exponentially rapid increase in risk of death. Patients with a 300% to 400% increase in LDH at week 12 had an approximately 7- to 14-fold greater risk than those with no LDH change (**Figure 3B**). In contrast, among 493 radium-223 patients with PSA values determined at baseline and week 12, PSA increased in 358 (73%) patients, often by factors of 10-fold or more. Multivariate analysis of the correlation between OS and PSA changes at week 12 showed that the impact of PSA changes at week 12 on risk of death was negligible (**Figure 3C**). PTE values based on Cox regression models for tALP, LDH, and PSA changes from baseline at week 12 as surrogate markers of survival were 0.34 (95% CI: 0-0.746), 0.07 (95% CI: 0-0.211), and 0 (95% CI: 0-0.082), respectively. tALP had the highest PTE, but only modest surrogacy; a PTE=0.34 indicates that the tALP decrease accounted for about 34% of the survival benefit from radium-223 treatment.

DISCUSSION

Multivariate analysis showed that elevated baseline tALP and LDH levels were associated with higher risk of death, compared with other factors, in placebo patients who did not receive radium-223 treatment, as well as in radium-223–treated patients and the entire ITT population. Our findings for mCRPC patients with bone-only disease are consistent with similar studies in less defined populations and highlight the relative importance of tALP in this setting [2-5].

In ALSYMPCA, radium-223 treatment prolonged survival for patients with CRPC and bone-only metastases [18]. In this post hoc analysis, we report confirmed tALP declines in 80% of

evaluable patients after 12 weeks of receiving radium-223 and their association with decreased risk of death, suggesting that changes in tALP could potentially be a surrogate for survival useful in managing patients receiving radium-223 therapy. The ALSYMPCA findings meet the requirements for a surrogacy analysis as described by Prentice [9]. PTE surrogacy analysis showed tALP decreases at 12 weeks from baseline to be a moderate predictor of survival, with PTE=0.34 and a broad CI (0.0, 0.746). The analysis also indicated that radium-223 effects on LDH or PSA contributed little or nothing to the radium-223–associated survival benefit. Our tALP findings were consistent with those reported in TAX327, which showed an association with OS but could not establish surrogacy for tALP changes in patients with bone metastases [16].

Responses to chemotherapy are likely related to a combination of factors: the patient's underlying physical condition and probably other factors reflected or not in biomarker levels, such as pain score and visceral organ involvement. Scher and colleagues [11], in their phase 3 study of abiraterone acetate–prednisone, reported a high level of surrogacy for a biomarker panel consisting of the combination of circulating tumor cell (CTC) count and LDH level at 12 weeks. They used Prentice criteria [9] to establish relative surrogacy, but did not assess PTE. The CTC-LDH combination was superior to CTC or LDH alone or to CTC combination with any other biomarkers, including tALP decreases and $\geq 30\%$ or $\geq 50\%$ PSA decreases. Future assessments of the validity of markers in predicting effectiveness of chemotherapy may be more successful when combinations of factors are considered.

Limitations in our study influenced our conclusions: The exploratory analysis was not included in the original ALSYMPCA study plan; other relevant bone markers and markers such as CTCs, not prospectively determined in this phase 3 study, could not be considered. We analyzed only

biomarker level decreases from baseline to 12 weeks. If we considered specific rates of decline, as in the PSA studies, we may have arrived at a higher PTE value, but the patient number in each group may have been inadequate for statistical analysis. We evaluated markers individually, not in combination; the proportion of patients showing LDH and PSA decreases did not appear to justify the more extensive analysis. Future prospective studies addressing these limitations may identify more promising candidates for surrogacy. With these caveats, we found that changes in tALP, LDH, and PSA levels after 12 weeks of treatment are not surrogates for survival for patients with CRPC and bone metastases treated with radium-223. The effective course of radium-223 treatment in ALSYMPCA was 24 weeks, with 6 cycles given at 4-week intervals. Using biomarker changes, particularly rising PSA levels, to make decisions about continuing radium-223 presents a substantial risk that a large fraction of patients who may benefit will be denied effective treatment. Monitoring biomarkers during treatment may have benefit as an indication for radiologic evaluation of disease status [8].

The observed tALP changes with treatment raise questions about radium-223 treatment duration and underline the need for a reliable marker of radium-223 efficacy. In ALSYMPCA with radium-223, the rapid and sustained tALP declines and the increasing tALP suppression with continued therapy reflected the radionuclide mechanism of action in the bone microenvironment, consistent with rapid and progressive inhibition of ALP production by osteoblasts. Dynamic profiles of both tALP and LDH levels during the study suggest that treatment durations more than 24 weeks should be tested. Although we could not determine whether tALP changes were a direct effect on cancer cells or on osteoblasts, preclinical studies suggest that tALP is a marker of pharmacodynamic effect and that radium-223 impacts both osteoblasts and tumor cells [21, 22]. In a human prostate cancer model, characterized by osteoblastic growth, PSA production, and

systemic metastases when inoculated into the bone marrow cavity, radium-223 inhibited disease progression, reduced tumor volume, and decreased areas of tumor in tumor-bearing tibias.

Tumor-induced osteoblastic bone growth was suppressed and normal architecture was maintained, leading to reduced bone volume in tumor-bearing bone. Radium-223 induced double-strand DNA breaks in tumor cells and osteoclasts, consistent with potent radiation effects of radium-223 in the tumor microenvironment [21, 22]. Such models in prostate cancer, and others in breast cancer [23], are important in addressing questions about radium-223 mode of action in cancer patients.

In conclusion, significant tALP declines (versus placebo) occurred as early as 4 weeks after initiation of radium-223 therapy. tALP or LDH decline at 12 weeks correlated with longer OS, but did not meet statistical surrogacy requirements. Changes in tALP and LDH are dynamic during radium-223 treatments and may be useful to monitor, but do not serve as surrogates for survival.

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DISCLOSURES

The authors have the following conflicts of interest to disclose: OS: grants from Tulane University Medical School/Bayer, during the conduct of the study, and personal fees from Bayer, outside the submitted work. REC: grants from Bayer and Amgen, outside the submitted work. DH: grants and non-financial support from Bayer AS (formerly Algeta ASA) and Bayer, during the conduct of the study; personal fees from Bayer AS (formerly Algeta ASA), Amgen, Astellas, Sanofi-Aventis, Roche, Novartis, Pfizer, Bristol-Myers-Squibb, Glaxo-Smith-Kline, and Norwegian Medicines Agency, personal fees and non-financial support from Bayer, and grants, personal fees, and non-financial support from Janssen-Cilag (J & J), outside the submitted work. JMO: personal fees from Astellas, grants and personal fees from Bayer, and personal fees from Janssen, outside the submitted work. NJV: personal fees from Bayer, during the conduct of the study; grants and personal fees from Janssen, and personal fees from Medivation and Sanofi Aventis, outside the submitted work. ØB: fees to his institution from Bayer HealthCare, during the conduct of the study. SK and SW: personal fees from Bayer HealthCare, during the conduct of the study and outside the submitted work, as they are employees of Bayer HealthCare, and Bayer stock ownership. LX: personal fees from Bayer HealthCare, during the conduct of the study. MS: personal fees from Bayer HealthCare, during the conduct of the study and outside the submitted work, as he is an employee of Bayer HealthCare, and Bayer stock ownership. CP: grants and personal fees from Bayer and personal fees from Janssen, BNIT, and Sanofi Aventis, outside the submitted work. SN, SIH, and MWK have declared no conflicts of interest.

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FIGURE LEGENDS

Figure 1. tALP and LDH dynamics in the ITT population. Mean percentage change in (A) baseline tALP and (B) baseline LDH at the end of each treatment cycle (6 cycles) and two follow-up visits. Six patients in the radium-223 arm and 1 in the placebo arm did not have baseline LDH determinations and were excluded from this analysis. ITT, intent to treat; LDH, lactate dehydrogenase; tALP, total alkaline phosphatase.

Figure 2 Overall survival in the radium-223 cohort with and without a confirmed decline in (A) baseline tALP and (B) baseline LDH at week 12. Confirmed decline was defined as any decrease from baseline at week 12, confirmed ≥ 3 weeks later. LDH, lactate dehydrogenase; tALP, total alkaline phosphatase.

Figure 3. Relationship between percentage change in (A) tALP, (B) LDH, and (C) PSA levels from baseline and risk of death relative to no change in tALP, LDH, or PSA in the ITT population with baseline marker analyses. The red lines in (A) define the area of decreasing risk of death with decreases in tALP from their baseline level. To make (C) PSA comparable to (A) tALP, its x axis was truncated to include only patients with PSA percentage changes from baseline between -100% and 300%; 46 of 910 (5.1%) patients with percentage changes in PSA >300% were excluded. LDH, lactate dehydrogenase; PSA, prostate-specific antigen; tALP, total alkaline phosphatase.

A

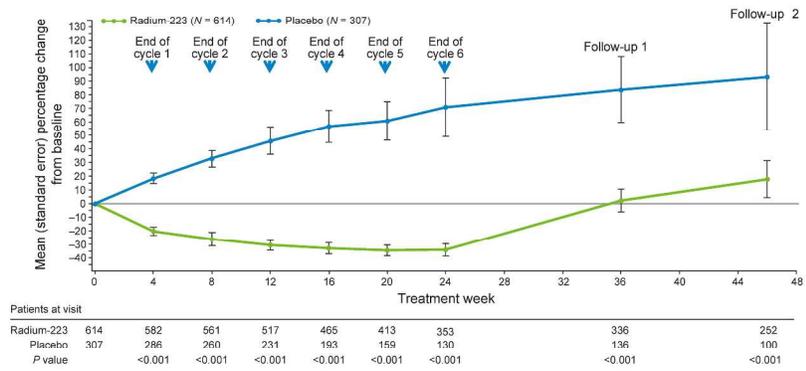


Figure 1A. Mean percentage change in tALP levels from baseline after each cycle of treatment (6 cycles) and at 2 follow-up visits (ITT population)

279x361mm (300 x 300 DPI)

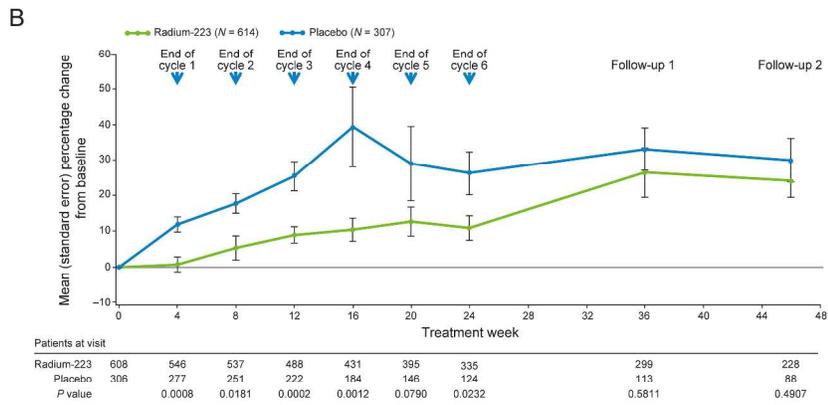


Figure 1B. Mean percentage change in LDH levels from baseline after each cycle of treatment (6 cycles) and at 2 follow-up visits (ITT population)

279x361mm (300 x 300 DPI)

A

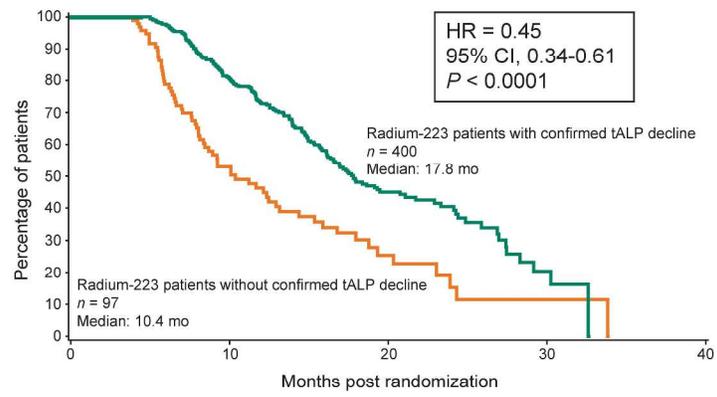


Figure 2A. Overall survival in radium-223 patients with and without a confirmed tALP decline at week 12.

279x361mm (300 x 300 DPI)

B

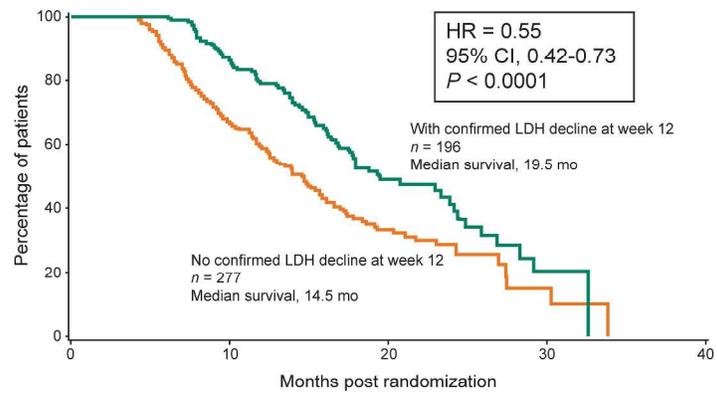
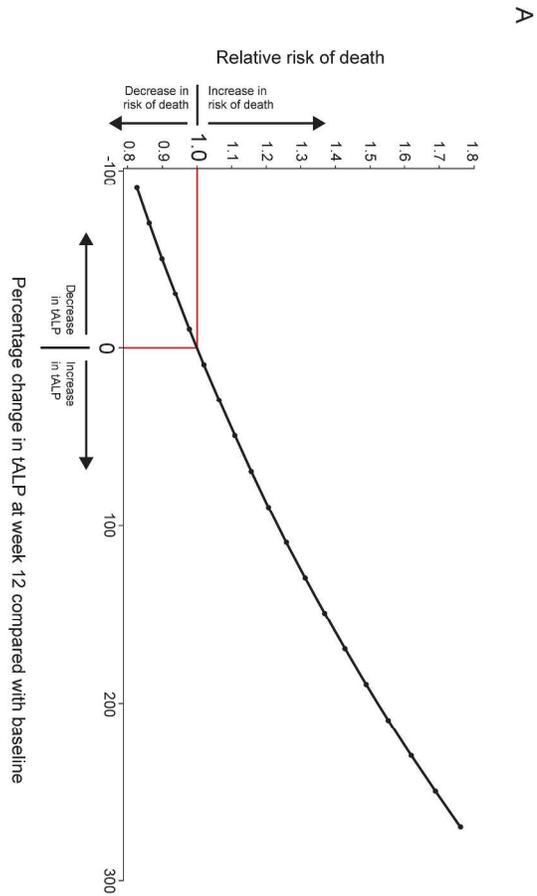


Figure 2B. Overall survival in radium-223 cohort with and without a confirmed decline in baseline LDH at week 12.

279x361mm (300 x 300 DPI)



A

Figure 3A. Relationship between percentage tALP change from baseline and risk of death.

279x361mm (300 x 300 DPI)

B

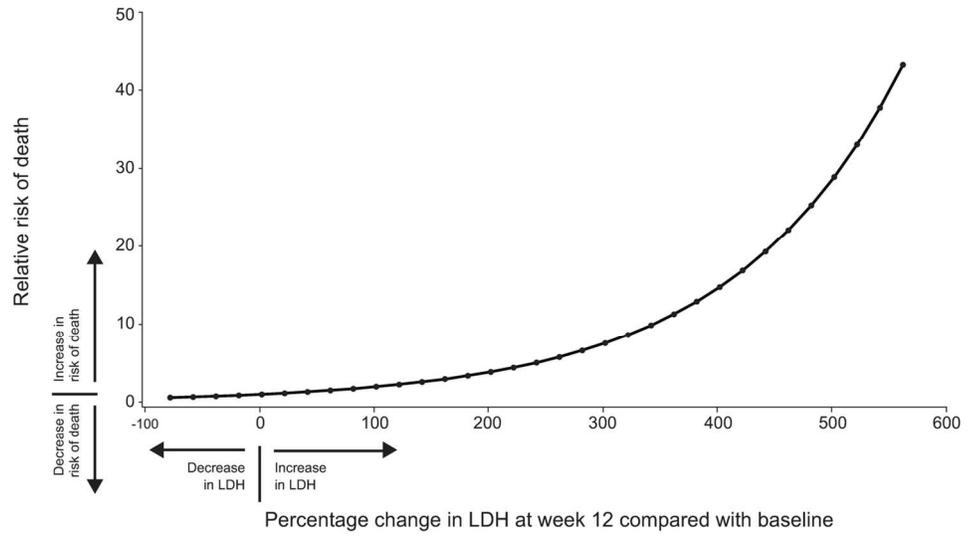


Figure 3B. Relationship between percentage change of LDH from baseline and risk of death.

122x72mm (300 x 300 DPI)

C

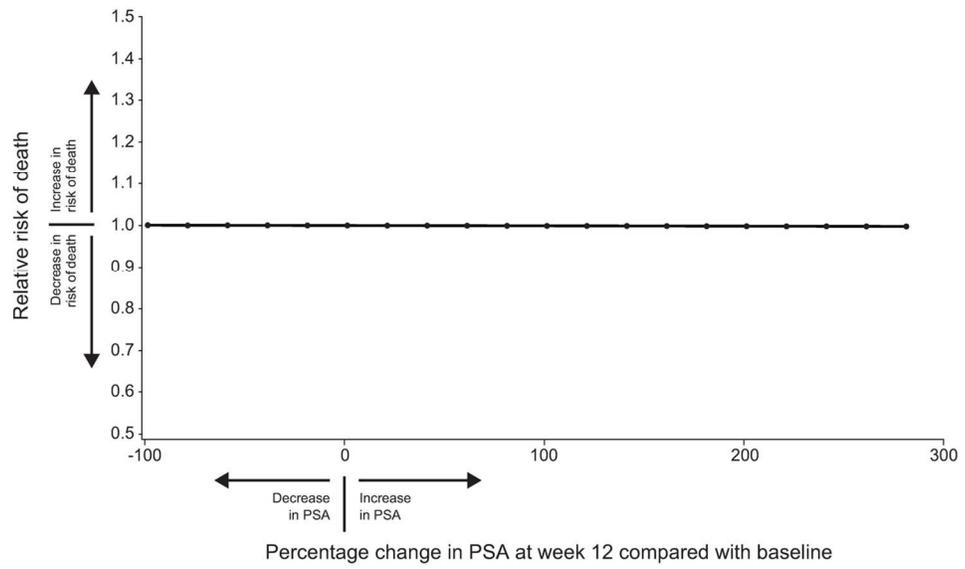


Figure 3C. Relationship between percentage change of PSA from baseline and risk of death.

123x72mm (300 x 300 DPI)

Table 1. Multivariate analysis of the correlation of baseline covariates with overall survival^a

Baseline variable	HR ^b	P value ^c
Placebo patients		
Albumin	0.970	0.0652
ECOG PS (≥ 2 vs 0 or 1)	1.441	0.0839
Log LDH ^d	2.632	0.0043
Log tALP ^d	2.332	<0.0001
Log PSA ^d	1.250	0.0569
Age	1.009	0.3804
Radium-223 patients		
Albumin	0.972	0.0224
ECOG PS (≥ 2 vs 0 or 1)	1.775	0.0002
Log LDH ^d	4.244	<0.0001
Log tALP ^d	1.857	0.0001
Log PSA ^d	1.498	<0.0001
Age	1.018	0.0172
Overall ITT population		
Randomized treatment group	0.779	0.0074
Albumin	0.974	0.0069
ECOG PS (≥ 2 vs 0 or 1)	1.576	0.0003
Log LDH ^d	3.407	<0.0001
Log tALP ^d	2.017	<0.0001
Log PSA ^d	1.405	<0.0001
Age	1.016	0.0080
Opiate use (yes or no)	1.214	0.0379

^aBaseline factors significantly associated with survival by univariate analysis were included in the multivariate analysis.

^bHRs are relative risk for a 1-unit increase in the baseline variable for those without log transformation, or a 10-fold increase for those with log transformation.

^cBased on Cox proportional hazards model.

^dLog transformation was performed for baseline variables with heavily skewed distributions. ECOG PS, Eastern Cooperative Oncology Group performance status; HR, hazard ratio; LDH, lactate dehydrogenase; ITT, intent-to-treat; PSA, prostate-specific antigen; tALP, total alkaline phosphatase.

SUPPLEMENTARY MATERIALS

Study Conduct and Patients

ALSYMPCA compared efficacy and safety of radium-223 versus placebo, each plus best standard of care, in castration-resistant prostate cancer (CRPC) patients with symptomatic bone metastases (Parker et al. *N Engl J Med* 2013; 369: 213-223). Randomized patients (2:1) received 6 intravenous injections of radium-223 (50 kBq/kg IV [55 kBq/kg IV following US National Institutes of Standards and Technology update]) (Zimmerman et al. *J Res Natl Stand Technol* 2015; 120: 37-57) or matching placebo, 1 injection every 4 weeks. The primary end point was overall survival (OS). An exploratory analysis was performed to assess the prognostic value for OS of selected baseline variables and the potential predictive value for OS of changes in total alkaline phosphatase (tALP), lactate dehydrogenase (LDH), and prostate-specific antigen (PSA) during treatment with radium-223.

Prognostic Value of Baseline Variables

Univariate and multivariate analyses with Cox proportional hazards models were used to assess the potential prognostic value of selected baseline variables for survival for placebo patients, radium-223 patients, and the intent-to-treat (ITT) population (separate analyses of baseline biomarker values for treatment interaction showed no significant treatment-covariate interactions at the 5% level). Selected variables included prior docetaxel, prior hormone therapy, hemoglobin, serum albumin, tALP, PSA, LDH, Eastern Cooperative Oncology Group performance status (ECOG PS), opiate use, and age at study entry (Halabi et al. *J Natl Cancer Inst* 2013; 105: 1729-1737). Analyses used continuous variables with no cutoffs. ALSYMPCA

laboratory analyses were conducted at each participating institution. Kaplan-Meier analysis, after tertile grouping using baseline values, further illustrated the association of baseline tALP, PSA, and LDH with OS for radium-223 and placebo patients.

Results of the multivariate analysis are described in the main text of the manuscript and in Table 1. For placebo patients, multivariate analysis showed that elevated baseline values for tALP and LDH were significantly associated with an increased risk of death. No significant association was seen between risk of death and age at study entry or baseline ECOG PS, albumin, or PSA (supplementary **Table S1**). For radium-223 patients, baseline albumin, ECOG PS, LDH, tALP, PSA, and age were associated with survival; highest risk of death was associated with poor ECOG PS and elevated baseline LDH, tALP, and PSA. For the overall ITT population, opiate use was an additional significant baseline prognostic variable for OS.

Kaplan-Meier analysis for tALP showed longer survival among radium-223 patients in the lowest tALP tertile (≤ 131 U/L), median 23.9 months, versus those in the highest tertile (≥ 334 U/L), median 10.2 months; no overlap in the 95% CIs indicated a consistent trend across subgroups (supplementary **Figure S1A**). Placebo patients in the lowest (≤ 153 U/L) versus highest (≥ 360 U/L) tALP tertile also had longer median survival (18.8 vs 7.5 mo), supporting prognostic value of baseline tALP for survival (supplementary **Figure S1B**). Overall, radium-223 patients had longer OS versus placebo patients across tertile subgroups. Similarly, longer survival appeared with lower versus higher baseline LDH among radium-223 (18.4 vs 9.1 mo) and placebo (13.7 vs 8.1 mo) patients (supplementary **Figures S1 C and D**). PSA showed longer survival for radium-223 and placebo patients in the lowest versus upper 2 tertiles, but with considerable overlap in CIs for each group (not shown).

Posttreatment Changes From Baseline

Changes from baseline in tALP, PSA, and LDH were assessed as least-squares mean percentage change at week 12, the halfway point of treatment, allowing consistency in protocol-defined timing of tALP and PSA measurements. Changes from baseline were assessed at week 12 for tALP, LDH, and PSA for patients with baseline and week 12 determinations (supplementary **Figure S2**). For tALP, 87% (433/497) of radium-223 patients had a decrease from baseline, versus 23% (49/211) of placebo patients. Radium-223 patients showed a mean 32.2% tALP decrease, whereas placebo patients showed a mean 37.2% tALP increase ($P<0.001$; supplementary **Table S1**). For LDH, the difference between radium-223 and placebo patients was more modest, with 51% (242/473) and 34% (70/206), respectively, showing a decrease; the mean change was an increase for both groups, 7.3% and 20.8%, respectively ($P=0.003$; supplementary **Table S1**). PSA declined in 27% (135/493) of radium-223 and 14% (30/210) of placebo patients, with mean increases of 83.3% and 543.8%, respectively ($P=0.160$; supplementary **Table S1**) The magnitude of the difference in tALP response between the radium-223 and placebo patients is shown in the waterfall plot of maximum change in tALP occurring at any time from baseline to week 12 (supplementary **Figure S3A**). This contrasts with the similarity of the waterfall plot of maximum LDH response between the radium-223 and placebo populations (supplementary **Figure S3B**).

Supplementary Table S1. tALP, LDH, and PSA mean percentage change from baseline at week 12

	Radium-223 (N = 614)		Placebo (N = 307)		P value ^a
	Decrease from baseline, n ^b /n ^c (%)	% change ^d (SE)	Decrease from baseline, n ^b /n ^c (%)	% change ^d (SE)	
tALP	433/497 (87)	-32.2 (1.80)	49/211 (23)	37.2 (2.77)	<0.001
LDH	242/473 (51)	7.3 (2.37)	70/206 (34)	20.8 (3.54)	0.003
PSA	135/493 (27)	83.3 (152)	30/210 (14)	543.8 (234)	0.160

^aFrom ANCOVA adjusting for the binary stratification factors, total ALP, current use of bisphosphonates and prior use of docetaxel

^bNumber of patients with a decrease from baseline and at week 12

^cNumber of patients with measurements at baseline and week 12

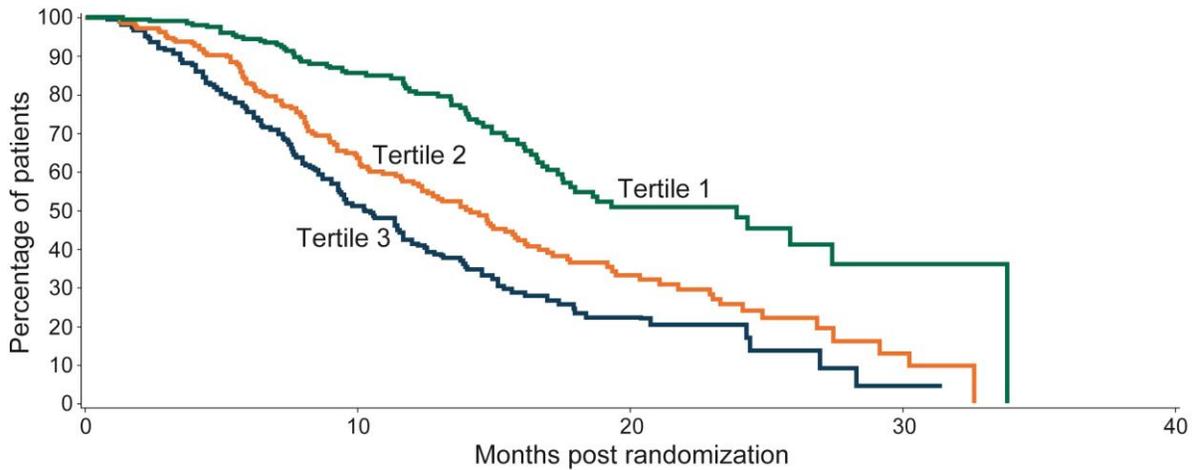
^dLeast squares mean

LDH, lactate dehydrogenase; PSA, prostate-specific antigen; SE, standard error of the mean; tALP, total alkaline phosphatase.

Supplementary Figure S1. Overall survival by tertiles in the (A, C) ITT radium-223 and (B, D) placebo patients as a function of (A, B) baseline tALP and (C, D) baseline LDH. Patients who did not experience an event are censored at the last date on which they were known to be alive. Six patients in the radium-223 arm and 1 in the placebo arm did not have baseline LDH determinations and were excluded from this analysis. ITT, intent-to-treat; LDH, lactate dehydrogenase; min, minimum; max, maximum; tALP, total alkaline phosphatase.

Supplementary Figure S1A. Overall survival by tertiles of baseline tALP in the radium-223 cohort.

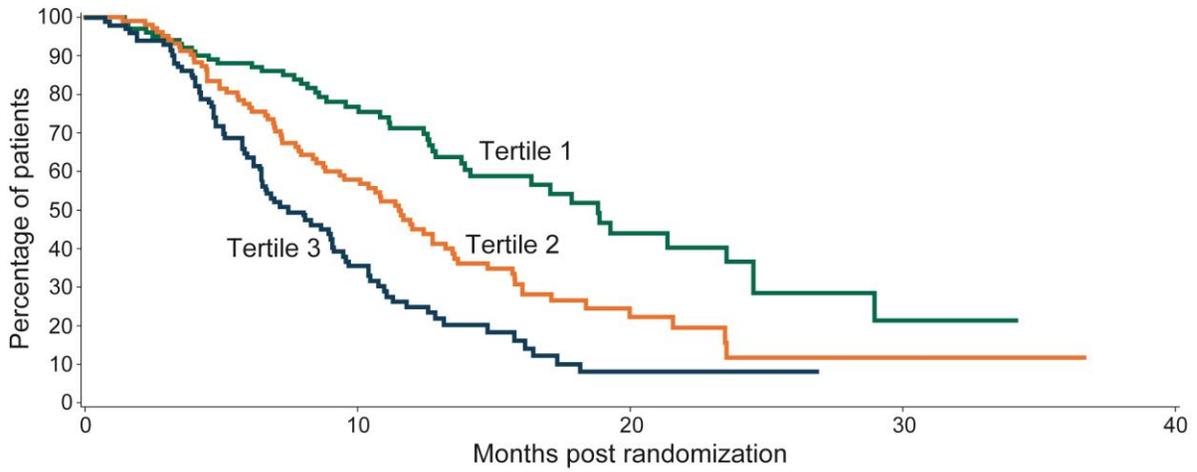
A



	Tertile 1 (n = 205)	Tertile 2 (n = 207)	Tertile 3 (n = 202)
tALP min-max	32-131	132-333	334-6431
Median overall survival time, mo (95% CI)	23.9 (17.5-33.8)	14.1 (12.0-15.9)	10.2 (9.1-11.7)

Supplementary Figure S1B. Overall survival by tertiles of baseline tALP in the placebo cohort.

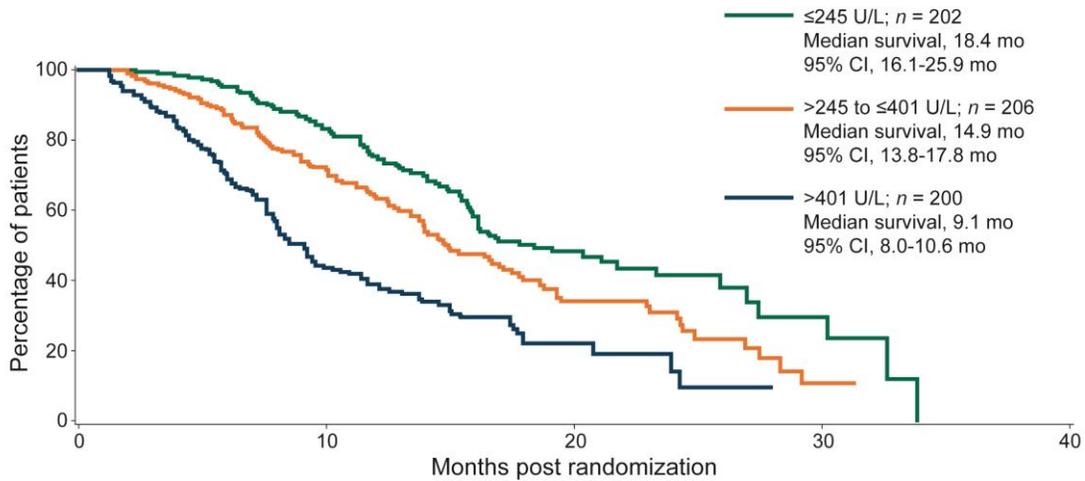
B



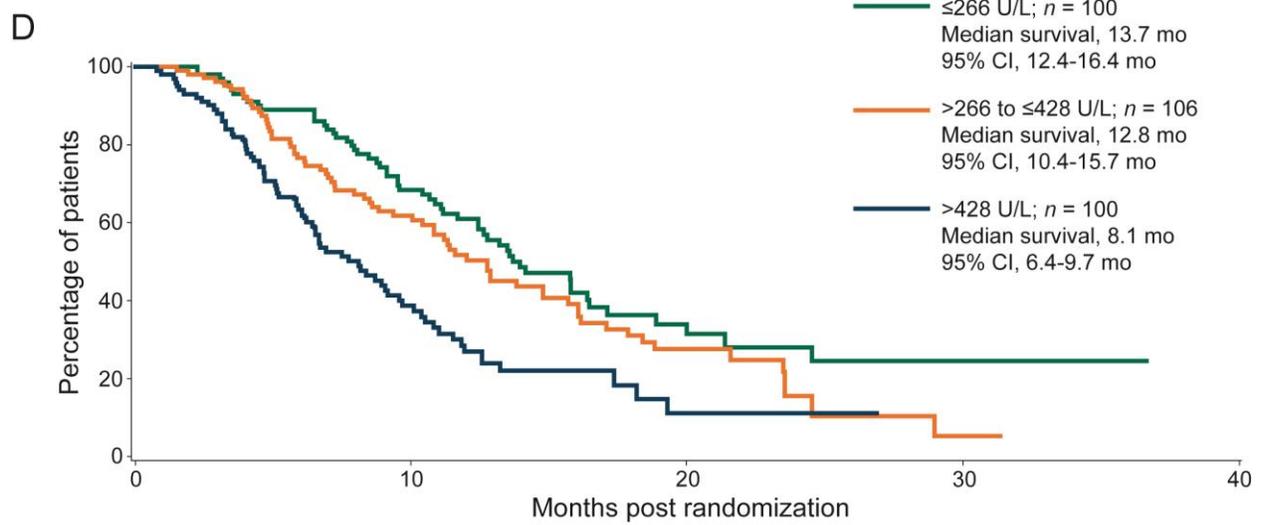
	Tertile 1 (n = 102)	Tertile 2 (n = 104)	Tertile 3 (n = 101)
tALP min-max	29-153	154-353	360-4805
Median overall survival time, mo (95% CI)	18.8 (13.9-24.5)	11.5 (9.3-13.5)	7.5 (6.5-9.1)

Supplementary Figure S1C. Overall survival by tertiles of baseline LDH in the radium-223 cohort.

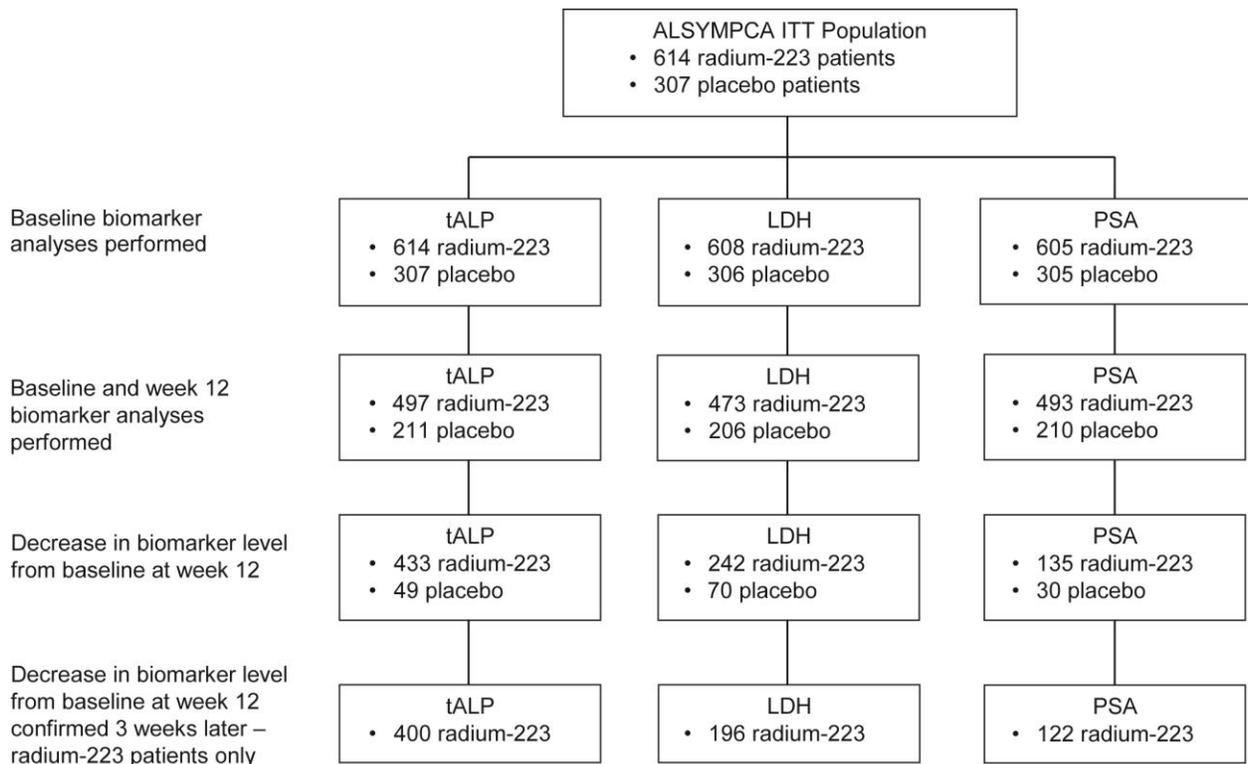
C



Supplementary Figure S1D. Overall survival by tertiles of baseline LDH in the placebo cohort.



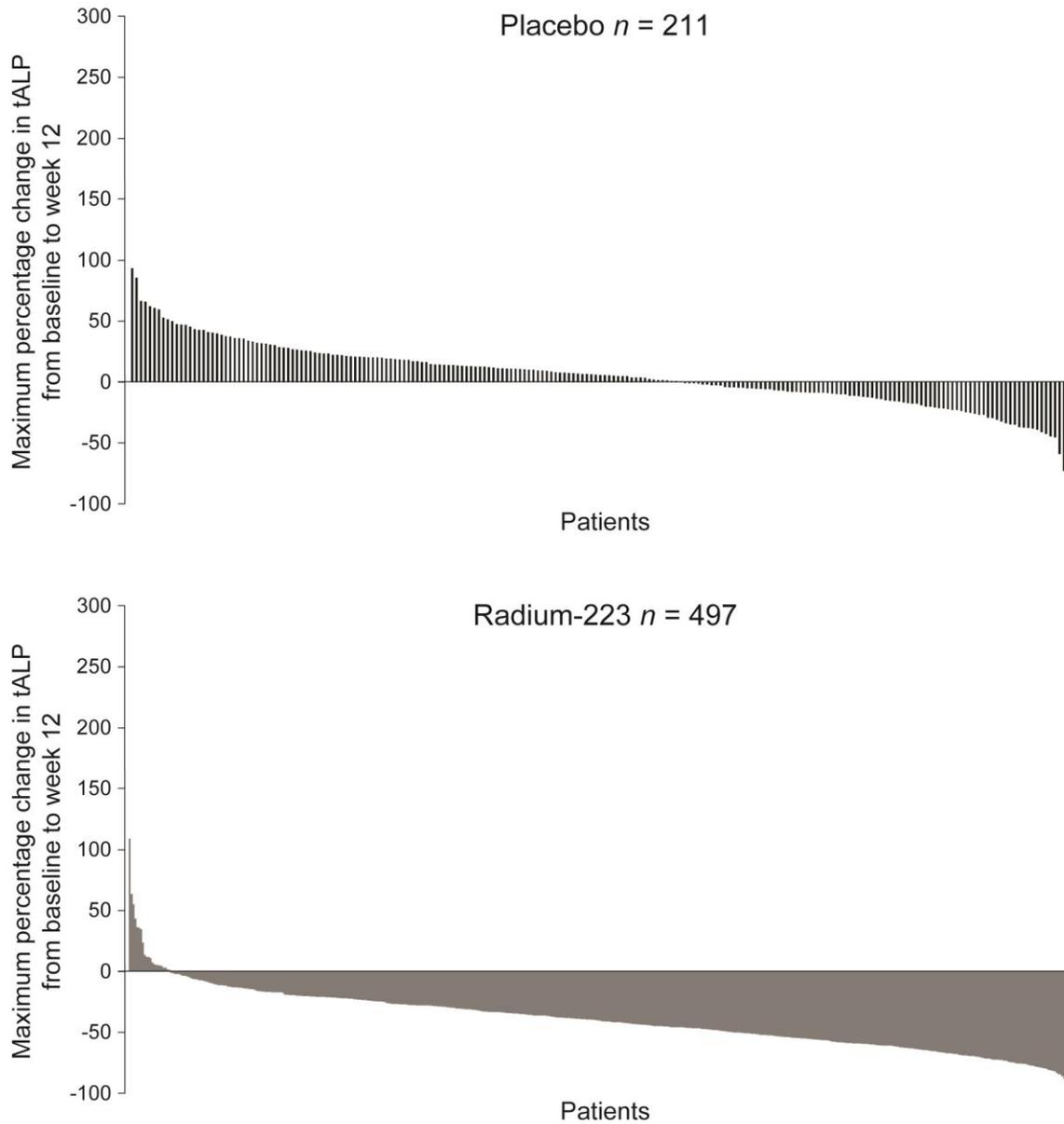
Supplementary Figure S2. Patient dispositions for the ALSYMPCA post hoc biomarker analyses. LDH, lactate dehydrogenase; ITT, intent-to-treat; PSA = prostate-specific antigen; tALP, total alkaline phosphatase.



Supplementary Figure S3: Maximum percentage change from baseline to week 12 for (A) tALP and (B) LDH in the placebo and radium-223 cohorts. Includes all patients with tALP and LDH determinations at baseline and week 12. LDH, lactate dehydrogenase; tALP, total alkaline phosphatase.

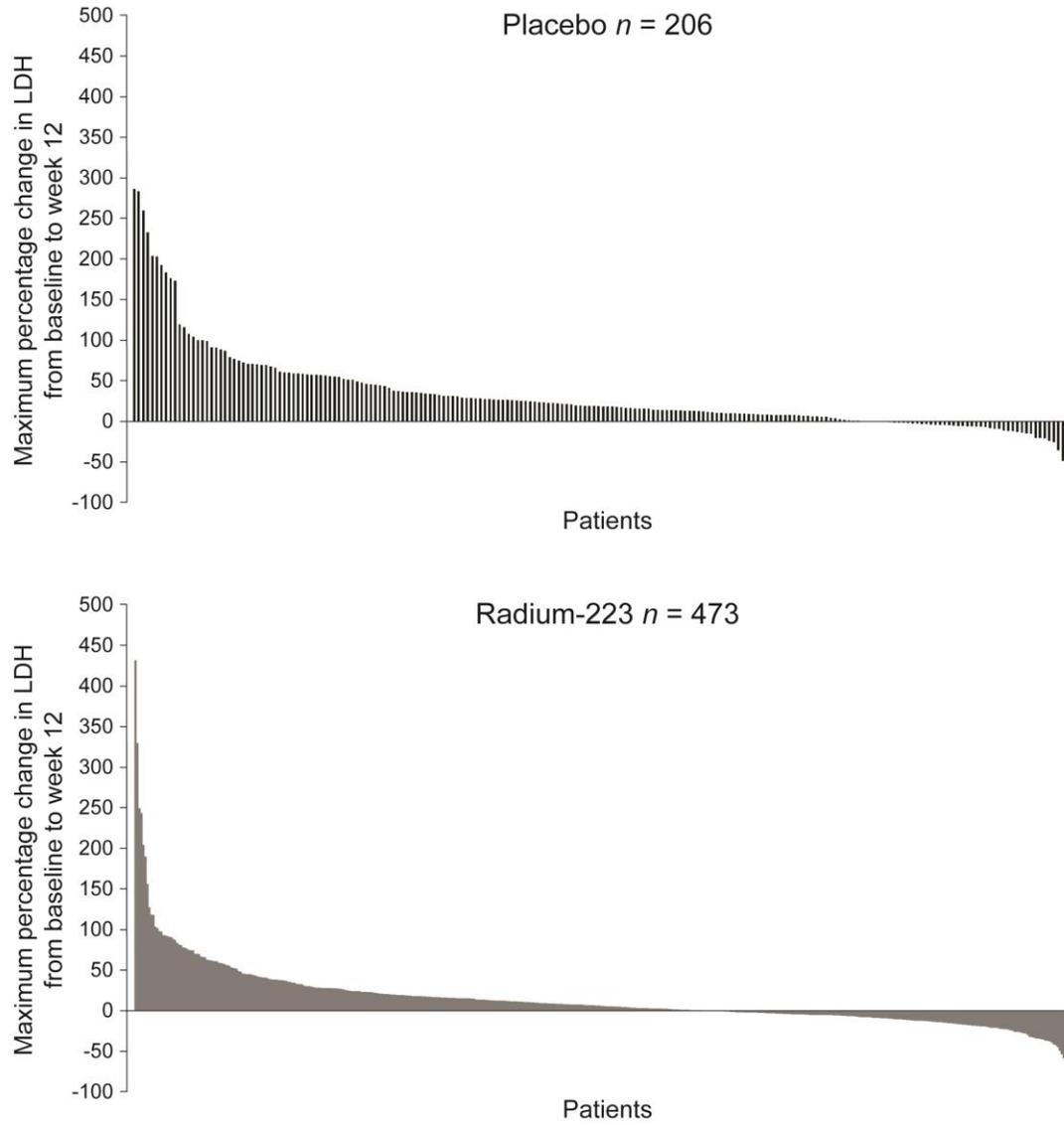
Supplementary Figure S3A. Maximum percentage change in tALP from baseline to week 12 in the placebo and radium-223 cohorts

A



Supplementary Figure S3B. Maximum percentage change in LDH from baseline to week 12 in the placebo and radium-223 cohorts.

B



Supplementary Table S1. tALP, LDH, and PSA mean percentage change from baseline at week 12

	Radium-223 (N = 614)		Placebo (N = 307)		P value ^a
	Decrease from baseline, n ^b /n ^c (%)	% change ^d (SE)	Decrease from baseline, n ^b /n ^c (%)	% change ^d (SE)	
tALP	433/497 (87)	-32.2 (1.80)	49/211 (23)	37.2 (2.77)	<0.001
LDH	242/473 (51)	7.3 (2.37)	70/206 (34)	20.8 (3.54)	0.003
PSA	135/493 (27)	83.3 (152)	30/210 (14)	543.8 (234)	0.160

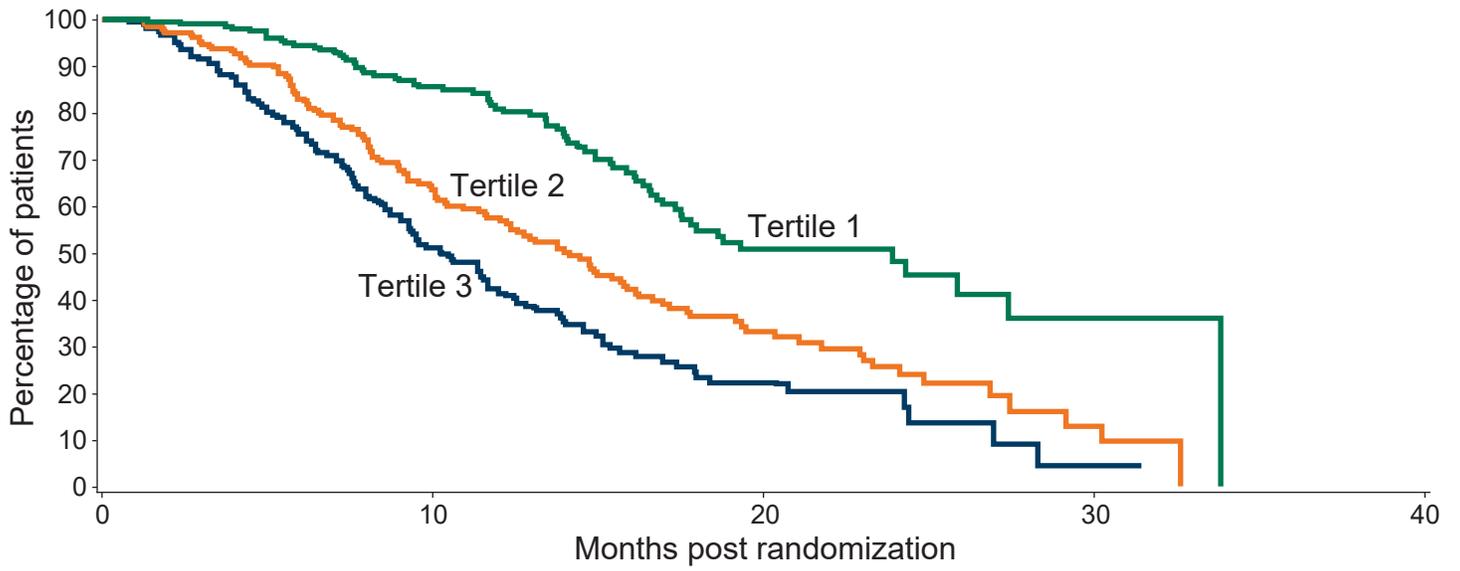
^aFrom ANCOVA adjusting for the binary stratification factors, total ALP, current use of bisphosphonates and prior use of docetaxel

^bNumber of patients with a decrease from baseline and at week 12

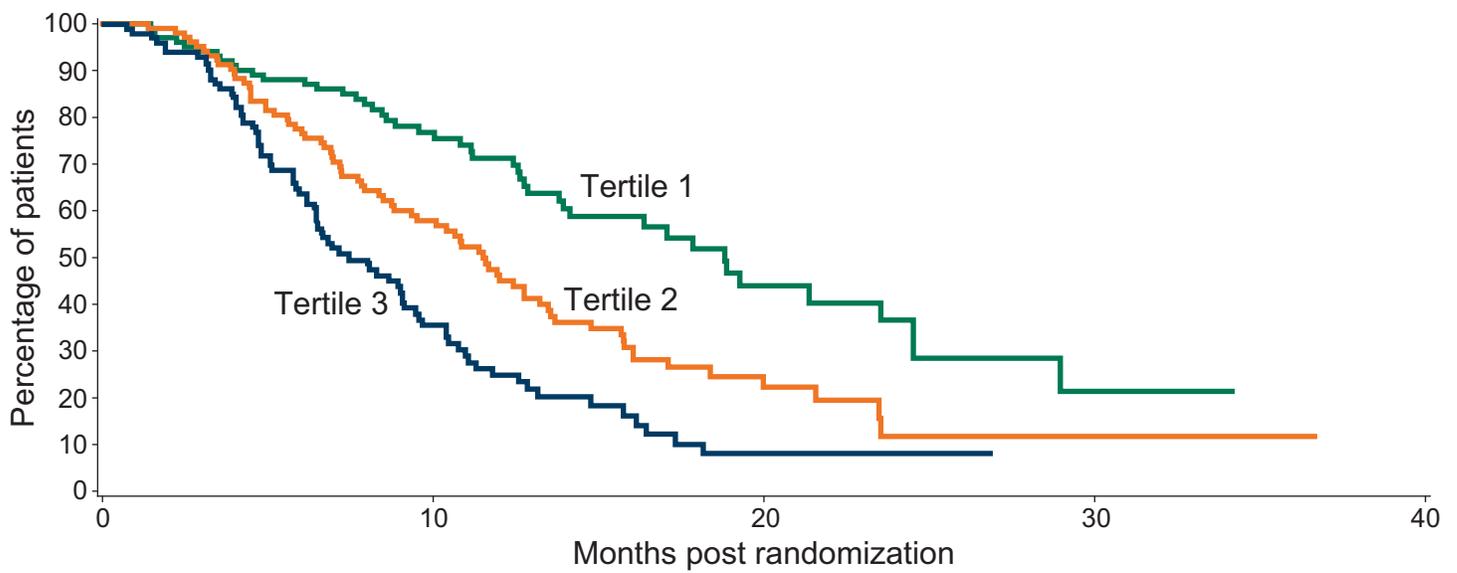
^cNumber of patients with measurements at baseline and week 12

^dLeast squares mean

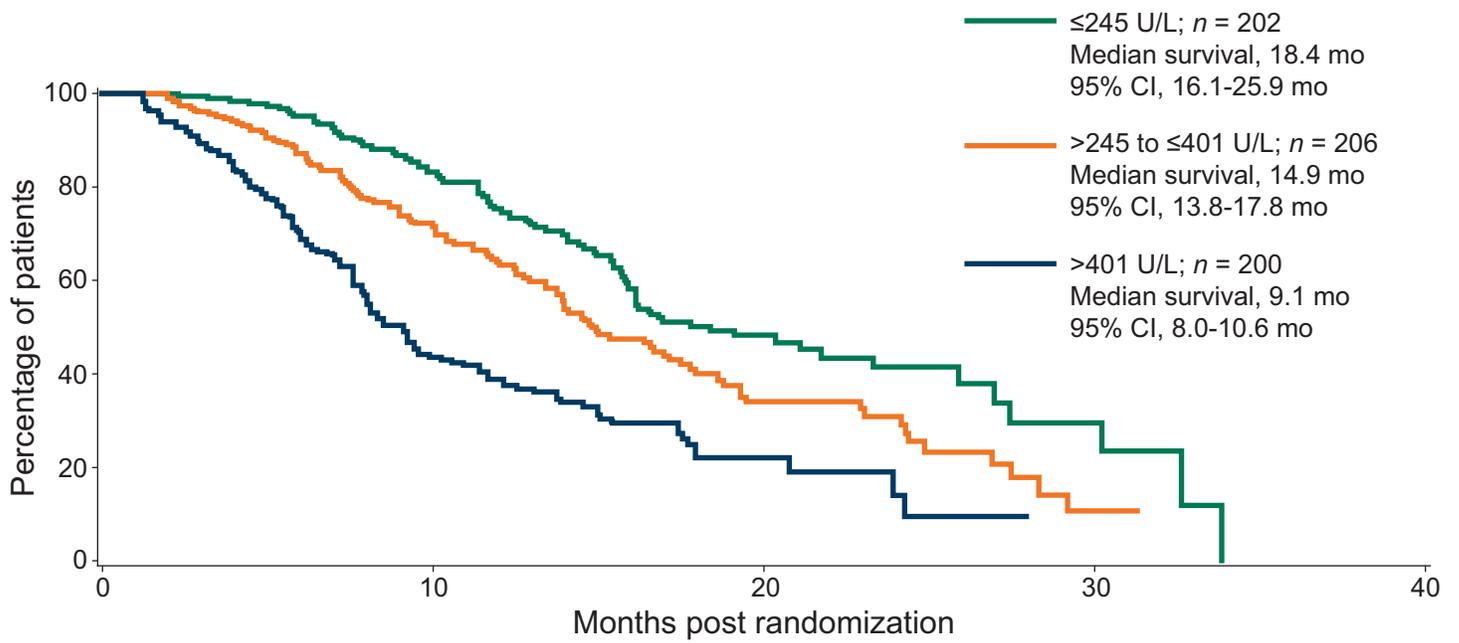
LDH, lactate dehydrogenase; PSA, prostate-specific antigen; SE, standard error of the mean; tALP, total alkaline phosphatase.

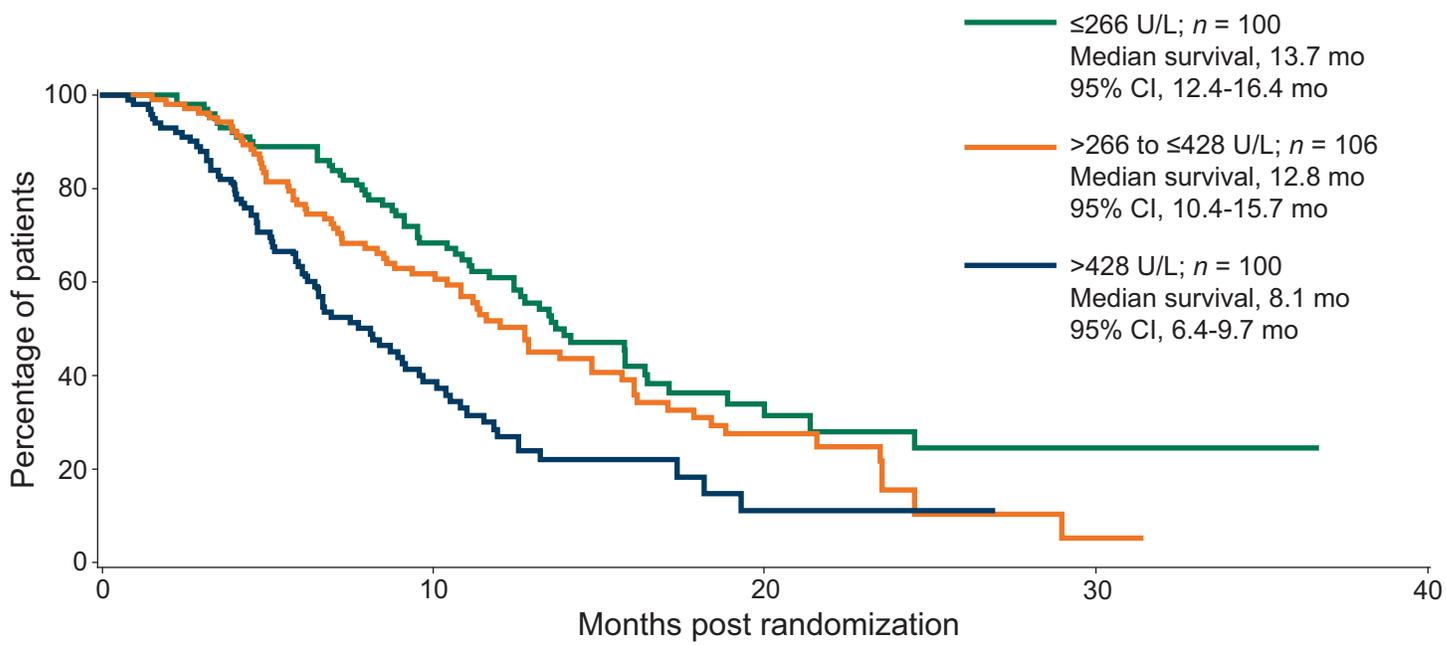


	Tertile 1 (n = 205)	Tertile 2 (n = 207)	Tertile 3 (n = 202)
tALP min-max	32-131	132-333	334-6431
Median overall survival time, mo (95% CI)	23.9 (17.5-33.8)	14.1 (12.0-15.9)	10.2 (9.1-11.7)



	Tertile 1 (n = 102)	Tertile 2 (n = 104)	Tertile 3 (n = 101)
tALP min-max	29-153	154-353	360-4805
Median overall survival time, mo (95% CI)	18.8 (13.9-24.5)	11.5 (9.3-13.5)	7.5 (6.5-9.1)





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Baseline biomarker analyses performed

Baseline and week 12 biomarker analyses performed

Decrease in biomarker level from baseline at week 12

Decrease in biomarker level from baseline at week 12 confirmed 3 weeks later – radium-223 patients only

