

Original Investigation

Subclinical Thyroid Dysfunction and Fracture Risk

A Meta-analysis

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IMPORTANCE Associations between subclinical thyroid dysfunction and fractures are unclear and clinical trials are lacking.

OBJECTIVE To assess the association of subclinical thyroid dysfunction with hip, nonspine, spine, or any fractures.

DATA SOURCES AND STUDY SELECTION The databases of MEDLINE and EMBASE (inception to March 26, 2015) were searched without language restrictions for prospective cohort studies with thyroid function data and subsequent fractures.

DATA EXTRACTION Individual participant data were obtained from 13 prospective cohorts in the United States, Europe, Australia, and Japan. Levels of thyroid function were defined as euthyroidism (thyroid-stimulating hormone [TSH], 0.45-4.49 mIU/L), subclinical hyperthyroidism (TSH <0.45 mIU/L), and subclinical hypothyroidism (TSH \geq 4.50-19.99 mIU/L) with normal thyroxine concentrations.

MAIN OUTCOME AND MEASURES The primary outcome was hip fracture. Any fractures, nonspine fractures, and clinical spine fractures were secondary outcomes.

RESULTS Among 70 298 participants, 4092 (5.8%) had subclinical hypothyroidism and 2219 (3.2%) had subclinical hyperthyroidism. During 762 401 person-years of follow-up, hip fracture occurred in 2975 participants (4.6%; 12 studies), any fracture in 2528 participants (9.0%; 8 studies), nonspine fracture in 2018 participants (8.4%; 8 studies), and spine fracture in 296 participants (1.3%; 6 studies). In age- and sex-adjusted analyses, the hazard ratio (HR) for subclinical hyperthyroidism vs euthyroidism was 1.36 for hip fracture (95% CI, 1.13-1.64; 146 events in 2082 participants vs 2534 in 56 471); for any fracture, HR was 1.28 (95% CI, 1.06-1.53; 121 events in 888 participants vs 2203 in 25 901); for nonspine fracture, HR was 1.16 (95% CI, 0.95-1.41; 107 events in 946 participants vs 1745 in 21 722); and for spine fracture, HR was 1.51 (95% CI, 0.93-2.45; 17 events in 732 participants vs 255 in 20 328). Lower TSH was associated with higher fracture rates: for TSH of less than 0.10 mIU/L, HR was 1.61 for hip fracture (95% CI, 1.21-2.15; 47 events in 510 participants); for any fracture, HR was 1.98 (95% CI, 1.41-2.78; 44 events in 212 participants); for nonspine fracture, HR was 1.61 (95% CI, 0.96-2.71; 32 events in 185 participants); and for spine fracture, HR was 3.57 (95% CI, 1.88-6.78; 8 events in 162 participants). Risks were similar after adjustment for other fracture risk factors. Endogenous subclinical hyperthyroidism (excluding thyroid medication users) was associated with HRs of 1.52 (95% CI, 1.19-1.93) for hip fracture, 1.42 (95% CI, 1.16-1.74) for any fracture, and 1.74 (95% CI, 1.01-2.99) for spine fracture. No association was found between subclinical hypothyroidism and fracture risk.

CONCLUSIONS AND RELEVANCE Subclinical hyperthyroidism was associated with an increased risk of hip and other fractures, particularly among those with TSH levels of less than 0.10 mIU/L and those with endogenous subclinical hyperthyroidism. Further study is needed to determine whether treating subclinical hyperthyroidism can prevent fractures.

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Overt hyperthyroidism is an established risk factor for osteoporosis and fractures.¹ More subtle alterations in thyroid function found in subclinical thyroid dysfunction, defined as abnormal thyroid-stimulating hormone (TSH) with normal free thyroxine (FT₄), could also be associated with increased fracture risk and bone loss.²⁻⁴

In prospective cohort studies, data about the association between subclinical thyroid dysfunction and fracture risk are in conflict because of inclusion of participants with overt thyroid disease^{3,5} and small sample sizes of participants with thyroid dysfunction^{6,7} or fracture events.⁸ To our knowledge, no clinical trial has examined the effect of treating subclinical thyroid dysfunction on fracture risks. A recent study-level meta-analysis of prospective cohorts found an increased fracture risk in subclinical hyperthyroidism, but interpretation was limited by population heterogeneity, discrepant definitions of fractures, and differing TSH cutoffs for defining subclinical thyroid dysfunction,⁹ which could not be addressed in a study-level meta-analysis.

For these reasons, we performed a pooled analysis of individual participant data of multiple large cohorts that assessed the association of subclinical thyroid dysfunction with risk for hip fractures, as well as nonspine, clinical spine, and fractures of any location. This approach allowed exploration of the relationship of age, sex, and TSH levels with the association of subclinical thyroid dysfunction and fractures, and is considered an optimal approach for combining evidence.¹⁰

Methods

This individual participant data analysis was performed according to a predefined protocol.¹¹

Study Selection

We performed a systematic literature search in MEDLINE and EMBASE, from inception to March 26, 2015, without language restriction, for prospective cohorts of adults with baseline TSH and FT₄ levels¹² and follow-up for incident fractures. We excluded studies that included only participants with overt thyroid dysfunction or individuals taking thyroid-altering medications (thyroxine, iodine, oral corticosteroids, amiodarone, antithyroid drugs). We conducted the search on an Ovid (MEDLINE) server using broadly defined Medical Subject Headings: *thyroid diseases, hypothyroidism, hyperthyroidism, thyroid hormones, thyrotropin, subclinical hyperthyroidism, subclinical hypothyroidism, subclinical dysthyroidism or subclinical thyroid, and fractures or osteoporosis*. We used a filter to extract prospective studies (MEDLINE cohort-study filter)¹³ but without year limitation. The search was also conducted in EMBASE using similar terms. We searched bibliographies of key articles in the field. Two authors (M.R.B. and C.D.W.) independently screened the abstracts of the search results and independently assessed the remaining full-text articles for eligibility. Any disagreement was resolved with the help of a third author (D.C.B.).⁹ We also asked cohorts of the Thyroid Studies Collaboration^{12,14-16} for unpublished prospective fracture data.

All qualifying cohorts were invited to join and provide individual participant data about baseline thyroid function, participant characteristics, bone metabolism-altering and thyroid medications, and fracture data. We conducted this individual participant data analysis in collaboration with investigators from each cohort to resolve data issues.¹⁷ Individual cohort results were validated against published results. Four cohorts that had not previously published fracture data¹⁸⁻²¹ provided exact procedures for data collection and adjudication of fracture data. For comparability with other cohorts in the present analysis, we used the random sample of the Osteoporotic Fractures in Men (MrOS) Study⁷ from 5994 participants at the baseline visit.⁹

Definition of Subclinical Thyroid Dysfunction

We used a uniform TSH threshold to maximize comparability, based on previously established thresholds.¹² Euthyroidism was defined as having a TSH level of 0.45 to 4.49 mIU/L. Subclinical hyperthyroidism was defined as having a TSH level of less than 0.45 mIU/L with normal FT₄ levels and was further stratified as suppressed TSH (<0.10 mIU/L) and low but not suppressed TSH (0.10-0.44 mIU/L). Subclinical hypothyroidism was defined as having a TSH level of 4.50 to 19.99 mIU/L with normal FT₄ levels. Participants with a missing FT₄ level and a TSH level within the range for subclinical thyroid dysfunction (1024 participants) were considered as having subclinical thyroid dysfunction because most adults with TSH levels in this range have subclinical and not overt thyroid dysfunction (eTable 1 in Supplement 1).²² Cohorts using first-generation TSH assays were excluded from analyses of subclinical hyperthyroidism because of insufficient sensitivity of first-generation thyroid assays.²³ Because of greater interstudy method variation, we used cohort-specific cutoffs for FT₄ and triiodothyronine (T₃) levels (eTable 1 in Supplement 1). We performed a sensitivity analysis on persistent thyroid dysfunction using repeated TSH and FT₄ measurements (available in 5 cohorts; follow-up duration in eTable 5 in Supplement 1). We performed additional sensitivity analyses excluding participants using thyroid-altering medications to estimate the risk associated with endogenous subclinical thyroid dysfunction, and excluding participants with missing FT₄ levels or abnormal total or free T₃ levels (measured in 4 out of 13 cohorts).

Outcomes

Our a priori-defined primary outcome was incident hip fracture. Secondary outcomes were incident fractures of any location, nonspine, and clinical spine fractures. We standardized outcome definitions (eTable 1 in Supplement 1). Incident hip fractures typically included fractures of the femoral neck, pertrochanteric, and subtrochanteric fractures, excluding pathologic and periprosthetic fractures. Incident nonspine fractures were defined as hip or any other nonpathologic fracture excluding the spine, and excluding fractures of the skull or face, ankle, finger, and toe, which are not typically affected by increased bone fragility. Incident spine fractures were defined as clinically diagnosed and radiographically confirmed thoracic and lumbar spine fractures, excluding cervical and sacral fractures because these usually occur due to trauma that is un-

related to bone fragility. We restricted our spine fracture outcome to those that were clinically diagnosed and did not consider spine fractures identified only by scheduled radiographs, to focus analyses on associations with outcomes that are more likely to be symptomatic²⁴ and therefore of greater clinical relevance to patients.²⁵ The outcome of any fracture was defined as the first event of either nonspine or clinically diagnosed spine fracture. Cohorts with fracture data only for parts of the skeleton, such as 1 study with hip fracture data only,⁸ were not included for this outcome.

In a secondary analysis, we compared fracture risk between thyroxine-treated and untreated participants at baseline, irrespective of thyroid function test results, to assess fracture risk associated with thyroxine use.

To evaluate study quality, we used the individual criteria of the Newcastle-Ottawa Quality Assessment Scale²⁶ (eTable 2 and eMethods in Supplement 1). We performed sensitivity analyses excluding cohorts that did not meet different individual criteria of this scale.

Statistical Analyses

We used established methods^{10,17} with a 2-step approach, first analyzing the association of subclinical thyroid dysfunction with outcomes using separate Cox proportional hazard models for each cohort (Stata version 12.1), and in a second step calculating pooled estimates using random-effects models.²⁷ Time to event was calculated for each outcome from baseline to first event. For cohorts with no event in some subgroups of thyroid function, penalized maximum likelihood estimation models²⁸ were used to derive hazard ratios (HRs) and 95% CIs (SAS version 9.3). Strata with fewer than 6 participants per cohort were excluded from pooling due to unreliable estimates. We summarized results using forest plots (Review Manager version 5.3.3). We calculated the variance estimate τ^2 as a measure of heterogeneity in estimates across cohorts. τ^2 values were prespecified to indicate low (≤ 0.04), moderate (> 0.04 – < 0.36), and high (≥ 0.36) to indicate heterogeneity.²⁹ *P* values of less than .05 were considered as significant and testing was 2-sided.

Primary analyses were adjusted for age and sex, and then for other known risk factors for fractures because some might be potential mediators (eg, body mass index [BMI]) of the association between subclinical thyroid dysfunction and fractures. Based on a literature search of potential confounders for this association, taking into account their prevalence and strength of their association with fractures and possible influence on thyroid function, we further adjusted for BMI (calculated as weight in kilograms divided by height in meters squared)³⁰ and smoking status,³¹ which were available in all cohorts. In sensitivity analyses, we also accounted for the following characteristics: (1) adjusted for diabetes mellitus³²; (2) excluded participants who were receiving thyroid-altering medication (oral corticosteroids, amiodarone, iodine) or anti-fracture medication (bisphosphonates, calcitonin, selective estrogen receptor modulators, parathyroid hormones); (3) limited the analysis to the 8 studies with formal adjudication or those with the most uniform fracture definition; (4) restricted the analysis to participants with repeated measurement of thyroid function to assess the association with persistent thyroid

dysfunction; (5) excluded cohorts with loss to follow-up rates of greater than 5%; (6) excluded cohorts with fracture ascertainment methods other than independent blind assessment or record linkage (eTable 2 in Supplement 1); (7) excluded participants with missing FT₄ levels or abnormal free or total T₃; (8) excluded studies inconsistent with the proportional hazard assumption; (9) excluded studies because of potential publication bias in funnel plots; and (10) applied age-specific TSH reference ranges.³³

To explore potential sources of heterogeneity, we performed predefined subgroup analyses according to age, sex, and TSH levels. We calculated linear *P* for trend and *P* for interaction for stratified analyses. We used Poisson models to calculate event rates.³⁴ The proportional hazard assumption was assessed by graphical methods (log-log graphs) and the Schoenfeld test.³⁵ We excluded cohorts violating the proportional hazard assumption in sensitivity analyses. We visually assessed funnel plots of age- and sex-adjusted estimates and used the Egger test to assess for publication bias.³⁶

Results

Among 1371 studies identified in our literature search, 13 prospective cohorts met inclusion criteria (eFigure 1 in Supplement 1). The final sample consisted of 70 298 participants (median age was 64 years; 61.3% women), a median (interquartile range) follow-up of 12.1 (8.3–13.0) years, and a total follow-up of 762 401 person-years (Table). A total of 63 987 (91.0%) of the participants were euthyroid, 4092 (5.8%) had subclinical hypothyroidism, and 2219 (3.2%) had subclinical hyperthyroidism, including 1669 (2.4%) with low but not suppressed TSH (0.10–0.44 mIU/L) and 550 (0.8%) with suppressed TSH (< 0.10 mIU/L). We excluded the Nagasaki Adult Health Study²⁰ from the analysis of subclinical hyperthyroidism because it used first-generation thyrotropin assays.

Incident hip fractures were collected in all cohorts except one,¹⁸ resulting in a study sample of 64 691 participants for the primary outcome. Data were available for any fracture in 28 561 participants from 8 cohorts, for nonspine fractures in 24 155 participants from 8 studies, and for clinical spine fractures in 22 491 participants from 6 cohorts. During follow-up, 2975 (4.6% in 12 studies) participants had an incident hip fracture, 2528 (9.0% in 8 studies) had a fracture in any location, 2018 (8.4% in 8 studies) had a nonspine fracture, and 296 (1.3% in 6 studies) had a spine fracture.

Although study quality was good (see eMethods and eTable 2 in Supplement 1), 2 cohorts did not ascertain fractures with independent blind assessment or record linkage, 5 cohorts did not formally adjudicate fractures, and 2 cohorts had a loss to follow-up of greater than 5%.

Subclinical Hyperthyroidism and Fracture Risk

In age- and sex-adjusted analyses, when compared with euthyroidism, subclinical hyperthyroidism was associated with HRs of 1.36 (95% CI, 1.13–1.64; 6.0 vs 4.9 per 1000 person-years, respectively) for hip fracture, 1.28 (95% CI, 1.06–1.53; 14.4 vs 11.2 per 1000 person-years) for any fracture, 1.16 (95% CI,

Table. Baseline Characteristics of Individuals in Included Studies (N = 70 298)

Study (Location)	Description of Study Sample	No. of Participants	Age, Median (Range), y ^a	Women, No. (%)	Subclinical Thyroid Dysfunction, No. (%) ^b			Thyroid Medication Users, No. (%)		Follow-up ^c	
					Hypothyroidism	Hyperthyroidism	At Baseline	During Follow-up	Start, y	Duration, Median (IQR), y	Person-Years
Cardiovascular Health Study, ⁴ (United States)	Community-dwelling adults with Medicare eligibility in 4 communities	3555	71 (65-100)	2185 (61.5)	543 (15.3)	159 (4.5)	295 (8.3) ^c	629 (17.7)	1989-1990	12.8 (7.5-18.8)	45 160
Health ABC Study, ³⁷ (United States)	Community-dwelling adults aged 70-79 y with Medicare eligibility in 2 communities	2764	74 (69-81)	1407 (50.9)	335 (12.1)	82 (3.0)	267 (9.7) ^c	383 (13.9)	1997	12.8 (8.1-13.2)	29 292
Osteoporotic Fractures in Men Study (MrOS), ⁷ (United States)	Community-dwelling men aged ≥65 y in 6 clinical centers	1588	73 (65-99)	0	147 (9.3)	30 (1.9)	121 (7.6) ^c	152 (9.6) ^d	2000-2002	11.1 (8.0-11.8)	15 133
EPIC-Norfolk Study, ³⁸ (England)	Adults aged 45-79 y	13 066	58 (40-78)	7104 (54.4)	720 (5.5)	360 (2.8)	439 (3.4)	NA ^d	1995-1998	12.4 (11.6-13.3)	155 661
HUNT Study, ³⁹ (Norway)	Adults	33 646	57 (19-99)	22 988 (68.3)	1313 (3.9)	945 (2.8)	1576 (4.7) ^c	NA ^d	1995-1997	12.2 (11.6-12.8)	369 413
InCHIANTI Study, ²¹ (Italy)	Community-dwelling adults aged ≥65 y	1186	71 (21-102)	664 (56.0)	33 (2.8)	87 (7.3)	28 (2.4)	48 (4.0) ^d	1998	9.1 (7.2-9.3)	9393
Leiden 85-Plus Study, ⁴⁰ (the Netherlands)	Adults aged 85 y	514	85	336 (65.4)	35 (6.8)	23 (4.5)	17 (3.3)	29 (5.6)	1997-1999	4.9 (2.2-8.2)	2736
OPUS Study, ⁴¹ (Germany, France, England) ⁹	Women aged 20-80 y	1433	63 (20-80)	1433 (100.0)	12 (0.8)	216 (15.1)	0	NA	1999-2001	6.0 (5.8-6.3)	8556
PROSPER Study, ¹⁸ (the Netherlands, Ireland, Scotland)	Older community-dwelling adults at high cardiovascular risk	5563	75 (69-83)	2824 (50.8)	306 (5.5)	133 (2.4)	184 (3.3)	252 (4.5) ^d	1997-1999	3.2 (3.0-3.5)	17 162
Rotterdam Study, ⁴² (the Netherlands)	Adults aged ≥55 y	1838	69 (55-93)	1127 (61.3)	107 (5.8)	120 (6.5)	42 (2.3) ^c	NA ^d	1989-1992	15.2 (10.2-16.2)	24 031
Sheffield Study, ⁶ (England)	Women aged 50-85 y	334	63 (50-86)	334 (100.0)	32 (9.6)	11 (3.3)	5 (1.5)	21 (6.3) ^d	1990-1991	10.0 (5.3-10.1)	2597
Busselton Health Study, ¹⁹ (Australia)	Adults	2049	51 (18-90)	1006 (49.1)	89 (4.3)	53 (2.6)	19 (0.9)	34 (1.7)	1981	20.0 (17.2-20.0)	35 607
Nagasaki Adult Health Study, ²⁰ (Japan)	Atomic bomb survivors	2762	57 (38-92)	1686 (61.0)	420 (15.2)	NA ^h	39 (1.4)	6 (0.2) ^d	1984-1987	20.2 (10.0-25.9)	47 660
Overall	13 Cohorts	70 298	64 (18-102)	43 094 (61.3)	4092 (5.8)	2219 (3.2)	3032 (4.3)	1554 (9.0)	1981-2002	12.1 (8.3-13.0)	762 401

Abbreviations: EPIC, European Prospective Investigation of Cancer; HUNT, Nord-Trøndelag Health Study; InCHIANTI, Invecchiare in Chianti Study; IQR, interquartile range; NA, not available; OPUS, Osteoporosis and Ultrasound Study; PROSPER, Prospective Study of Pravastatin in the Elderly at Risk; TSH, thyroid-stimulating hormone.

^a Participants younger than 18 years were excluded.

^b We used a common definition of subclinical thyroid dysfunction, whereas TSH cutoff values varied among the previous reports from different cohorts, resulting in different numbers from previous reports.

^c Data on baseline thyroid medication use (thyroxine, antithyroid drugs) were unavailable for 273 participants of the HUNT Study, 1 participant of the Cardiovascular Health Study, 64 participants of the Osteoporotic Fractures in Men Study, 8 participants of the Health ABC Study, and 1 participant of the Rotterdam Study.

^d Data on thyroid medication use during follow-up were unavailable for 294 participants of the Osteoporotic Fractures in Men Study, 119 participants of the Invecchiare in Chianti Study, 2509 participants of the Nagasaki

Adult Health Study, 56 participants of the Sheffield Study, and for all participants of the HUNT Study, EPIC-Norfolk Study, Rotterdam Study, and Osteoporosis and Ultrasound Study.

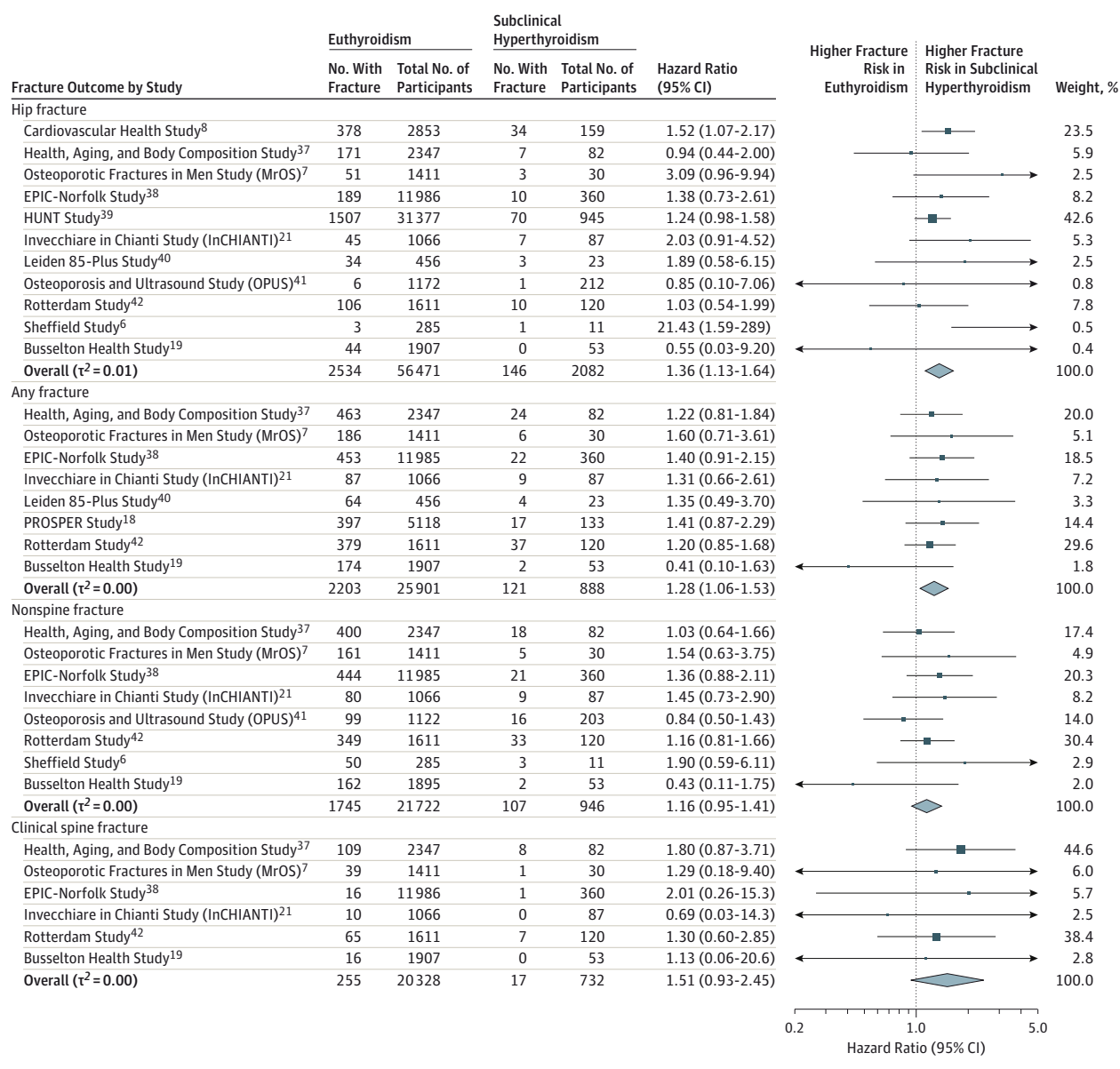
^e For all cohorts, we used the maximum follow-up data available (calculated as time to first hip or any fracture or censor date/death), which might differ from previous reports for some cohorts.

^f The sample included for the original article of the HUNT study used several inclusion/exclusion criteria that differed from those used here (such as excluding participants younger than 40 years and those with previous fractures or previous thyroid disease), resulting in different numbers of participants.

^g The original OPUS was a population-based study with no exclusions. The sample included here is the thyroid hormone substudy of OPUS, which excluded thyroid medication users.

^h Twenty-one participants with TSH<0.45mIU/L and free thyroxine within the normal range were excluded from the Nagasaki cohort due to the use of a first-generation TSH assay that is not sensitive enough to detect subclinical hyperthyroidism.

Figure 1. Association Between Subclinical Hyperthyroidism and Fracture Risk



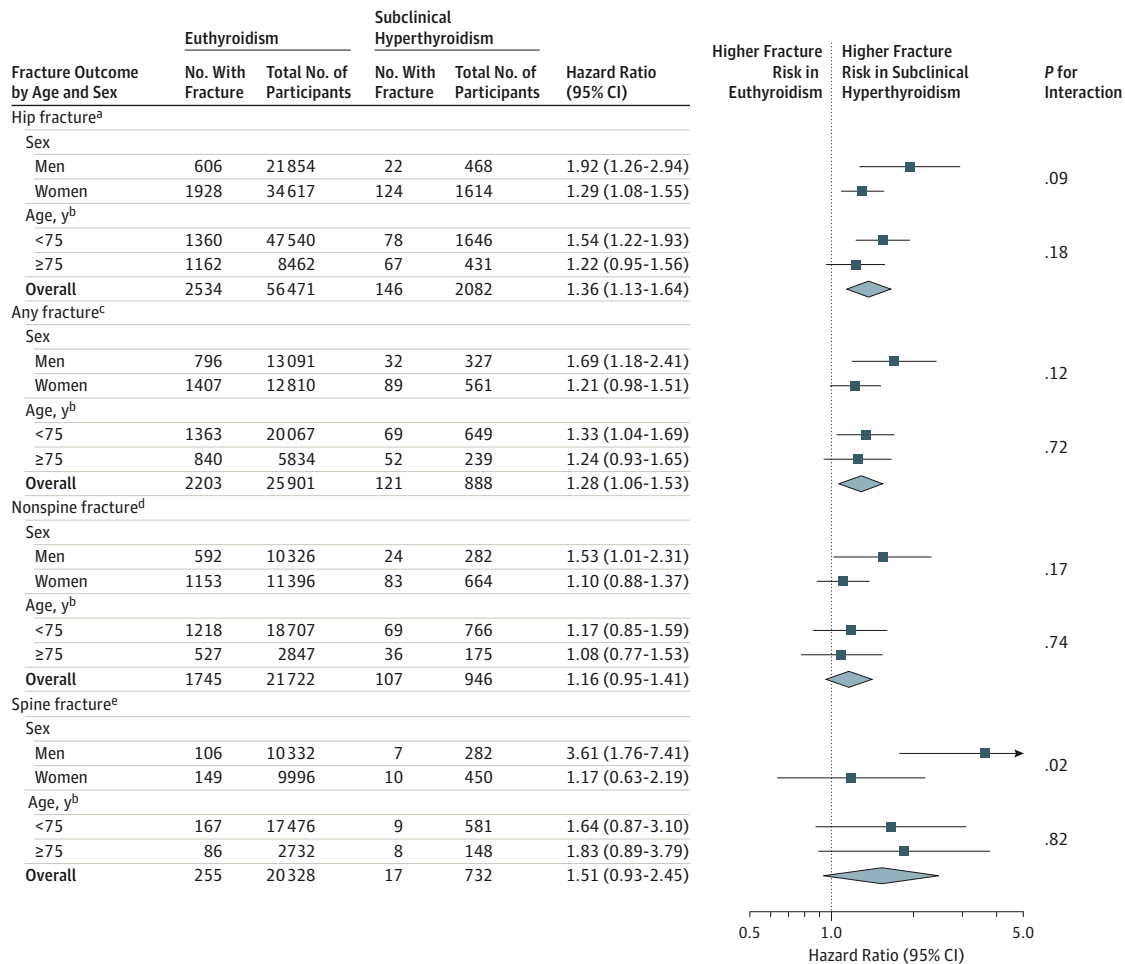
Hazard ratios (HRs) were adjusted for age and sex. Data marker sizes are proportional to the inverse of the variance of the HRs. Error bars indicate 95% CIs. Not every outcome was available for each study. Calculations of τ^2 were used to measure heterogeneity in effect estimates across cohorts, with a prespecified τ^2 (≤ 0.04) indicating low heterogeneity and greater than 0.04 to 0.36 indicating moderate heterogeneity.

0.95-1.41; 9.9 vs 8.1 per 1000 person-years) for nonspine fracture, and 1.51 (95% CI, 0.93-2.45; 1.8 vs 1.2 per 1000 person-years) for spine fracture (Figure 1). Numbers of fracture events and participants, as well as individual HRs with CIs for each cohort, are described in Figure 1. Two individual studies found that subclinical hyperthyroidism was associated with increased risk for hip fractures (Cardiovascular Health Study⁸ and the Sheffield Study⁶). No individual study found a statistically significant association of subclinical hyperthyroidism with the secondary outcomes: any fracture, nonspine fracture, or clinical spine fracture. Although 95% CIs were large in some cohorts, heterogeneity was low for all outcomes (all $\tau^2 \leq 0.01$).

Figure 2 displays stratified analyses for incident hip, any, nonspine, and spine fracture events, comparing subclinical hyperthyroidism vs euthyroidism. Men with subclinical hyperthyroidism had higher HRs than women for all fracture outcomes, without statistically significant interactions except for spine fractures (P for interaction $\leq .02$). Risks did not differ when stratified by age.

Figure 3 displays the association between subclinical hyperthyroidism and the risk of fracture by TSH category. Risks for hip, any, and spine fracture were higher in participants with lower TSH levels. TSH levels of less than 0.10mIU/L were not associated with increased risk of non-

Figure 2. Stratified Analyses for the Association Between Subclinical Hyperthyroidism and Fracture Risk



All hazard ratios (HRs) were age and sex adjusted. Error bars indicate 95% CIs. The multivariable analysis yielded similar results (eTable 3 in Supplement 1).

^a The PROSPER (Prospective Study of Pravastatin in the Elderly at Risk) Study was not included because follow-up data were only available for any fracture.

^b These HRs were adjusted for sex and age as a continuous variable to avoid residual confounding within age strata.

^c The HUNT (Nord-Trøndelag Health Study), Cardiovascular Health Study, Sheffield, and OPUS (Osteoporosis and Ultrasound Study) studies were not

included because follow-up data for any fracture were not available.

^d The HUNT, Cardiovascular Health Study, Leiden 85-Plus, and PROSPER studies were not included because follow-up data for nonspine fractures were not available.

^e The HUNT, Cardiovascular Health Study, Leiden 85-Plus, Sheffield, OPUS, and PROSPER studies were not included because follow-up data for spine fractures were not available.

spine fracture. The multivariable analysis yielded similar results (eTable 3 in Supplement 1).

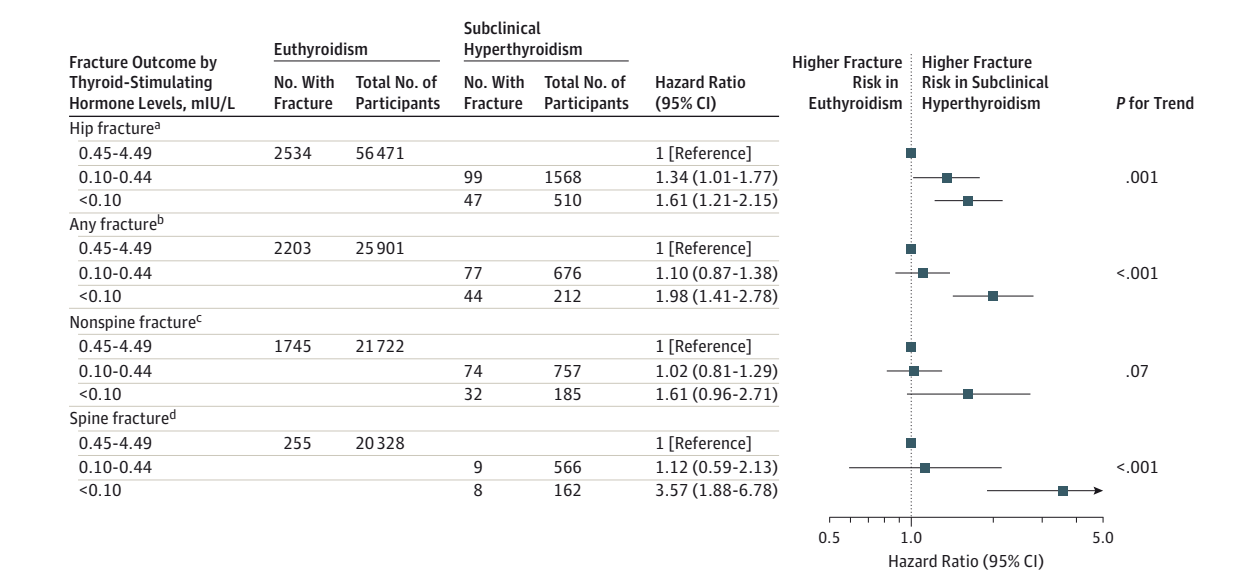
Sensitivity analyses excluding participants with missing FT₄, T₃, or those who had been prescribed antiosteoporotic medication; restricting the analysis to studies with formal adjudication or those with the most uniform fracture definition; or excluding studies inconsistent with the proportional hazard assumption (possible publication bias in funnel plots), with a greater than 5% loss to follow-up, with fracture ascertainment methods other than independent blind assessment, or record linkage all yielded similar results (eTables 4-6 in Supplement 1). After excluding participants who had been prescribed thyroid or antithyroid medication at baseline (4%), participants with endogenous subclinical hyperthyroidism had statistically significant increased risk estimates for all frac-

ture outcomes except for nonspine fractures. Although point estimates were similar for persistent thyroid dysfunction, our findings were not statistically significant with larger CIs. Restricting the analysis to 9 cohorts with previously published fracture data generally yielded similar risk estimates (eTable 6 in Supplement 1) without statistically significant interactions, when compared to 4 cohorts with unpublished fracture data. When restricting analyses to 4 cohorts with unpublished fracture data, results were not statistically significant.

Subclinical Hypothyroidism and Fracture Risk

We found no association between subclinical hypothyroidism and fracture risks either overall (eFigure 2 in Supplement 1) or in stratified analyses (eTable 7 in Supplement 1), with an HR compared with euthyroid participants of 0.96 (95% CI, 0.83-

Figure 3. Association Between Subclinical Hyperthyroidism and Fracture Risk Categorized by Thyroid-Stimulating Hormone Level



All hazard ratios (HRs) were age and sex adjusted. Error bars indicate 95% CIs. The multivariable analysis yielded similar results (eTable 3 in Supplement 1).

^a The PROSPER (Prospective Study of Pravastatin in the Elderly at Risk) Study was not included because follow-up data were only available for any fracture.

^b The HUNT (Nord-Trøndelag Health Study), Cardiovascular Health Study, Sheffield, and OPUS (Osteoporosis and Ultrasound Study) studies were not included because follow-up data for any fracture were not available.

^c The HUNT, Cardiovascular Health Study, Leiden 85-Plus, and PROSPER studies were not included because follow-up data for nonspine fractures were not available.

^d The HUNT, Cardiovascular Health Study, Leiden 85-Plus, Sheffield, OPUS, and PROSPER studies were not included because follow-up data for spine fractures were not available.

1.10) for hip fracture, 1.02 (95% CI, 0.89-1.18) for any fracture, 1.06 (95% CI, 0.90-1.24) for nonspine fracture, and 0.96 (95% CI, 0.59-1.55) for spine fracture. Sensitivity analyses did not change results (eTable 8 in Supplement 1).

Treatment With Thyroxine and Fracture Risk

When comparing between participants treated with thyroxine at baseline vs untreated participants regardless of thyroid function, treatment with thyroxine was not associated with any of the fracture outcomes (eTable 9 in Supplement 1).

Discussion

In this analysis of 70 298 individual participants from 13 prospective cohorts, subclinical hyperthyroidism was associated with an increased risk for hip and other fractures, with the highest risks in individuals with suppressed TSH (<0.10 mIU/L) and in those with endogenous subclinical hyperthyroidism. Conversely, our study found no association between subclinical hypothyroidism and fractures. Our pooled data analysis demonstrates that subclinical hyperthyroidism was associated with increased fracture risk and provides insight on defined subgroups.

To our knowledge, no pooled individual participant data analysis has previously assessed the association of subclinical thyroid dysfunction and fracture events. The Cardiovascular Health Study prospectively followed a cohort of 3567 older adults and found that in men, there was an association be-

tween increased hip fracture risk and subclinical hyperthyroidism (HR, 3.07; 95% CI, 1.11-8.46), as well as subclinical hypothyroidism (HR, 1.86; 95% CI, 1.09-3.16).⁸ Our results confirm the association of subclinical hyperthyroidism with risk of hip fracture. A prospective case-cohort study of 686 women aged 65 years and older found an odds ratio of 4.5 (95% CI 1.3-15.6) for spine fracture, detected in serial radiographs in women with a TSH level 0.10 mIU/L or less, compared with normal TSH levels after a mean follow-up of 3.7 years.³ Our study also found that endogenous subclinical hyperthyroidism was associated with increased risk of clinically diagnosed spine fractures (HR, 1.74; 95% CI, 1.01-2.99). However, because not all radiographic fractures are clinically diagnosed,⁴³ it is difficult to directly compare results with the prior study. Although there is some evidence that thyroid hormone level is associated more strongly with changes in cortical than in trabecular bone,^{44,45} we did not observe a stronger association with a more cortical (hip) vs a more trabecular (spine) fracture site.

Thyroid function may influence fracture risk through several mechanisms. First, thyroid hormones have been shown to have effects on osteoclasts and osteoblasts, with thyroid status in the upper normal range or excess thyroid hormones leading to accelerated bone turnover with bone loss and increased fracture risk.⁴ Second, the association of subclinical hyperthyroidism with increased fracture risk might be mediated by an increased risk of falls⁴⁶ through effects on muscle strength and coordination.^{41,47} Third, the increase in fracture risk could be related to thyroxine supplementation. In the TEARS study, participants receiv-

ing thyroid hormone replacement therapy had a higher rate of fractures when TSH was suppressed, compared with treated euthyroid participants (adjusted HR, 2.02; 95% CI, 1.55-2.62). However, participants with overt thyroid dysfunction might have been included in the TEARS study. FT₄ levels were not measured and the study did not include an untreated control group.⁵ Another nested case-control study of more than 120 000 prevalent levothyroxine users showed that levothyroxine use was associated with increased fracture risk when compared with discontinuation of levothyroxine more than 6 months previously. However, TSH levels were not considered in these analyses.⁴⁸ Our results showed an association of subclinical hyperthyroidism with increased risk of all fracture outcomes except nonspine fractures when thyroid medication users (thyroxine and antithyroid medication) were excluded from analyses. These results suggest that endogenous hyperthyroidism is associated with increased fracture risk. Endogenous subclinical hyperthyroidism may be undetected for years because symptoms of subclinical hyperthyroidism are often nonspecific or absent. This phenomenon has the potential to lead to a greater length of time for adverse associations with bone metabolism. Baseline thyroxine use was not associated with increased fracture risk when TSH levels were not taken into account. A possible explanation for this is that patients receiving replacement therapy have more frequent thyroid function tests followed by thyroxine dosage change when overtreatment is detected, and thus do not exhibit a long-standing form of subclinical hyperthyroidism.

Our study has important strengths. First, to our knowledge, this is the largest study of adults with subclinical thyroid dysfunction and prospective follow-up of fracture outcomes. An individual participant data analysis is not subject to potential aggregation bias arising in study-level meta-analyses⁴⁹ and is therefore seen as the optimal approach to combining evidence across multiple studies and performing time-to-event analyses.⁵⁰ In addition, individual participant data analysis enables use of standardized definitions of predictors and outcomes, and standardized adjustment for confounding factors,¹⁰ thus producing more robust results. We were also able to include 4 cohort studies that have not previously published their data on thyroid dysfunction and fractures (Busselton Health Study,¹⁹ PROSPER Study,¹⁸ InCHIANTI Study,²¹ and Nagasaki Adult Health Study²⁰), and all prospective cohorts identified through our systematic search agreed to participate, which increased our power to detect potential associations.

Our study has limitations. First, in the majority of cohorts, thyroid function was assessed at baseline only, which is a limitation of most published large cohorts on the risk of subclinical thyroid dysfunction.^{12,38} Subclinical hypothyroidism has an annual rate of 2% to 6% for spontaneous progression to overt thyroid dysfunction,⁵¹ while 15% to 65% revert to normal thyroid function over follow-up periods of 1 to 6 years.⁵² Subclinical hyperthyroidism similarly progresses to overt disease in 1% to 2% of affected individuals per year.^{53,54} In our pooled data, 5.3% of partici-

pants with baseline subclinical hyperthyroidism developed overt hyperthyroidism on follow-up thyroid function assessment vs 1.6% of participants when excluding thyroxine use at baseline (endogenous form). A sensitivity analysis, restricted to participants with persistent subclinical thyroid dysfunction using repeated thyroid function measurement in 5 cohorts with available data, yielded similar HRs for hip and any fracture outcomes, with nonstatistically significant results, possibly due to smaller sample sizes. Second, it was not possible to achieve a uniform definition for each fracture type across all cohorts. Sensitivity analyses limited to cohorts with the most uniform fracture definition, however, yielded similar results. Third, we defined subclinical hyperthyroidism by low TSH and normal FT₄ levels because T₃ levels were measured only in 4 cohorts. Consequently, participants with T₃ toxicosis may have been defined as having subclinical hyperthyroidism, but results remained similar in sensitivity analyses excluding participants with abnormal T₃ levels in the cohorts that had this measurement available. Likewise, we may have included participants with nonthyroidal illness from other cohorts in which T₃ levels were not measured. Fourth, only 8 of 13 studies formally adjudicated fracture outcomes; sensitivity analyses limited to these studies yielded similar results. Fifth, our pooled data contained relatively few young adults and a primarily white population, thus limiting generalizability. Sixth, in spite of the large number of participants, event numbers were low for some outcomes, such as clinical spine fractures, limiting power for subgroup analyses. Seventh, younger participants may have been more likely to experience traumatic fractures and mechanism of injury was not collected in most cohorts. However, fractures in locations not typically associated with osteoporosis or low bone mass density were excluded. Eighth, history of fracture or history of maternal and parental hip fracture were unavailable for most participants or we could not rule out the possibility of residual confounding.

Current guidelines recommend that treatment of subclinical hyperthyroidism should be strongly considered if TSH is persistently lower than 0.1 mIU/L in all individuals aged 65 years or older and that treatment should also be considered if TSH is low but at least 0.1 mIU/L in individuals who are at least 65 years old.⁵⁵ Our results from pooling data of all available prospective cohorts, showing increased fracture risk in subclinical hyperthyroidism with even higher risk for participants with TSH levels of less than 0.10 mIU/L, are consistent with these recommendations. Due to the previously mentioned limitations, evidence from observational data should be used with caution in clinical decision making. Some small randomized controlled trials (14-66 participants) have studied the short-term effect (follow-up time of 6-14 months) of subclinical thyroid dysfunction treatment on bone mineral density with conflicting results,⁵⁶⁻⁵⁹ but no randomized controlled trial has been conducted regarding treatment of subclinical thyroid dysfunction to reduce fracture risk. There are also no studies comparing the relative benefit of treatment of subclinical hyperthyroidism vs treatment with bisphosphonates or other antifracture agents.

Conclusions

Subclinical hyperthyroidism was associated with an increased risk of hip and other fractures, particularly

among those with TSH levels lower than 0.10 mIU/L and those with endogenous subclinical hyperthyroidism. Further study is needed to determine whether treating subclinical hyperthyroidism can prevent fractures.

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Participating Studies of the Thyroid Studies

Collaboration: United States: Cardiovascular Health Study; Health, Aging, and Body Composition Study; and the Osteoporotic Fractures in Men (MrOS) Study. United Kingdom: EPIC-Norfolk Study; and the Sheffield Study. United Kingdom/France/Germany: Osteoporosis and Ultrasound Study (OPUS). Norway: Nord-Trøndelag Health Study (HUNT Study). the Netherlands: Leiden 85-Plus Study; and the Rotterdam Study. the Netherlands/Ireland/Scotland: PROSPER Study. Italy: Invecchiare in Chianti (InCHIANTI) Study. Australia: Busselton Health Study. Japan: Nagasaki Adult Health Study.

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