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RESEARCH

Cost-effectiveness of opportunistic osteoporosis screening using chest radiographs with deep learning in Germany

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Abstract

Background Osteoporosis is often underdiagnosed due to limitations in traditional screening methods, leading to missed early intervention opportunities. AI-driven screening using chest radiographs could improve early detection, reduce fracture risk, and improve public health outcomes.

Aims To assess the cost-effectiveness of deep learning models (hereafter referred to as AI-driven) applied to chest radiographs for opportunistic osteoporosis screening in German women aged 50 and older.

Methods A decision tree and microsimulation Markov model were used to calculate the cost per quality-adjusted life year (QALY) gained (€2024) for screening with AI-driven chest radiographs followed by treatment, compared to no screening and treatment. Patient pathways were based on AI model accuracy and German osteoporosis guidelines. Women with a fracture risk below 5% received no treatment, those with 5–10% risk received alendronate, and women 65 + with a risk above 10% received sequential treatment starting with romosozumab. Data was validated by a German clinical expert, incorporating real-world treatment persistence, DXA follow-up rates, and treatment initiation. Sensitivity analyses assessed parameter uncertainty.

Results The cost per QALY gained from screening was €13,340, far below the typical cost-effectiveness threshold of €60,000. Optimizing follow-up, treatment initiation, and medication adherence further improved cost-effectiveness, with dominance achievable by halving medication non-persistence, and in women aged 50–64.

Conclusion AI-driven chest radiographs for opportunistic osteoporosis screening is a cost-effective strategy for German women aged 50+, with the potential to significantly improve public health outcomes, reduce fracture burdens and address healthcare disparities. Policymakers and clinicians should consider implementing this scalable and cost-effective screening strategy.

Keywords Artificial intelligence · Chest radiographs · Cost-effectiveness · Health economics · Osteoporosis · Prevention · Screening

Introduction

Osteoporotic fractures pose a significant and growing challenge to patients, healthcare systems, policymakers, and society as a whole. It is estimated that one in four men and one in two women over the age of 50 will experience an osteoporotic fracture in their lifetime [1]. These fractures, particularly those affecting the hip or vertebrae, are linked to increased morbidity, excess mortality, and a reduced quality of life. In Germany alone, approximately 831,000 fragility fractures occurred in 2019, with osteoporosis-related healthcare costs reaching €13.8 billion that same year [2]. As life expectancy rises, the burden of fragility fractures is expected to grow, placing increasing pressure on healthcare

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systems worldwide. Early identification and treatment of at-risk individuals are critical for mitigating this burden, yet osteoporosis often remains undiagnosed until a fracture occurs.

Despite the availability of effective pharmacological interventions, osteoporosis screening continues to be suboptimal. Dual-energy X-ray absorptiometry (DXA) is the standard for measuring bone mineral density (BMD), but its high cost and limited accessibility make it impractical for widespread screening. As a result, many high-risk individuals remain undiagnosed and untreated, estimated between 66% and 76% in Germany [3, 4]. These diagnostic challenges underscore the urgent need for alternative screening strategies that are cost-effective, accessible, and scalable.

Advances in artificial intelligence (AI) have opened new possibilities for opportunistic osteoporosis screening using medical imaging. Deep learning, a subset of AI, involves the use of multi-layered neural networks that can automatically learn and extract complex patterns from large datasets, such as radiographic images. Recent studies suggest that deep learning algorithms can effectively assess bone health using routinely performed radiographs [5, 6]. Since chest radiographs are among the most frequently conducted imaging procedures worldwide, utilizing these existing images for opportunistic osteoporosis screening offers a unique chance to enhance early detection rates at a population level, particularly for women over 50 who are eligible for a BMD test but remain unaware of or have not undergone DXA screening. Opportunistic screening refers to the use of existing medical data, such as chest radiographs taken for other clinical purposes, to identify individuals at risk for a condition like osteoporosis without the need for additional tests or appointments. This type of screening has the advantage of leveraging existing imaging infrastructure and reaching a broader population without the need for dedicated screening programs.

Evaluating the cost-effectiveness and long-term impact of opportunistic osteoporosis screening is essential to determine its feasibility for widespread implementation and the efficient use of healthcare resources. Therefore, this economic study assessed the cost-effectiveness of using deep learning model (hereafter referred to as AI-driven) of chest radiographs for opportunistic osteoporosis screening, followed by treatment, compared to no screening or treatment.

Materials and methods

Screening pathways and economic model

The analysis employed a two-stage economic model: a decision tree to categorize patients by fracture risk and treatment options, followed by a previously validated Markov microsimulation model [7] to estimate long-term costs and outcomes. As illustrated in Fig. 1, the decision tree compared an opportunistic screening strategy using AI-driven chest radiographs, functioning based on the tool's sensitivity and specificity, with a scenario where no screening or treatment was provided. This comparison reflects real-world settings where screening programs are unavailable, leading to a significant number of untreated individuals. To enhance realism, we assumed that a subset of patients suspected of having osteoporosis subsequently underwent a DXA scan for confirmation. In accordance with the German osteoporosis guidelines [8], patients in the model were categorized based on their 3-year fracture risk for vertebral or hip fractures as follows:

- *< 5%: No treatment recommended.* Per German guidelines, treatment may be considered for patients with a fracture risk between 3% and 5% if severe or irreversible risk factors are present or if imminent fracture risk is very high. However, as this subgroup is presumed to be minimal, we conservatively assumed no treatment below 5%.
- *5-<10%: Initiate monotherapy with alendronate (ALN) as the first-line treatment*. While German guidelines allow for osteoanabolic treatment in select cases, depending on contraindications, we assumed ALN as the primary treatment due to the small number of patients in this category.
- *> 10%: Recommend sequential treatment*, *beginning with anabolic therapy such as romosozumab (ROMO) for patients with vertebral fractures*, *followed by ALN* [9].

Additionally, treatment initiation and persistence are based on real-world estimates.

At the end of each branch of the decision tree, a Markov microsimulation model was used to track fracture events and simulate health outcomes and healthcare costs over a lifetime, up to 100 years [10–12]. The model accounted for hip, vertebral and non-hip non-vertebral (NHNV) fractures, considering the possibility of multiple fractures occurring at the same or different sites. The economic model was built using TreeAge Pro 2024 R1.0 software (TreeAge Pro Inc., Williamston, MA).

The study adhered to the guidelines for conducting and reporting economic evaluations in osteoporosis, as specified by the ESCEO-IOF [11] and the 2022 Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement [13]. The completed CHEERS 2022 checklist, along with the ESCEO-IOF checklists for reporting and designing economic evaluations in osteoporosis, can be found in

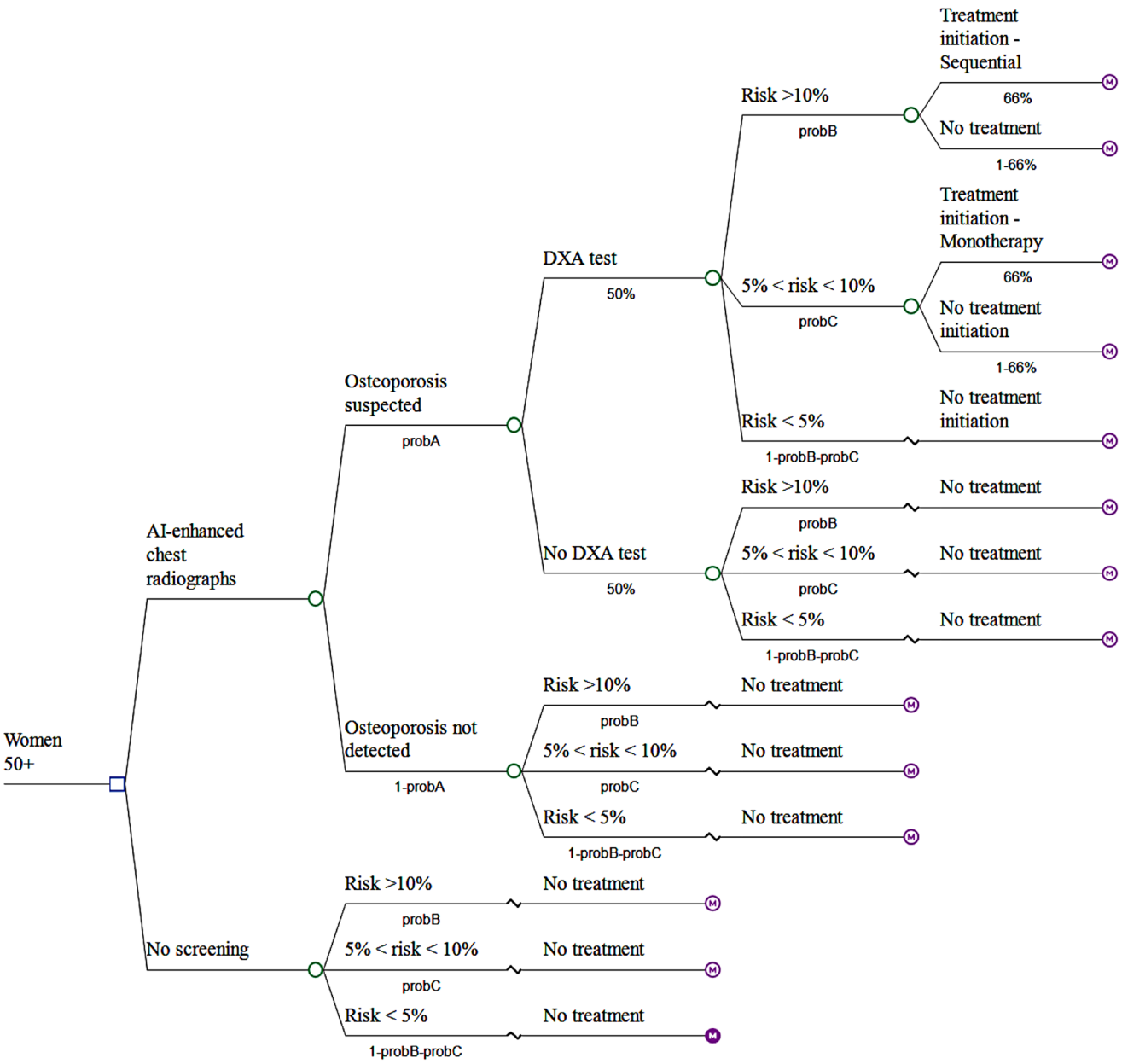

Fig. 1 Decision tree for osteoporosis screening and treatment pathways in German women aged 50 years and over

Appendix A. To verify the model's robustness, several validation steps were conducted, including a protocol review by a German clinical expert before analyses, sensitivity analyses with alternative parameters and assumptions to assess whether the direction of changes aligned with expectations. Table 1 presents the key parameters used in the model.

Population and transitions probabilities

The analyses focused on German women aged 50 years and older, segmented into 5-year age groups and their 3-year risk of hip or vertebral fractures. Based on the Study of Osteoporotic Fractures (SOF), which included 10,366 women aged over 64, 15% of participants presented a 3-year risk of hip or vertebral fracture between 5% and 10%, while 8% had a risk exceeding 10%. Consequently, 23% of women aged 65 years and over meet the German eligibility criteria for osteoporosis treatment. These estimations are used in the model for the women aged 65 years and over. This proportion closely aligns with the prevalence of osteoporosis based on BMD observed in German women aged 65 and older, estimated at 21.3% [4]. No data are currently available on the distribution of German women aged 50 to 64 years across fracture risk groups. Based on

Table 1 Key model parameters

Parameter	Data	
Mortality excess [11, 14]		
Hip (0–6 m / 7–12 m / subs. y)	4.54 (3.56–5.88)/1.76 (1.43–2.16)/1.78 (1.33–2.39)	
Vertebral (0–6 m / 7–12 m / subs. y)	4.54 (3.56–5.88)/1.76 (1.43–2.16)/1.78 (1.33–2.39)	
% attributable to Fx	25%	
Fracture costs (estimated in €2024)		
Hip	15,162	
Vertebral	11,880	
NHNV	6,746	
Health state utility values		
Baseline utility	0.860 (50-64y), 0.850 (65-74y), 0.830 (75-79y), 0.630 (80+)	
RR after hip (1st y / subs. y)	0.55 (0.53–0.57) / 0.86 (0.84–0.89)	
RR after vertebral (1st y / subs. y)	0.68 (0.65–0.70) / 0.85 (0.82–0.87)	
RR after NHNV (1st y / subs. y)	0.79 (0.65–0.93) / 0.95 (0.81–1.09)	
	ROMO	ALN
Persistence rate	80%	30% (17.5% from year 2)
Drug cost (€ per 3-month)	1,783.20	35.56
Non-drug costs		
General physician visit	35	
DXA	31.98	
Screening pathway		
Specificity and sensitivity	74.19%; 86.16%	
Cost of AI-tool	9.59	
% DXA after OP suspected	50%	
Treatment initiation after OP diagnosed	66%	

ABL abaloparatide, ALN alendronate, M Months, NHNV nonhip nonvertebral, OP osteoporosis, SUBS Subsequent, RR Relative Reduction, Y years

the differences in the prevalence of osteoporosis between the age groups 50–64 years and 65 years and older [4], we estimated that 7.41% of women aged 50–64 years would be eligible for osteoporosis treatment. All these women were classified as having a 3-year risk between 5% and 10%, as BMD alone cannot indicate a risk greater than 10% in this age group following the German guideline [8].

The baseline fracture probability of the female general population was derived from Bleiber et al. [15]. Fracture risk estimate was refined in the model to align with the risk profiles of the targeted groups. Specifically, patients with a vertebral or hip fracture risk between 5% and 10% were assigned an average risk of 7.5% over a 3-year period. For those with a risk exceeding 10%, an average risk of 12.5% is assumed for this group (other assumptions including 10% and 15% are tested in sensitivity analyses). Patients with a risk below 5% were assumed to have a risk of 1.5%. However, this assumption does not affect the incremental cost-effectiveness ratio (ICER) between interventions, as these patients did not receive treatment in either group. Fracture risk is assumed to remain constant after this 3-year period. Incidence rates were converted into probabilities within the model. An elevated risk was assumed following a fracture occurring during the simulation, with the increased risk based on the time elapsed since the initial fracture, as outlined in Soreskog et al. [16].

Mortality rates (averaged over 2021–2023) were obtained from the German Federal Statistical Office (Wiesbaden 2024). In line with prior economic studies, the model incorporated increased mortality following hip and vertebral fractures [7, 12, 17], and 25% of the excess mortality was directly attributed to the fractures themselves [18, 19].

Fracture costs and quality of life

The perspective of Statutory Health Insurance (SHI) was selected as recommended by the German guideline for economic evaluation [20]. Costs were adjusted to 2024 using the Harmonised Index of Consumer Prices (HICP) of the Federal Statistical Office. Fracture costs are derived from Bleibler et al. [15], as recently used in a German cost-effectiveness study [21], and include hospital and rehabilitation costs for hip and clinical vertebral fracture. The average hospitalization costs for wrist and humerus fractures were used for NHNV fractures. Long-term care costs of hip fractures were based on the proportion of patients entering a nursing home following hip fractures, estimated at 15% in women aged 65 years and above in the study of Rapp et al. [22]. For those aged 50–64, a 3.6% admission is assumed in line with the lower estimate in women aged 65–69 years [22]. These patients are assumed to incur the cost of institutional nursing home care (€136 per day) until death. Furthermore, it is estimated that a large proportion of patients with maximum need for help are cared for at home and not institutionally (estimated at 52% and 39% for German women aged 50–80 and over 80 years, respectively. The monthly costs for these women are estimated at €1,000. In case of multiple fractures, only the higher incremental cost of one fracture is taken into account.

Utility values for the model were derived from two sources: Marten and Greiner's reference values for the German elderly population, used for women aged 65 and over [23], and Grochtdreis et al.'s estimation of normative EQ-5D-5 L index values based on a representative German population sample [24]. The impact of fractures on utility was obtained from the International Costs and Utilities Related to Osteoporotic Fractures Study (ICUROS), the

largest study of its kind, which assessed the quality of life of 3,021 patients (86% women) with fractures across 11 countries [25].

Screening and treatment

The sensitivity and specificity of AI-driven chest radiographs to detect osteoporosis as defined by BMD T-score ≤-2.5, derived from the external validation of Jang et al. [5], are estimated at 86.16% and 74.19%, respectively, using a predefined threshold of 0.5. German expert opinion suggests that 50% of patients suspected of having osteoporosis proceed to a DXA examination and that 66% of patients initiate osteoporosis medication after receiving a positive DXA result.

ROMO was chosen as the most effective anabolic treatment in Germany for sequential therapy in women with a risk higher than 10%, with a duration of 1 year, while ALN was selected as the most common bisphosphonate therapy, used for 4 years in the sequential treatment after ROMO and 5 years in monotherapy. For consistency, the efficacy of both the ROMO/ALN sequence and ALN monotherapy was derived from the same sources (the ARCH trial and a meta-analysis) [26, 27], consistent with the recent study by Gielen et al. [28], which estimated the cost-effectiveness of sequential treatment with ROMO in Belgium (see Appendix B Table 1). The risk of gastrointestinal effects with ALN follows assumptions used in previous National Institute for Health and Care Excellence (NICE) evaluations. It is assumed that ALN-treated patients require additional GP consultations and proton-pump inhibitors during treatment cycles. In contrast, no side effects are assumed for ROMO, consistent with previous economic studies [28]. Treatment monitoring, based on expert recommendations, included four GP visits per year, each costing €35, with no additional DXA scans over the five-year treatment period. The drug costs were derived from National Statistics (AiD Klinik, Vidal MMI Germany GmbH, December 2024).

Real-world medication persistence is included in base-case. Persistence to ALN was estimated at 30% after one year, and 17.5% after two years based on the German IMS database including 90,077 receiving oral alendronate [29]. This low percentage of 17.5% is assumed to persist up to the 5-year treatment. Persistence to ROMO in real life setting has not been reported, and is assumed to be 80% during the single year of treatment in line with previous economic studies [30]. This persistence estimate has been accepted by several HTA and reimbursement bodies such as NICE. Persistence to ALN in the sequential therapy was conservatively assumed to reach 17.5% after two years in line with the German study referenced above. The costs, treatment efficacy and offset times of medications are proportional to persistence.

Simulations and sensitivity analyses

Based on 5,000,000 individual simulations, the model estimated total healthcare costs, number of fractures, life years, and quality-adjusted life years (QALYs) for both the opportunistic osteoporosis screening followed by treatment and the no screening/treatment scenarios. The primary outcome assessed was the ICER, which quantifies the additional cost required for the opportunistic osteoporosis screening to gain one extra QALY. In Germany, there is no defined cost-effectiveness threshold; however, commonly accepted thresholds are generally around €60,000 [31]. If opportunistic osteoporosis screening results in more QALYs at a lower cost, it is considered a dominant strategy.

To evaluate the robustness of the results, multiple sensitivity analyses were conducted. One-way sensitivity analyses were performed by adjusting individual parameters across both screening and non-screening pathways. Screening parameters were varied to account for uncertainty, including ± 50% adjustments for the proportion of patients undergoing DXA after osteoporosis detection, osteoporosis prevalence and treatment initiation rates. Sensitivity and specificity values from the internal test of Jang et al. [5] were also tested, along with separate analyses for women aged 50–64 and those over 65. Additional scenarios examined full medication adherence and a 50% reduction in non-persistence rates. Screening costs were varied between 10% and 50% of DXA costs, and a threshold cost analysis was conducted to determine the AI-tool cost required to achieve an ICER of €60,000. Non-screening parameters were also tested, including variations in fracture incidence (± 25%), fracture costs (± 25%), and the impact of fractures on utilities (± 25%). Other parameters varied included discount rates (0–5%), mortality following fractures (± 25%), anti-fracture efficacy (± 25%), and drug prices (± 25%).

To assess the uncertainty across model variables, a probabilistic sensitivity analysis (PSA) was conducted. In each of the 200 iterations, which included 250,000 microsimulations per iteration, random values were drawn for nearly all model variables based on their respective probability distributions (see Appendix B Table 2 for details). The PSA results were presented on a cost-effectiveness plane and through a cost-effectiveness acceptability curve, illustrating the proportion of simulations where opportunistic osteoporosis screening was deemed cost-effective at various willingness-to-pay thresholds per QALY gained.

Table 2 (Incremental) lifetime costs, QALYs, number of fractures prevented, and ICER of opportunistic osteoporosis screening using AI-driven chest radiographs vs. no screening and treatment in German women aged 50+

	Opportunistic screening	No screening and treatment	Incremental per women	Incremental per 1,000 women
Total costs	6,035	5,996	39	39,000
Healthcare costs	5,912	5,996	-84	-84,000
Treatment costs	123	0	+123	+123,000
Number of fractures	0.3172	0.3216	-0.0044	4.4
Life years	15.6117	15.6104	0.0013	1.3
Quality-adjusted life years	9.0270	9.0241	0.0029	2.9
ICER of opportunistic screening (€ per QALY gained)			**13,340**	

ICER Incremental cost-effectiveness ratio

Results

Base-case analysis

Table 2 presents the lifetime costs, number of fractures, life years, QALYs, and the ICER (expressed in € per QALY gained) of the opportunistic osteoporosis screening using AI-driven chest radiographs followed by treatment compared to no screening and treatment in German women aged 50 years and above. Under real-world conditions, per 1,000 screened women, the incremental lifetime costs were €39,000, with healthcare savings of €84,000 offset by treatment costs of €123,000. The opportunistic screening strategy resulted in the prevention of 4.4 fractures and an increase of 2.9 QALYs, yielding an ICER of €13,340 per QALY gained.

Sensitivity analyses

The sensitivity analyses confirmed the cost-effectiveness of opportunistic osteoporosis screening (Fig. 2). Medication adherence emerged as a key factor significantly influencing cost-effectiveness. Reducing medication non-persistence by 50% lead to opportunistic osteoporosis screening being associated with lower total costs (€18 per patient) and more QALY (0.048 per patient) being therefore dominant. Full

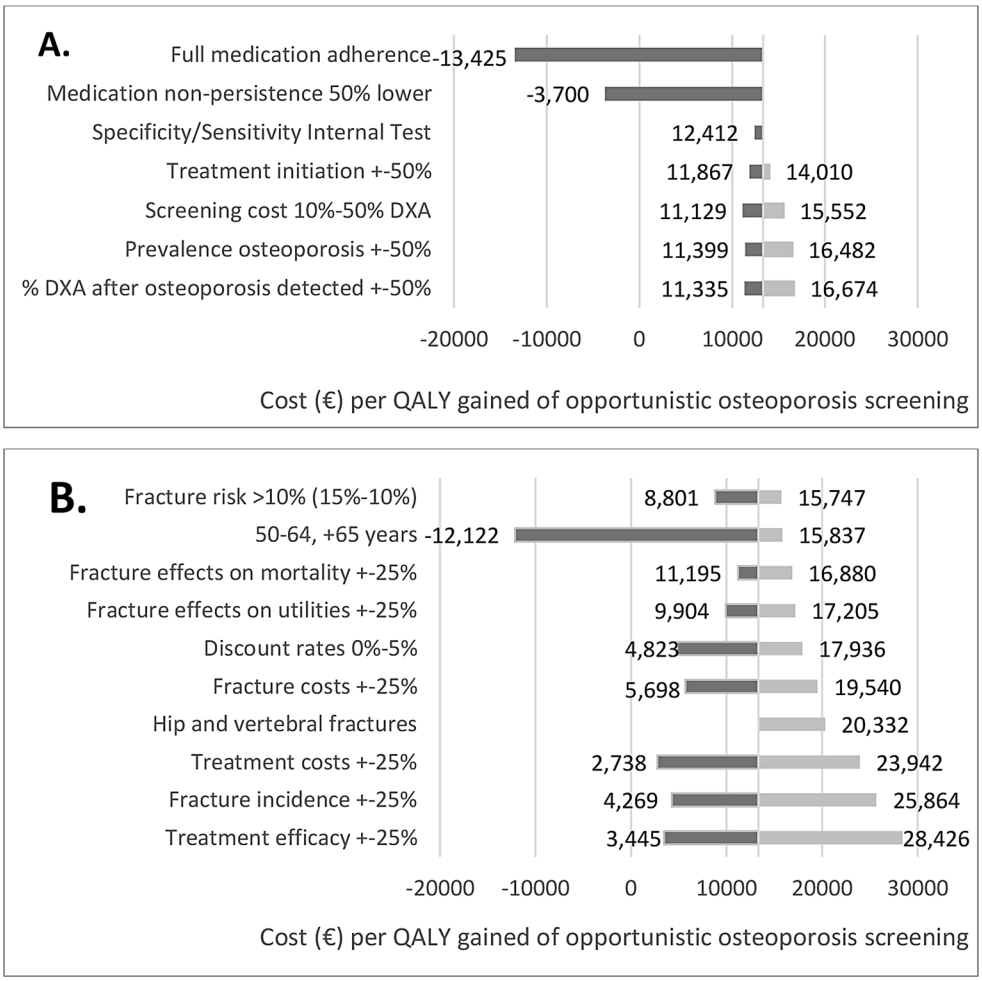

Fig. 2 Tornado diagrams depicting sensitivity analyses of cost-effectiveness (€ per QALY gained) of opportunistic screening using AI-driven chest radiographs followed by treatment vs. no screening and treatment in German women aged 50+: (**A**) screening pathway parameters and (**B**) non-screening parameters. DXA Dual-energy X-ray absorptiometry, QALY quality-adjusted life-years

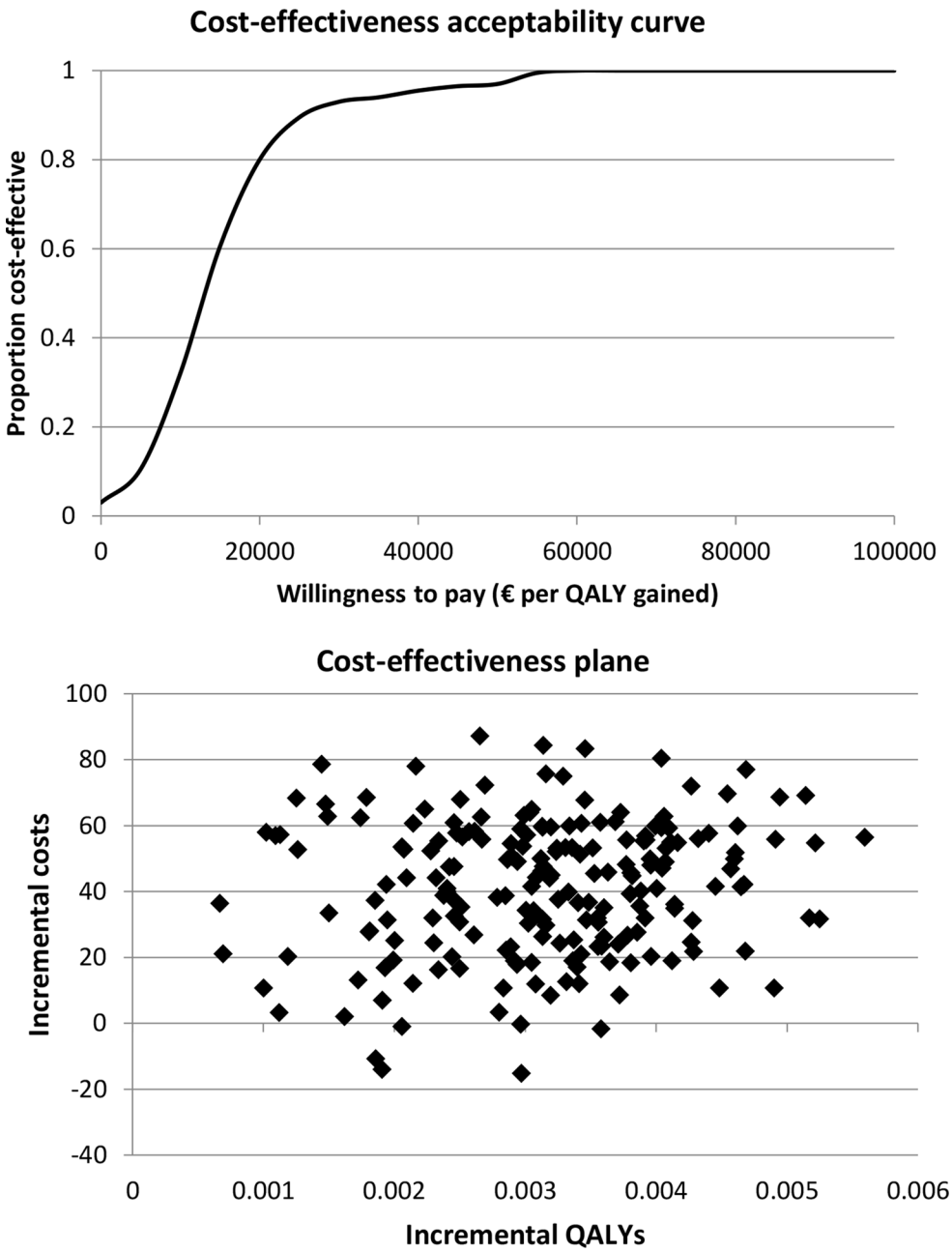

Fig. 3 Cost-effectiveness analysis of opportunistic osteoporosis screening using AI-driven chest radiographs: probabilistic sensitivity analysis results. *The cost-effectiveness acceptability curve illustrates the probability that opportunistic osteoporosis screening is cost-effective at different cost-per-QALY thresholds. It shows the proportion of simulations where the screening strategy is deemed cost-effective compared to no screening and treatment. The cost-effectiveness plane presents the incremental costs and QALYs for each simulation.* ,

medication adherence would increase the costs saving to €81 per patient, and QALY gained to 0.0061. Other screening parameters, such as higher prevalence of osteoporosis, increased rates of treatment initiation, screening costs and a greater percentage of DXA scans after osteoporosis detection, moderately enhance cost-effectiveness. an AI-screening cost of €144.15 would result in an ICER of €60,000. The use of specificity and sensitivity from the internal test had almost no impact on cost-effectiveness.

Sensitivity analyses of non-screening parameters revealed that treatment efficacy, fracture incidence, drug costs, discount rates, and fracture-related costs moderately affect cost-effectiveness. Even under conservative scenarios, the ICER remains below €30,000. Conversely, factors such as excess mortality following fractures and fracture effects on utility have a more limited impact. Interestingly, opportunistic osteoporosis screening was dominant in women aged 50–64 years, while the ICER was estimated at €15,837 in those aged 65 years and over.

Figure 3 displays the results of the PSA. As shown in the cost-effectiveness acceptability curves, opportunistic osteoporosis screening strategy has a probability of 100% to be cost-effective at the threshold of €60,000 per QALY gained confirming the robustness of the findings.

Discussion

The results of this study suggest that opportunistic osteoporosis screening using AI-driven chest radiographs, followed by treatment, is a cost-effective intervention compared to no diagnosis and treatment in German women aged 50 years. The ICER was estimated at €13,340 per QALY gained among all women aged 50 and older. Although there is no defined cost-effectiveness threshold in Germany, the ICER falls largely below the commonly accepted cost-effectiveness thresholds, which are generally in the range of €50,000–60,000.

The sensitivity analyses confirmed the robustness of the results, demonstrating that cost-effectiveness can be further improved by optimizing follow-up, treatment initiation, and medication adherence. Notably, when medication non-persistence is reduced by half, the strategy becomes dominant, yielding both lower costs and increased QALYs. This underscores the significant economic potential of opportunistic screening. Interestingly, opportunistic osteoporosis screening was found to be dominant (providing more QALYs at lower costs) in the youngest population group (women aged 50–64 years). Despite the lower prevalence of osteoporosis in this age group, the cost-effectiveness of the strategy is driven by the affordability of ALN, the first-line therapy for these individuals, and the low cost of treatment monitoring, making it a highly favorable intervention.

The cost-effectiveness of the strategy was further validated under conservative assumptions. Even in scenarios with a 25% reduction in treatment efficacy, a 25% increase in drug costs, or suboptimal screening follow-up, the ICER remained below €30,000 per QALY gained. Our economic analysis also suggests that if the cost of the AI model remains below €144.5, this approach could serve as a cost-effective osteoporosis screening tool at a willingness-to-pay threshold of €60,000 per QALY.

Given the findings of this study, it is crucial for policymakers, hospital managers and clinicians to consider incorporating AI-driven opportunistic osteoporosis screening through chest radiographs, especially in areas where osteoporosis remains underdiagnosed. The affordability and scalability of this method make it a promising strategy for enhancing public health outcomes and alleviating the burden of fractures in aging populations. Policymakers can use this evidence to advocate for reimbursement and funding of AI-based healthcare solutions, which would increase accessibility and reduce long-term healthcare expenses related to osteoporotic fractures. Moreover, AI-driven screening could play a key role in addressing healthcare disparities, particularly in underserved or resource-constrained areas. By providing a more accessible and cost-effective way to detect osteoporosis, AI tools have the potential to close gaps in diagnosis and treatment [32], particularly in populations with limited access to healthcare and DXA scanning.

The findings of this economic study should be interpreted with certain limitations in mind. Uncertainties remain regarding screening follow-up, particularly the proportion of patients identified with osteoporosis who undergo DXA and subsequently initiate treatment after a positive DXA result. As expert opinion was used for these estimates, real-world data would help refine them and enhance the accuracy of future assessments. However, multiple sensitivity analyses were conducted to address these uncertainties, consistently confirming cost-effectiveness. Importantly, the base-case analysis demonstrating cost-effectiveness was based on realistic assumptions regarding screening follow-up and medication adherence. Additionally, we accounted for the specificities of the German osteoporosis guideline, which recommends treatment based on a patient's 3-year risk of hip or vertebral fracture rather than directly on BMD. The specificity and sensitivity of the AI-tool to identifying at-risk patients were assumed to be comparable to those for detecting low BMD. Furthermore, there are uncertainties in classifying patients into risk groups under the German classification system, particularly among women aged 50–64 years. Large-scale studies aimed at refining patient risk classification and validating the tool's performance within German fracture risk groups would be valuable. Furthermore, our analysis did not include other incidental musculoskeletal findings, such as compression fractures, which AI-based screening could also detect [33]. Incorporating these findings could provide additional economic benefits by enabling earlier diagnosis and intervention for related conditions.

Furthermore, this cost-effectiveness analysis builds on the performance of the AI-enhanced screening tool reported by Jang et al. [5], which is among the few tools validated using an external dataset. While other AI-driven tools have also been developed to diagnose osteoporosis from standard radiographs [34–36], the generalizability of our economic findings does not extend to all such tools, as their clinical performance and associated costs vary, factors that directly impact cost-effectiveness outcomes. To our knowledge, this is the first economic evaluation of AI-based chest radiographs for opportunistic osteoporosis screening, underscoring the broader economic potential of AI-enabled approaches in this context. Another consideration is the lack of direct comparison with other diagnostic tools like REMS, QCT, and QUS [12, 37], which are available for early osteoporosis diagnosis and can be cost-effective in certain cases. However, making such comparisons is challenging due to differences in populations, osteoporosis severity, and methodologies. These tools are not mutually exclusive and can complement each other. AI screening using chest radiographs offers a simpler, more accessible method, utilizing

routine chest X-rays to reduce patient burden and healthcare costs without the need for additional imaging. Finally, while this study demonstrates the cost-effectiveness of opportunistic osteoporosis screening for German women aged 50 and older, these findings may not be directly generalizable to other populations such as men or other countries due to potential variations in screening practices, treatment protocols, fracture incidence rates, and drug costs [38]. Interestingly, even within a country with highly specific osteoporosis treatment guidelines, opportunistic screening exhibits strong economic potential.

In conclusion, opportunistic osteoporosis screening using AI-driven chest radiographs is a highly cost-effective strategy for German women aged 50 and older in real-world conditions. It was found to be dominant (less costs, better health outcomes) in women aged 50–64 years, primarily due to the low cost of ALN recommended for this age group, as well as when medication non-persistence was reduced by 50%. This study underscores the public health significance of AI-driven chest radiographs for opportunistic osteoporosis screening, highlighting its potential to improve early detection and address the unmet diagnostic needs in osteoporosis care.

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Author contributions Concept and design: JYR and MH; protocol review and approval: all authors; acquisition of data: JYR and MH; model analyses: JYR and MH; interpretation of data: all authors; critical revision of the paper for important intellectual content: all authors.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests JYR has received consulting fees from Promedius. RS is president of the German osteology association (DVO Dachverband Osteologie) and member of the DVO guideline committee for osteoporosis. He received consultancy funding from Alexion, Amgen, Sandoz and UCB, speeking fees from Alexion, Amgen, Blueprint, Takeda/Shire, Theramex and UCB. MA has no conflict of interest relevant to this paper. MH has received research grants (paid to institution) from Radius Health, and Angelini Pharma, lecture fees from IBSA (paid to institution) and Echolight, and was grant advisor for Pfizer (paid to institution) and consultant (paid to institution) for Grünenthal.

References

1. Beaudart C, Demonceau C, Sabico S, Veronese N, Cooper C, Harvey N et al (2023) Efficacy of osteoporosis Pharmacological treatments in men: a systematic review and meta-analysis. Aging Clin Exp Res 35(9):1789–1806
2. Borgstrom F, Karlsson L, Ortsater G, Norton N, Halbout P, Cooper C et al (2020) Fragility fractures in Europe: burden, management and opportunities. Arch Osteoporos 15(1):59
3. Kanis JA, Norton N, Harvey NC, Jacobson T, Johansson H, Lorentzon M et al (2021) SCOPE 2021: a new scorecard for osteoporosis in Europe. Arch Osteoporos 16(1):82
4. Hadji P, Esterberg E, Obermuller D, Bartsch R (2024) Bone evaluation study-2: update on the epidemiology of osteoporosis in Germany. Arch Osteoporos 19(1):26
5. Jang M, Kim M, Bae SJ, Lee SH, Koh JM, Kim N (2022) Opportunistic osteoporosis screening using chest radiographs with deep learning: development and external validation with a cohort dataset. J Bone Min Res 37(2):369–377
6. Paderno A, Ataide Gomes EJ, Gilberg L, Maerkisch L, Teodorescu B, Koc AM, Meyer M (2024) Artificial intelligence-enhanced opportunistic screening of osteoporosis in CT scan: a scoping review. Osteoporos Int 35(10):1681–1692
7. Hiligsmann M, Silverman SL, Singer AJ, Pearman L, Wang Y, Caminis J, Reginster JY (2024) Comparison of the cost-effectiveness of sequential treatment with abaloparatide in US men and women at very high risk of fractures. Aging Clin Exp Res 36(1):14
8. Pfeil A, Lange U (2024) Update DVO-Leitlinie 2023 „prophylaxe, diagnostik und therapie der osteoporose Bei postmenopausalen Frauen und Bei Männern Ab dem 50. Lebensjahr– Was Ist Neu für die rheumatologie?? [Update on the DVO Guideline 2023 Prophylaxis, diagnosis and treatment of osteoporosis in postmenopausal women and in men aged over 50-What's new for rheumatology?]. Z Rheumatol 83:401–406
9. Veronese N, Briot K, Guanabens N, Albergaria BH, Alokail M, Al-Daghri N et al (2024) Recommendations for the optimal use of bone forming agents in osteoporosis. Aging Clin Exp Res 36(1):167
10. Hiligsmann M, Reginster JY, Silverman S (2020) The value of a Patient-Level modeling approach and need for better reporting in economic evaluations of osteoporosis. J Manag Care Spec Pharm 26(3):334–335
11. Hiligsmann M, Reginster JY, Tosteson ANA, Bukata SV, Saag KG, Gold DT et al (2019) Recommendations for the conduct of economic evaluations in osteoporosis: outcomes of an experts' consensus meeting organized by the European society for clinical and economic aspects of osteoporosis, osteoarthritis and

musculoskeletal diseases (ESCEO) and the US branch of the international osteoporosis foundation. Osteoporos Int 30(1):45–57
12. Reginster JY, Silverman SL, Alokail M, Al-Daghri N, Hiligsmann M (2025) Cost-effectiveness of radiofrequency echographic multi-spectrometry for the diagnosis of osteoporosis in the united States. JBMR Plus 9(1):ziae138
13. Husereau D, Drummond M, Augustovski F, de Bekker-Grob E, Briggs AH, Carswell C et al (2022) Consolidated health economic evaluation reporting standards 2022 (CHEERS 2022) statement: updated reporting guidance for health economic evaluations. Value Health 25(1):3–9
14. Haentjens P, Magaziner J, Colon-Emeric CS, Vanderschueren D, Milisen K, Velkeniers B, Boonen S (2010) Meta-analysis: excess mortality after hip fracture among older women and men. Ann Intern Med 152(6):380–390
15. Bleibler F, Rapp K, Jaensch A, Becker C, König HH (2014) Expected lifetime numbers and costs of fractures in postmenopausal women with and without osteoporosis in Germany: a discrete event simulation model. Bmc Health Serv Res.;14
16. Soreskog E, Strom O, Spangeus A, Akesson KE, Borgstrom F, Banefelt J et al (2020) Risk of major osteoporotic fracture after first, second and third fracture in Swedish women aged 50 years and older. Bone 134:115286
17. Hiligsmann M, Williams SA, Fitzpatrick LA, Silverman SS, Weiss R, Reginster JY (2020) Cost-effectiveness of sequential treatment with abaloparatide followed by alendronate vs. alendronate monotherapy in women at increased risk of fracture: A US payer perspective. Semin Arthritis Rheum 50(3):394–400
18. Kanis JA, Oden A, Johnell O, De Laet C, Jonsson B (2004) Excess mortality after hospitalisation for vertebral fracture. Osteoporos Int 15(2):108–112
19. Kanis JA, Oden A, Johnell O, De Laet C, Jonsson B, Oglesby AK (2003) The components of excess mortality after hip fracture. Bone 32(5):468–473
20. IQWIQ General methods. Version 6.1 of 24 January 2022. Accesible at: https://www.iqwig.de/methoden/general-methods_version-6-1.pdf
21. Svedbom A, Hadji P, Hernlund E, Thoren R, McCloskey E, Stad R, Stollenwerk B (2019) Cost-effectiveness of Pharmacological fracture prevention for osteoporosis as prescribed in clinical practice in France, Germany, Italy, Spain, and the united Kingdom. Osteoporos Int 30(9):1745–1754
22. Rapp K, Rothenbacher D, Magaziner J, Becker C, Benzinger P, Konig HH et al (2015) Risk of nursing home admission after femoral fracture compared with stroke, myocardial infarction, and pneumonia. J Am Med Dir Assoc 16(8):715 e7- e12
23. Marten O, Greiner W (2021) EQ-5D-5L reference values for the German general elderly population. Health Qual Life Outcomes 19(1):76
24. Grochtdreis T, Dams J, Konig HH, Konnopka A (2019) Health-related quality of life measured with the EQ-5D-5L: Estimation of normative index values based on a representative German population sample and value set. Eur J Health Econ 20(6):933–944
25. Svedbom A, Borgstom F, Hernlund E, Strom O, Alekna V, Bianchi ML et al (2018) Quality of life for up to 18 months after low-energy hip, vertebral, and distal forearm fractures-results from the ICUROS. Osteoporos Int 29(3):557–566
26. Saag KG, Petersen J, Brandi ML, Karaplis AC, Lorentzon M, Thomas T et al (2017) Romosozumab or alendronate for fracture prevention in women with osteoporosis. N Engl J Med 377(15):1417–1427
27. Willems D, Javaid MK, Pinedo-Villanueva R, Libanati C, Yehoshua A, Charokopou M (2022) Importance of time Point-Specific indirect treatment comparisons of osteoporosis treatments: A systematic literature review and network Meta-Analyses. Clin Ther 44(1):81–97
28. Gielen E, Aldven M, Kanis JA, Borgstrom F, Senior E, Willems D (2024) Cost-effectiveness of Romosozumab for the treatment of postmenopausal women with osteoporosis at high risk of fracture in Belgium. Osteoporos Int 35(7):1173–1183
29. Hadji P, Kyvernitakis I, Kann PH, Niedhart C, Hofbauer LC, Schwarz H et al (2016) GRAND-4: the German retrospective analysis of long-term persistence in women with osteoporosis treated with bisphosphonates or denosumab. Osteoporos Int 27(10):2967–2978
30. Borgstrom F, Lorentzon M, Johansson H, Harvey NC, McCloskey E, Willems D et al (2024) Cost-effectiveness intervention thresholds for Romosozumab and teriparatide in the treatment of osteoporosis in the UK. Osteoporos Int 35(12):2183–2193
31. Ryen L, Svensson M (2015) The willingness to pay for a quality adjusted life year: A review of the empirical literature. Health Econ 24(10):1289–1301
32. Fuggle NR, Curtis B, Clynes M, Zhang J, Ward K, Javaid MK et al (2021) The treatment Gap: the missed opportunities for osteoporosis therapy. Bone 144:115833
33. Bendtsen MG, Hitz MF (2024) Opportunistic identification of vertebral compression fractures on CT scans of the chest and abdomen, using an AI algorithm, in a Real-Life setting. Calcif Tissue Int 114(5):468–479
34. Asamoto T, Takegami Y, Sato Y, Takahara S, Yamamoto N, Inagaki N et al (2024) External validation of a deep learning model for predicting bone mineral density on chest radiographs. Arch Osteoporos 19(1):15
35. Sato Y, Yamamoto N, Inagaki N, Iesaki Y, Asamoto T, Suzuki T, Takahara S (2022) Deep learning for bone mineral density and T-Score prediction from chest X-rays: A multicenter study. Biomedicines.;10(9)
36. He Y, Lin J, Zhu S, Zhu J, Xu Z (2024) Deep learning in the radiologic diagnosis of osteoporosis: a literature review. J Int Med Res 52(4):3000605241244754
37. Ruhling S, Schwarting J, Froelich MF, Loffler MT, Bodden J, Hernandez Petzsche MR et al (2023) Cost-effectiveness of opportunistic QCT-based osteoporosis screening for the prediction of incident vertebral fractures. Front Endocrinol (Lausanne) 14:1222041
38. Li N, Beaudart C, Cauley JA, Ing SW, Lane NE, Reginster JY et al (2023) Cost effectiveness analyses of interventions for osteoporosis in men: A systematic literature review. PharmacoEconomics 41(4):363–391