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Comprehensive Update on Implants in Patients With Head and Neck Cancer (2021–2024): Systematic Review and Meta-Analysis of the Impact of Radiotherapy and Chemotherapy on Implant Survival

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ABSTRACT

Objectives: This study aimed to investigate implant outcomes in patients with head and neck cancer undergoing radiotherapy or chemotherapy by incorporating the latest research findings.

Methods: The present review was conducted to update the focused question: What is the survival rate of implants placed in patients with head and neck cancer receiving radiotherapy or chemotherapy compared to non-irradiated patients? It built upon two previous systematic reviews (2014 and 2022) and provided an updated synthesis of the literature, focusing on clinical studies published between 2021 and 2024. The earlier reviews were included in the quantitative synthesis only to offer a broader longitudinal perspective.

Results: Nine studies were identified, with seven included in the quantitative synthesis and meta-analysis. The implant survival rate was significantly lower in irradiated patients (85.6%) compared to non-irradiated patients (90.0%) (RR = 1.62, 95% CI: 1.33–1.98, $p < 0.0001$, $I^2 = 0.2\%$). Additionally, implant failure risk was higher in grafted bone (RR = 2.03, 95% CI: 1.39–2.96, $p = 0.0018$, $I^2 = 21.9\%$) than in native bone. Among irradiated patients, those receiving radiochemotherapy exhibited an even greater risk of implant failure (RR = 1.97, 95% CI: 1.09–3.56, $p = 0.0331$, $I^2 = 0\%$) compared to non-irradiated patients.

Conclusions: Current evidence indicates that radiotherapy/chemotherapy significantly increases the risk of implant loss in patients with head and neck cancer, with higher radiation doses possibly being associated with increased peri-implant bone loss, while implants placed in native bone exhibit a lower risk of failure compared to those placed in grafted bone.

1 | Introduction

Advancements in technology, digital workflows, and clinical assessments have continuously enhanced dental implant treatment (Wismeijer et al. 2018). These innovations have improved the precision and predictability of implant placement and rehabilitation, even in patients undergoing head and neck cancer (HNC) therapy (Moreno Soriano et al. 2022). Recent studies provide consistent clinical evidence on the outcomes of dental implants in patients who have undergone radiotherapy

(Ettl et al. 2016) and surgery for HNC (Garner et al. 2023). Additionally, systematic reviews have highlighted the improvements in health-related quality of life associated with implant-based rehabilitation (Quadri et al. 2020).

Nowadays, intensity-modulated radiotherapy (IMRT) in HNC patients delivers radiation doses more precisely compared to traditional methods, which might reduce the incidence of treatment-related side effects on nearby tissues (Chrcanovic et al. 2010; Raj et al. 2022). Besides, studies emphasize the importance of considering cancer treatment side effects that impact implant longevity and functions (Shaw et al. 2019; Shokouhi and Cerajewska 2022). Altered anatomy after cancer treatment, coupled with the effects of radiation and chemotherapy, are potential factors influencing implant survival and the success of prosthodontic reconstruction. Research has shown that radiotherapy and chemotherapy affect bone remodeling and healing, leading to bone loss both in the short- and long-term (Neckel et al. 2021).

An early study by Kovács (2001) showed how chemotherapy did not significantly affect the survival of dental implants in HNC patients. However, a more recent study by Schiegnitz et al. (2021) reported that implants placed in irradiated grafted bone showed a statistically significant lower implant survival rate compared to those placed without radiotherapy. Regarding radiochemotherapy, Li et al. (2022) highlighted that doses over 40 Gy significantly reduced the success rate of pre-existing dental implants in comparison with lower dosages. Additionally, one review identified that the timing of implant placement and radiotherapy are crucial factors influencing implant survival (Zhang et al. 2016). Therefore, different study designs and treatments have shown varying impacts and controversies on implant survival and success in HNC patients.

The present systematic review and meta-analysis aims to incorporate the latest research findings to provide up-to-date knowledge, building on Schiegnitz et al. (2014, 2022) systematic reviews. The objective is to comprehensively assess the current state of implant treatment outcomes in patients with HNC who have undergone radiotherapy or chemotherapy.

2 | Methods

2.1 | Protocol and Patient, Intervention, Comparison, and Outcome Question

The protocol for this systematic review was designed and registered before the conduction of this review (PROSPERO: CRD42024552080) in accordance with Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines (Page et al. 2021). The focused question of the evaluation was worked out in the Patient, Intervention, Comparison, and Outcome (PICO).

This systematic review aims to synthesize and critically appraise the available evidence on the survival rate of dental implants in patients with HNC who have received radiotherapy, with or without chemotherapy, compared to non-irradiated patients, as follows:

Population (P): Patients with cancer of the head and neck region rehabilitated with dental implants.

Intervention (I): Radiotherapy with or without chemotherapy of the head and neck (before and/or after implant placement).

Comparison (C): Non-irradiated patients.

Outcome (O): Implant survival rate.

2.2 | Inclusion Criteria

The following detailed criteria had to be met:

- Studies performed on adult (over 18 years) humans and written in English or German.
- The sample size of at least 5 patients and 20 implants receiving radiotherapy with or without chemotherapy in the head and neck region (affecting the mandible, maxilla, or both) and with an edentulous area that was restored using at least 1 dental implant. Only intra-oral implants were considered.
- Articles including patients undergoing comedications or cointerventions (e.g., additional radiation, reconstructive bone grafted surgery, hyperbaric oxygen therapy) were allowed, and those procedures were specifically recorded.
- Eligible studies had to report on essential data (number of patients, number of implants placed, number of failed implants, and the period of follow-up). If subgroups (e.g., nonirradiated control) were present, the division had to be reproducible, and essential data had to be assignable to each group individually.
- The study design was a randomized controlled clinical trial, prospective cohort studies, retrospective studies, case–control studies, cross-sectional studies, or case series with more than 20 implants involved.
- If a case of osteoradionecrosis (ORN) was diagnosed, there needed to be a topological and chronological correlation between the placed implant and the occurrence of ORN.
- The mean follow-up was at least 12 months.

If a study did not meet all the criteria listed above or important information was missing and could not be provided, it was excluded from the evaluation. Another criterion for exclusion was the use of replacement implants after implant loss if they could not be excluded from the evaluation of the overall implant survival rate. If a study met all the listed criteria but lacked a comparator arm, such as in a single-arm design, it was included in the quantitative synthesis to ensure a comprehensive evaluation of the available evidence.

2.3 | Search Strategy

This research was based on two previous literature reviews (Schiegnitz et al. 2014, 2022), which evaluated articles published between January 1990 and February 2021. Electronic searches were conducted by two independent reviewers (SF

and LD), using five electronic databases: PubMed/Medline, Scopus, Ebsco, Web of Science, and Cochrane Library. The search string was created by combining MeSH terms and keywords with the Boolean operators "AND" and "OR" related to the survival of implants placed in patients with cancer treated by radiotherapy as follows: ("Dental Implants"[Mesh] OR "Dental Implants, Single-Tooth"[Mesh] OR "Dental Implantation"[Mesh] OR "Dental Implantation, Endosseous"[Mesh]) AND ("Radiotherapy"[Mesh] OR "Radiotherapy" OR "Radiation Therapy" OR "Radiation Treatment" OR "Targeted Radiotherapy" OR "Targeted Radiation Therapy") AND ("Head and Neck Neoplasms"[Mesh] OR "Mouth Neoplasms"[Mesh] OR "Head and neck cancer" OR "Oral Tumor" OR "Head Neoplasms" OR "Oral Cancer" OR "Cancer of Head" OR "Neck Neoplasms" OR "Mouth Cancer" OR "Neck Cancer"). This search included articles in English and German and was performed with date range search filters between February 1, 2021, and May 26, 2024. Search queries are available in Supplementary File S1.

2.4 | Study Selection

The titles and abstracts of the studies identified using the protocol described above were screened by two independent reviewers (SF and LD). The reviewers were blinded to each other's decisions, and full texts were assessed as required. A Cohen's κ for inter-rater agreement was conducted using Microsoft Excel 2018 (Microsoft). Inter-rater agreement was interpreted according to the categories proposed by Landis and Koch (1977). The full texts of all potentially relevant articles were read in detail to comply with eligibility criteria in duplicate. Disagreements were discussed among the authors until agreement was achieved or by the decision of a third reviewer (GSR).

2.5 | Risk of Bias

The analysis of the risk of bias was conducted using the Newcastle-Ottawa Scale (Wells et al. 2014) for studies comparing irradiated and non-irradiated patients. If the study was missing a non-irradiated control group, the risk of bias assessment was performed according to Moga et al. (2012), based on the following questions:

1. Were the cases adequately described?
2. Has the intervention been adequately described and has the relevant data been adequately collected?
3. Has the outcome been adequately described, and the corresponding data adequately collected?
4. Was follow-up long enough for outcomes to occur?

2.6 | Quantitative Synthesis

Quantitative synthesis was conducted in studies with comparable outcomes as well as in single-arm studies, using as effect estimates the risk ratios (RR) for the implant survival or the proportions, respectively. The unit of analysis was at the implant level. To account for dependency and cluster effects (Alimohamadi and Sepandi 2019; Flynn 2001) (i.e., more than 1 implant per patient), intra-class correlation coefficient (ICC) was extracted from the literature (Faggion Jr. et al. 2024) to adjust the variance according to the number of implants per patient (m) to the following equation: $\sigma^2_{\text{adj}} = \sigma^2_{\text{obs}} \times \left(\frac{1+(m-1)\cdot \text{ICC}}{m}\right)$.

A generic inverse variance random-effects meta-analytical model with Hartung–Knapp adjustment and a random intercept logistic regression model using restricted maximum likelihood (REML) and Hartung-Knapp adjustment, and a random intercept logistic regression model with a logit transformation were used for comparative studies and single-arm trials, respectively. The restricted maximum-likelihood estimator was used to estimate the τ^2. Confidence intervals of τ and τ^2 were estimated with the Q-profile method. Effect estimates were expressed as RR and Events per 100 observations and its 95% confidence interval (CI) for comparative and single-arm trials, respectively. A prediction interval was estimated according to the Hartung-Knapp method. To evaluate the existence of heterogeneity and the total proportion of variability due to between-study heterogeneity, chi-squared ($p<0.1$) and I^2 tests were used, respectively. Publication bias was investigated for each outcome by visual inspection of the asymmetries in the funnel plot, and if possible, a statistical assessment of publication bias was performed using Egger's test for funnel plot symmetry ($p<0.05$). In addition, the trim and fill method using the L-estimator was conducted to test the impact of possible publication bias as small study effects. Statistical analysis was performed using the "meta" package in R version 4.4.1 (http://www.r-project.org/index.html). The certainty of the evidence for each key outcome was assessed using the GRADE approach (https://gdt.gradepro.org/app/handbook/handbook.html) (Schünemann et al. 2013), evaluating risk of bias, inconsistency, indirectness, imprecision, and publication bias in accordance with current PRISMA and Cochrane guidelines.

3 | Results

3.1 | Paper Selection Process

The last search of all databases was conducted on May 26, 2024. 164 articles were retrieved through database searching, and 3 were retrieved through manual search. After removing duplicates ($n=82$), 85 articles were screened using title-abstract-keyword reading, leaving 26 reports eligible (substantial agreement, $\kappa=0.95$). After full-text reading and a subsequent search for relevant citations, 9 studies were included in this systematic review (100% agreement among the reviewers). Seventeen articles were excluded from the final selection for the following reasons: presenting fewer than 5 patients ($n=1$), providing insufficient information ($n=7$), not being related to the topic ($n=7$), and being included in past reviews ($n=2$). Detailed reasons for excluding articles are summarized in Supplementary File S1. The flow chart of the review process, which includes 2 systematic reviews from Schiegnitz et al. (2014, 2022), is shown in Figure 1.

Three meta-analyses were conducted, incorporating the results of previous research by Schiegnitz et al. (2014, 2022), to assess

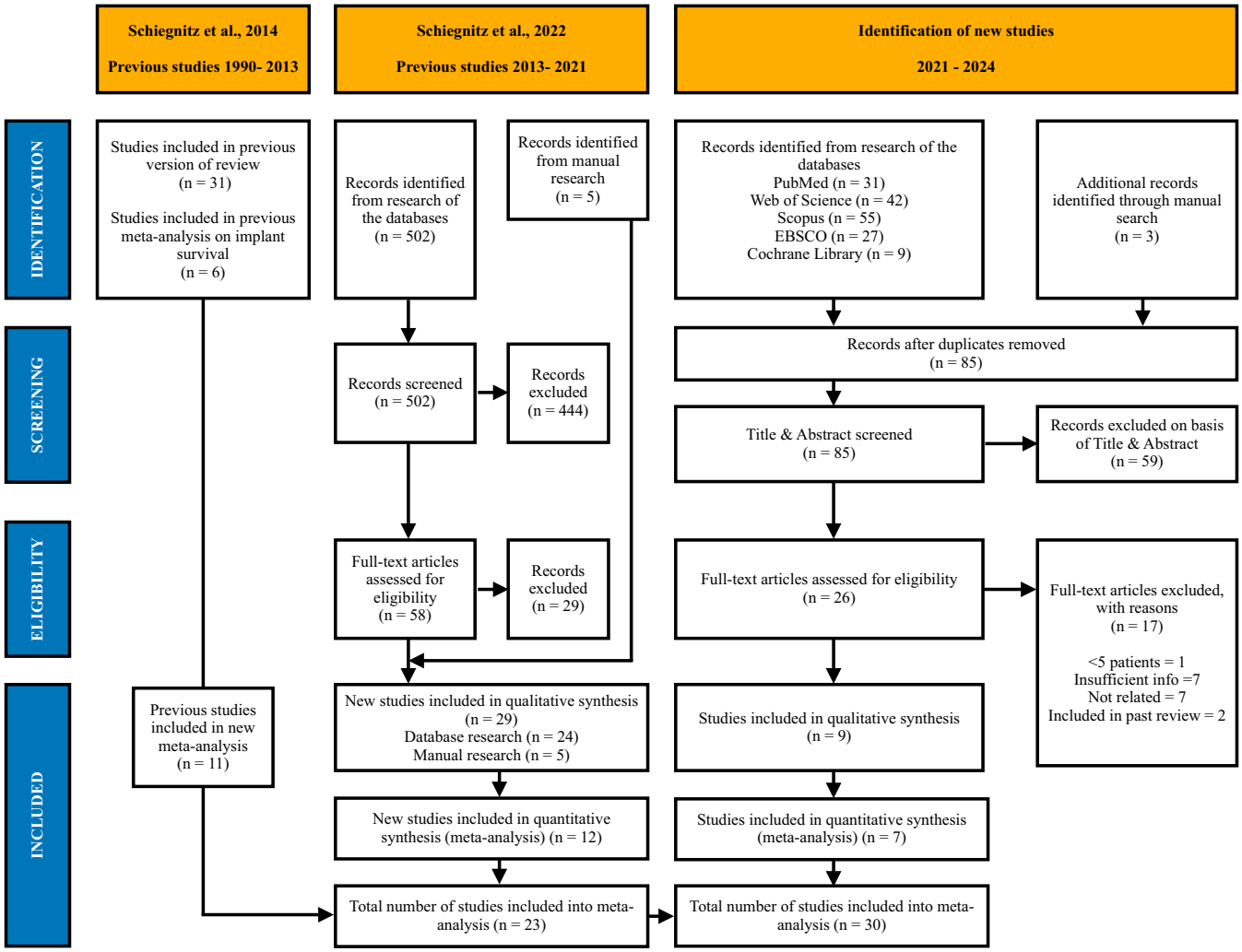

FIGURE 1 | PRISMA flow chart.

the influence of radiotherapy/chemotherapy on implant survival based on studies published from 1990 to 2021. From the present systematic review, 7 studies were included in the quantitative synthesis. Three comparative studies (Schiegnitz et al. 2021; Wüster et al. 2023; Mattila et al. 2024) were included to compare implant survival in irradiated and non-irradiated bone across 24 studies from 1990 to 2024. The same three studies (Schiegnitz et al. 2021; Wüster et al. 2023; Mattila et al. 2024) were also used to compare implant survival in irradiated native bone versus grafted bone within 12 studies from the same period. Additionally, four studies with a single-arm design reported by Alberga et al. (2023), Li et al. (2022), Lee et al. (2022), and Wolf et al. (2021) were updated for the implant survival within irradiation bone placement.

3.2 | Characteristics of the Included Studies: An Update From 2021 to 2024

A total of 9 retrospective studies, with 7 comparative analyses, were retrieved from the updated search. The main characteristics of the included studies are described in Table 1 and Supplementary File S2 according to patients, study design, implant amount, radiotherapy, chemotherapy, other risk factors, and conclusions. In total, 3357 implants in 836 HNC patients were included in this review of the literature from 2021 to 2024. Of the 9 included studies, 397 patients were treated with radiotherapy, 168 patients were treated with radiochemotherapy in 7 studies, and 265 patients without any radiotherapy or chemotherapy were included as the control group in 5 studies. Additionally, 6 patients from 1 study did not have their treatment method reported. Therefore, 1839 implants were inserted into the irradiated bone, while the non-irradiated bone received 509 implants, and 1009 implants were described as unclear. The mean follow-up period of the included studies ranged from 27.3 to 60 months.

Regarding the implanted bone type, 2 studies reported 207 implants placed in only native bone in 86 patients; 1 study reported 739 implants placed in only grafted bone in 190 patients; and 6 studies reported 2411 implants placed in both native and grafted bone in 560 patients. The types of grafted bone are described in Table 1.

Regarding the implantation timing, 219 implants were performed before the completion of radiotherapy in 3 studies with 12 implant failures. 1595 implants were performed after completion of radiotherapy in 6 studies with 117 implant failures.

TABLE 1 | The main characteristics of the included studies.

Author, year	Study type	No. patients (no. per group)	Gender	Age (range)	Mean follow-up (range)	No. failed/ total implants	No. failed/ total implants with RT, RCT, NI	No. implant in bone type (%)	Implant placement timing (P1: before RT/ RCT, P2: after RT/ RCT)	Overall survival/ SR/CSR	Cancer	Radiotherapy	Chemotherapy and hyperbaric oxygen therapy
Alberga, 2023	R	28 (22, RT; 6, RCT)	12M, 16F	68.2 (NM)	46.0 months (NM)	5/56	5/56, RCT + RT	NB, 56 (100%)	P1, 56 (between implant placement and RT/RCT was 6 weeks)	Survival: 91%	Tongue 12, floor of mouth 10, mandibular gingiva 6	The RT dose on the tumor site was 66 Gy for all the patients	NM
Khadembaschi, 2021	R	130 (72, RT; 58, NI)	77M, 77F	NB, 59 (NM) GB, 50 (NM)	38 months (3–113 months)	31/461	31/461, RCT + RT	NB, 221 (47.9%) GB, 240 (52.1%)	P2, 461	Survival: 93.2%	Cell carcinoma, ameloblastoma, keratocystic odontogenic tumor, and ameloblastoma	NM	NM, 21 patients had hyperbaric oxygen therapy
Lee, 2022	R	37 (25, RT; 12, RCT)	15M, 12F	63 (37–77)	27.3 months (1.2–128.6 months)	8/45	8/45, RCT + RT	NB, 28 (62.2%) GB, 17 (37.8%)	P2, 45	RCT + RT survival: 82.2% RCT + RT CSR: 76.9% after −3 years	Oral cavity 12, nasopharynx 14, paranasal sinus 3, parotid gland 3, oropharynx 2, mandible, 2 thyroid 1	All patients underwent RT using 3D conformal RT or IMRT. The median value for Dmean was 35.7 Gy (range 0.0–64.8)	12 patients (44.4%) received concurrent chemoradiotherapy
Li, 2022	R	58 (49, RT; 9, RCT)	38M, 20F	59 (53–68)	At least 3 years (NM)	4/151	4/151, RCT + RT	NB, 151 (100%)	P1, 151	RCT + RT survival: 97.4% RCT + RT CSR: 99.94% and 97.4% after 1 and 3 years	Sinus 7, oral cavity 38, oropharynx 3, multilevel 6	The Dmean was 40.3 Gy, (range 30.7–49.7). All patients had completed RT with a median dose of 62.4 Gy (range 62.2–67.7 Gy), 4 of which as definitive (6.9%) and 54 as adjuvant (93.1%). In addition, 16 (27.6%) patients IMRT and 42 (72.4%) received VMAT	A total of 9 patients (15.5%) received chemotherapy in addition to radiotherapy

(Continues)

TABLE 1 | (Continued)

Author, year	Study type	No. patients (no. per group)	Gender	Age (range)	Mean follow-up (range)	No. failed/ total implants	No. failed/ total implants with RT, RCT, NI	No. implant in bone type (%)	Implant placement timing (P1: before RT/ RCT, P2: after RT/ RCT)	Overall survival/ SR/CSR	Cancer	Radiotherapy	Chemotherapy and hyperbaric oxygen therapy
Mahendran, 2022	R	190 (54, RCT; 72, NI; 64, RT)	119M, 71F	66 (NM)	36 months (NM)	39/739	9/NM, RCT 2/ NM, RT 5/NM, NI	GB, 739 (100%)	P2, NM (more than 12 months) NI, NM	Survival: 95%	Oral squamous cell carcinoma 77%, ameloblastoma 13%, others 10%	All patients received between 45 and 65 Gy, with the most common protocol being 65 Gy in 30 fractions over 6 weeks	Nm
Mattila, 2024	R	59 (18, RT; 14, RCT; 27, NI)	27M, 32F	68 (44–92)	2 years and 10 months (9–82 months)	24/196	10/91, RCT + RT 11/93, NI	NB, 158 (80.6%) GB, 38 (19.4%)	P1, 12 P2, 91 (with mean time of 50 months) NI, 93	Survival: 88%	Oral cavity cancer 50, other head and neck cancer 9.	The Dmean was 61 Gy (range 50–70 Gy). RT was given to 3 nonvascularized GB, 12 vascularized GB, and 72 to NB	NM
Schiegnitz, 2021	R	164 (72, RT; 86, NI; 6, NM)	110M, 54F	67.3 (NM)	45 (0 to 227 months)	70/711	NM/366, RCT + RT NM/318, NI	NB-NI, NM (91.3%) NB, NM (94.6%) GB-NI, NM (82.2%) GB, NM (64.0%)	NM	Survival: 90.2% CSR: 97.3% and 80.0% after −5 and −10 years	Intraoral, squamous cell, and carcinoma	64 Gy in 30 fractions was delivered to the primary tumor region in the form of IMRT	No
Wolf, 2021	R	121 (62, RT; 59, RCT)	91M, 30F	65.7 (45–89)	3.8 years (0.6–18.5 years)	62/751	366/521, inside PTV 180/230, near/ outside PTV	NB, 590 (78.5%) GB, 161 (21.5%)	P2, 751 (with the mean time of 48.7 months)	RCT + RT survival: 91.7% (CSR: 96.5%, 94.8%, 92.4%, and 90.4% after 1-, 3-, 5-, and 10-year) (RCT + RT SR: 76.3%, 74.9% and 73.5% after 3-, 5-, and 10-year) (RCT SR: 74.8%; RT SR: 70)	Multi-level 16, oral cavity 66, oropharynx 27, larynx hypopharynx 8, sinus 3, parotid gland 1	All patients required RT with Dmean of 62.6 Gy (range 35–74 Gy), thereof 31 definitive (25.6%) and 90 adjuvant (74.4%). Modulating radiation techniques (IMRT, IMAT VMAT, IGRT) were used in 84 (69.4%) patients whereas 37 (30.6%) patients received conventional 2D or 3D planned RT	26 for definitive chemoradiation (44.1%), 33 for adjuvant chemoradiation (55.9%)

(Continues)

TABLE 1 | (Continued)

Author, year	Study type	No. patients (no. per group)	Gender	Age (range)	Mean follow-up (range)	No. failed/ total implants	No. failed/ total implants with RT, RCT, NI	No. implant in bone type (%)	Implant placement timing (P1: before RT/ RCT, P2: after RT/ RCT)	Overall survival/ SR/CSR	Cancer	Radiotherapy	Chemotherapy and hyperbaric oxygen therapy
Wüster, 2023	R	49 (13, RT; 14, RCT; 22, NI)	31M, 18F	63.6 (41–88)	5 years (NM)	6/247	6/149, RCT + RT 0/98, NI	NB, 214 (86.6%) GB, 33 (13.4%)	P2, 149 (more than 6 months) NI, 98	Overall CSR: 99.6% after −1, −2, and −3 years and 97.1% after −5 years	Oral squamous cell carcinoma 39, oropharyngeal squamous cell carcinoma 7, ameloblastoma 1, odontogenic keratocyst 1, and cancer of unknown primary 1	RCT was conducted over 6 weeks, with a dose of up to 50–72 Gy in fractions of 2 Gy for 5 days per week	During this time, platinum-based chemotherapy (30 mg/m^2 of body surface area) was given once weekly in weeks 1 and 6

Abbreviations: CSR, cumulative survival rate; Dmean, mean radiotherapy dose; GB, grafted bone; IGRT, Image-Guided Radiation Therapy; IMAT, Intensity-Modulated Arc Therapy; IMRT, intensity-modulated radiation therapy; NB, native bone; NI, non-irradiated; NM, not mentioned; ORN, osteoradionecrosis; PTV, planning target volume; R, retrospective; RCT, radiochemotherapy; RT, radiotherapy; SR, success rate; VMAT, volumetric-modulated arc therapy.

Furthermore, one study (Mattila et al. 2024) reported implant placement both before and after radiotherapy, and one study (Schiegnitz et al. 2021) reported the placement timing regarding primary or secondary surgery.

Five studies (Schiegnitz et al. 2021; Wolf et al. 2021; Li et al. 2022; Alberga et al. 2023; Wüster et al. 2023) reported on marginal bone loss over different periods using various examination tools. Due to the diverse study designs and examination methods, quantitative synthesis of marginal bone loss could not be performed. Instead, descriptive statistics were pooled to report the data, as shown in Table 2. Regarding the report of ORN, 3 studies (Wolf et al. 2021; Lee et al. 2022; Mahendran et al. 2022) reported a total of 21 ORN events occurring around implant sites.

Regarding the studies that reported on radiochemotherapy/chemotherapy as an individual group, a total of 8 studies from Schiegnitz et al. (2014, 2022) were included, consisting of 7 retrospective designs (Doll et al. 2014; Hessling et al. 2015; Kovács 2001; Laverty et al. 2019; Linsen et al. 2012; Wolf et al. 2021; Yerit et al. 2006) and 1 prospective design (Nack et al. 2015). However, no study was found within the period from 2021 to 2024. All included studies were observational designs; the main characteristics of these studies are detailed in Table 3 and Supplementary File S3. A total of 3413 implants were analyzed: 1392 implants were placed in patients undergoing radiochemotherapy, 106 in patients receiving chemotherapy, 1114 in non-irradiated patients (control group), and 801 in patients treated with radiotherapy or without specific treatment details. Five studies with a comparative design (Doll et al. 2014; Hessling et al. 2015; Laverty et al. 2019; Linsen et al. 2012; Yerit et al. 2006) involving radiochemotherapy and a non-irradiated control group were included in the meta-analysis. However, 1 study by Kovács (2001), which reported implant survival in patients treated only with chemotherapy, was excluded from the meta-analysis.

3.3 | Risk of Bias

For studies comparing the outcome of implants in irradiated and non-irradiated bone, the Newcastle-Ottawa scale was used to assess the risk of bias, and for studies without a non-irradiated control group, using the questionnaire described by Moga et al. (2012). The studies from the 2 previous reviews (Schiegnitz et al. 2014, 2022) that included a control group were considered to be of "good quality" in 67.7% of cases. For the studies that did not include the control group, 87.5% completed affirmatively at least 3 of the 4 questions associated with the quality of selection, intervention, outcomes, and follow-up. For the updated studies included in the present review, 80.0% of those evaluated on the basis of the Newcastle-Ottawa Scale presented "good quality" and of those evaluated in relation to the questions of Moga et al. (2012), 100.0% completed affirmatively at least 3 of the 4 questions associated with the quality of selection, intervention, outcomes, and follow-up.

The risk of bias for the new studies included in the present systematic review, from February 2021 to May 2024, is shown in Table 4. The risk of bias for the studies included in the previous review is presented in Supplementary File S1.

3.4 | Meta-Analysis of Implant Survival Rates and Failure Prevalence in Irradiated Bone From Single-Arm Trials: An Update From 2021 to 2024

For the update from 2021 to 2024, the mean implant survival rate in single-arm trials was 91.14%. A total of 903 implants were evaluated across 4 single-arm studies, with 80 implant failures reported (Figure 2). The studies included in the analysis were conducted by Alberga et al. (2023), Li et al. (2022), Lee et al. (2022), and Wolf et al. (2021). The prevalence of implant failure on irradiated bone varied among the studies, with reported failure rates ranging from 7.84% to 17.78%. The heterogeneity of the studies was low ($\tau^2 = 0$; $\chi^2 = 4.45$, $p = 0.22$; df = 3, $I^2 = 33\%$), indicating a moderate level of variability among the study results.

3.5 | Meta-Analysis of Implant Survival in the Irradiated Jaw Versus Implant Survival in the Non-Irradiated Jaw: A Comprehensive Update

All included studies were observational design with comparison groups. For the comparison group, all included non-irradiated patients who had a history of HNC; however, the implants were placed in non-irradiated bone. The overall survival rate for implants in irradiated patients was 85.6%, while the survival rate for non-irradiated patients was significantly higher at around 90.0% (Figure 3). There was moderate heterogeneity between the studies within these subgroups, with heterogeneity metrics of $\tau^2 = 0.0385$, $\chi^2 = 23.05$, df = 23, $p = 0.4577$, and $I^2 = 0.2\%$. Therefore, the general survival rate of implants in irradiated patients was lower compared to non-irradiated patients, with a significant ($p < 0.0001$) overall RR of 1.62 (95% CI: 1.33–1.98) for implant failure in irradiated patients. Even though the visual assessment of the funnel plot indicated asymmetry, Egger's test (p-value = 0.0543) did not find strong evidence of publication bias (Figure 4). Nevertheless, after conducting a trim-and-fill adjustment for visual funnel plot asymmetry, 7 hypothetical studies were added, increasing the observed cases to 9314 (irradiated = 4775, non-irradiated = 4539) with a total of 1089 events, the adjusted effect estimates slightly decreased to a relative risk (RR) of 1.40 (95% CI: 1.118–1.77, $p < 0.01$), and a prediction interval of 0.78 to 2.51. Notably, heterogeneity slightly increased to 23.3% ($p = 0.012$).

3.6 | Meta-Analysis of Influence of Bone Origin and Irradiation on Implant Survival: A Comprehensive Update

The comparison of implant survival rates in irradiated patients with native bone versus grafted bone revealed a higher risk of failure in grafted bone (Figure 5). The meta-analysis revealed a significantly higher RR for implant failure in grafted bone compared to native bone, with a RR of 2.03 (95% CI: 1.39–2.96, $p = 0.0018$) and heterogeneity metrics of $\tau^2 = 0.138$, $\chi^2 = 14.09$, df = 11, $p = 0.2282$ and $I^2 = 21.9\%$. The visual assessment of the funnel plot indicated slight asymmetry. However, statistical analysis using Egger's test (p-value = 0.5414) did not show significant evidence of publication bias in the included studies (Figure 6). Nevertheless, after conducting a trim-and-fill adjustment for visual funnel plot asymmetry, 3 hypothetical studies were added, increasing the observed cases to 2901 (grafted bone = 741, native bone = 2160) with a total of 485 events. The adjusted effect estimate slightly decreased to a RR of 1.67 (95% CI: 1.09–2.581, $p = 0.03$) with a prediction interval of 0.43 to 6.53. Notably, heterogeneity increased to 47.4% ($p = 0.02$). However, due to the non-standardized descriptions provided by the studies, a meta-analysis could not be performed to further distinguish between subgroups of vascularized and non-vascularized bone flaps from different bone origins.

3.7 | Meta-Analysis of the Influence of Implant Survival in Patients With Radiochemotherapy Versus Non-Irradiated Patients: A Comprehensive Update

The comparison of implant survival rates in patients with radiochemotherapy with non-irradiated patients reveals a higher risk of failure in the group of radiochemotherapy (Figure 7). The meta-analysis revealed a significantly higher RR for implant failure in radiochemotherapy compared to non-irradiated patients, with a RR of 1.97 (95% CI: 1.09–3.56, $p = 0.0331$) and heterogeneity metrics of $\tau^2 = 0$, $\chi^2 = 2.77$, df = 4, $p = 0.5962$, and $I^2 = 0\%$. The visual assessment of the funnel plot showed slight asymmetry. Statistical analysis using Egger's test (p-value = 0.1245) did not show significant evidence of publication bias in the included studies (Figure 8). Nevertheless, after conducting a trim-and-fill adjustment for visual funnel plot asymmetry, 2 hypothetical studies were added, increasing the observed cases to 2441 (radiochemotherapy = 1248, non-irradiated = 1193) with a total of 177 events; the adjusted effect estimated slightly decreased to a RR of 1.75 (95% CI: 0.981–3.12, $p = 0.055$) and a prediction interval of 0.96 to 3.19. Notably, heterogeneity tests remain stable ($I^2 = 0\%$, $p = 0.5$).

3.8 | GRADE Assessment of Evidence Quality

The certainty of evidence for all key outcomes was rated as moderate. This includes implant survival in irradiated versus non-irradiated patients, implant failure in grafted versus native bone, and implant failure in radiochemotherapy-treated versus non-irradiated patients. Downgrades were primarily due to the risk of bias. Detailed results are summarized in Table 5.

4 | Discussion

Studies have reported that dental implants can achieve osseointegration and maintain functional stability over extended periods in both healthy individuals and those with medical conditions, including patients who have undergone HNC therapy (Chappuis et al. 2018; Duttenhoefer et al. 2019; Schimmel et al. 2018). Radiotherapy, either as a standalone definitive therapy or following surgery, is commonly used, with concomitant chemotherapy being the most widely used regimen across all tumor sites. Implant-based rehabilitation represents a viable option for HNC patients following radiotherapy treatment (Schiegnitz et al. 2014, 2022). An updated review of the impact of radiotherapy on implant survival in HNC patients is essential for improving clinical outcomes and guiding evidence-based

TABLE 2 | The characteristics of studies reporting implant bone loss.

Author, year	Examination method	Observation	1 year bone loss (mm)	3 year bone loss (mm)	5 year bone loss (mm)
Schiegnitz, 2021	Orthopantomogram or intraoral radiographs	Mean marginal bone loss was 0.98 ± 1 mm (range 0 to 6.5 mm)	/	/	/
Wolf, 2021	Panoramic radiographs	Increased marginal bone resorption (20.9%) was the most common reason for implant failure followed by implant not in situ or unloaded (9.6%) and peri-implantitisn (7.5%)	Mesial: 0.39 Distal: 0.44	Mesial: 0.82 Distal: 0.80	Mesial: 1.12 Distal: 1.01
Li, 2022	CT images	RT negatively worsens peri-implant bone resorption	Mesial: 0.38 Distal: 0.43 Buccal: 0.17 Lingual: 0.29	1.14 mm mesial side, 1.14 mm distal side, 1.20 mm buccal side, and 0.35 mm lingual side	Mesial: 1.14 Distal: 1.14 Buccal: 1.20 Lingual: 0.35
Alberga, 2023	Panoramic radiographs	Radiographic peri-implant bone loss occurred when the implants were exposed to a Dmean above 40 Gy. The peri-implant bone loss had increased to 1.3 mm (range 0–5.8) mesially and 1.5 mm (range 0–5.5) distally of the implants	Mesial: 0.7 (range 0–4.7) Distal: 0.6 mm (range 0–4.0)	/	/
Wüster, 2023	NM	Radiation caused a significant change in mesial bone loss after 3 years ($p = 0.04$). Significantly higher mesial and distal bone loss in the maxilla compared to the mandible (mesial: $p = 0.04$; distal: $p = 0.003$)	NB (214 implants) and FFF bone flaps (33 implants): The groups showed no significant differences after 1 year	A significantly lower bone loss after 3 years (mesial and distal; $p = 0.047$) was observed in implants inserted in the FFF	A significantly lower bone loss after 5 years (mesial: $p = 0.05$; distal: $p = 0.44$) was observed in implants inserted in the FFF

Abbreviations: Dmean, mean radiotherapy dose; FFF, fibula free flap; NB, native bone; NM, not mentioned.

TABLE 3 | The main characteristics of studies reported on radiochemotherapy/chemotherapy as an individual group.

Author, year	Implant survival rate (%)	Radiotherapy	Chemotherapy	Hyperbaric oxygen therapy
Doll et al. 2014	Overall 92.2% (RCT: 89.7%; NI: 93.5%) (the cumulative survival rate was 94.9% at 3 years and 92.5% at 7 years and 11 years with 90.8%)	The radiation therapy was delivered up to a dose of 50–72 Gy in fractions of 2 Gy over 6 weeks (5 days/week)	Platinum-based CH was given weekly (30 mg/m^2 body surface area)	NM
Hessling et al. 2015	Overall 96.3% (RCT: 95.5%; NI: 100%)	Neoadjuvant 40 Gy (21 patients) Adjuvant 61–66 Gy (28 patients)	NM	NM
Kovács 2001	99% (CH); 98% (NI)	Not applied	Carboplatin +5- fl uorouracil (15 patients) and cisplatin +5- fl uorouracil (15 patients)	Not applied
Laverty, 2019	Overall 95.7% (RCT: 92.3%; NI: 96.8%; RT: 96.1%)	The radiation dose for therapeutic RT ranged from 50 to 70 Gy in 72 patients. 2 patients received palliative RT at 30 Gy with one of these patients stopping at a 7.5-Gy dose due to radiation-related complications and one patient received a higher dose of 88 Gy	Carboplatin, cisplatin, cetuximab, MAP chemo, R-CHOP, TPF, carboplatin, and paclitaxel	NM
Linsen, 2012	Overall 86.9% (10-year) (RCT, 91.5%; RT, 95.6%; NI, 84.7%)	Dose of 36 or 60 Gy	NM	Not applied
Nack et al. 2015	RCT 79.4%	The radiation therapy was delivered up to a dose of 50–72 Gy in fractions of 2 Gy over 6 weeks	Platin-based CH was given weekly (30 mg/m^2 body surface area)	Not applied
Wolf, 2021	RCT success: 74.8% (317/424)	Dmean of 62.6 Gy (range 35–74 Gy), thereof 31 definitive (25.6%) and 90 adjuvant (74.4%)	26 for definitive chemoradiation (44.1%), 33 for adjuvant chemoradiation (55.9%)	NM
Yerit, 2006	Overall 86% (RCT, 81.0%; NI, 98.1%)	All patients underwent the same radiation therapy with a total of 50 Gy	CH with mitomycin C and 5-fluorouracil	Not applied

Abbreviations: CH, chemotherapy; NI, non-irradiated; NM, not mentioned; ORN, osteoradionecrosis; R, retrospective; RCT, radiochemotherapy; RT, radiotherapy.

TABLE 4 | The risk of bias.

Newcastle-Ottawa Scale

	Selection (max. 4*)				Comparability (max. 2*)	Outcome (max. 3*)			Total
Study	**Representativeness of exposed cohort**	**Selection of the non-exposed cohort**	**Ascertainment of exposure**	**Demonstration that outcome of interest was not present at start of study**	**Comparability of cohorts on the basis of the design or analysis controlled for confounders**	**Assessment of outcome**	**Was follow-up long enough for outcomes to occur**	**Adequacy of follow-up of cohorts**	**Total number of stars, quality of study**
Mattila et al. (2024)	*	*	*	*	*	*	*	*	8, good
Wüster et al. (2023)	*	*	*	*	0	*	*	*	7, poor
Mahendran et al. (2022)	*	*	*	*	*	*	*	*	8, good
Schiegnitz et al. (2021)	*	*	*	*	*	*	*	*	8, good
Khadembaschi et al. (2021)	*	*	*	*	*	*	*	*	8, good

Evaluation according to Moga et al. (2012)

Study	**Were the cases adequately described?**	**Has the intervention been adequately described and has the relevant data been adequately collected?**	**Has the outcome been adequately described, and the corresponding data adequately collected?**	**Was follow-up long enough for outcomes to occur?**	**Total**
Alberga et al. (2023)	Yes	Yes	Yes	Yes	****
Li et al. (2022)	Yes	Yes	Yes	Yes	****
Lee et al. (2022)	Yes	Yes	Yes	No	***
Wolf et al. (2021)	Yes	Yes	Yes	No	***

Note: Each * represents 1 point awarded when a study satisfies a specific criterion within a domain.

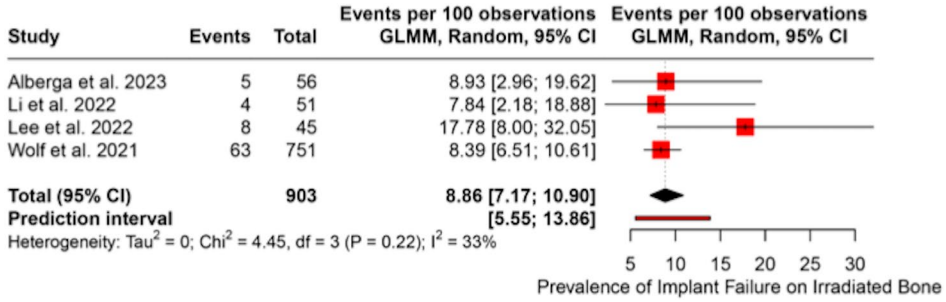

FIGURE 2 | Forest plot of the prevalence of implant failure on irradiated bone from single-arm trials.

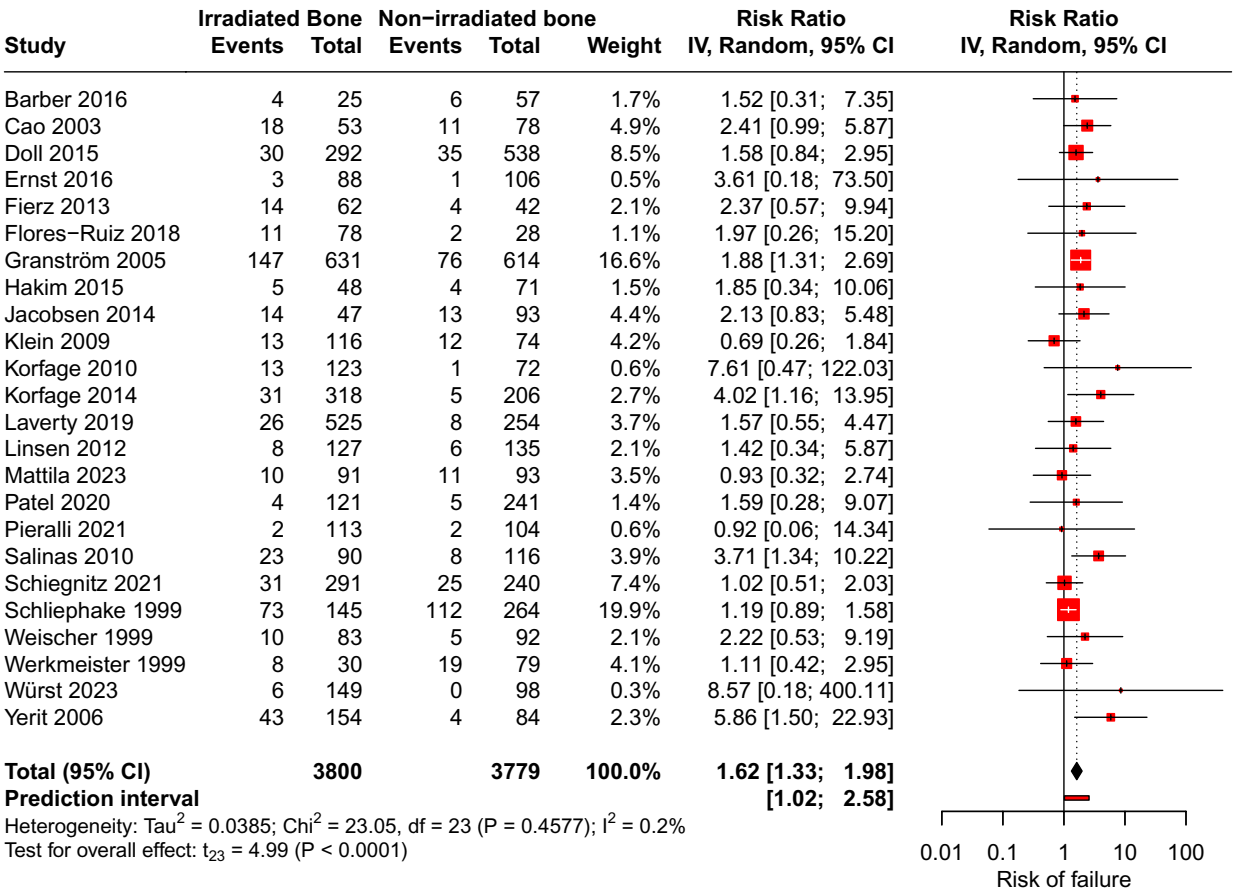

FIGURE 3 | Forest plot of the risk of implant failure in irradiated patients compared to non-irradiated patients.

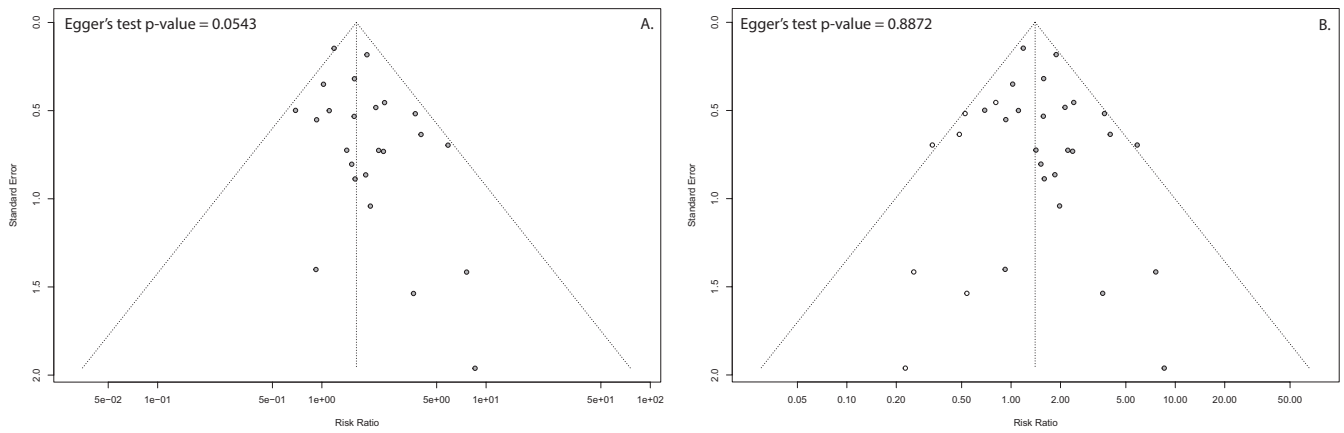

FIGURE 4 | Funnel plot of the meta-analysis of the risk of implant failure in irradiated compared to non-irradiated patients. (A) Baseline meta-analysis; (B) trim-and-fill method.

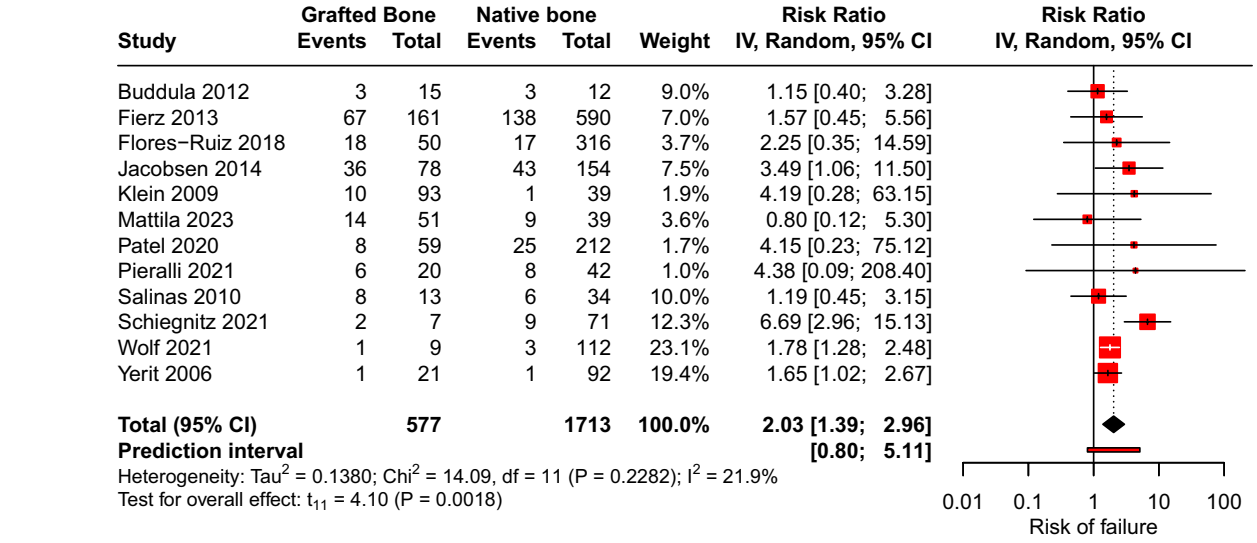

FIGURE 5 | Forest plot of the risk of failure in irradiated patients comparing grafted bone to native bone.

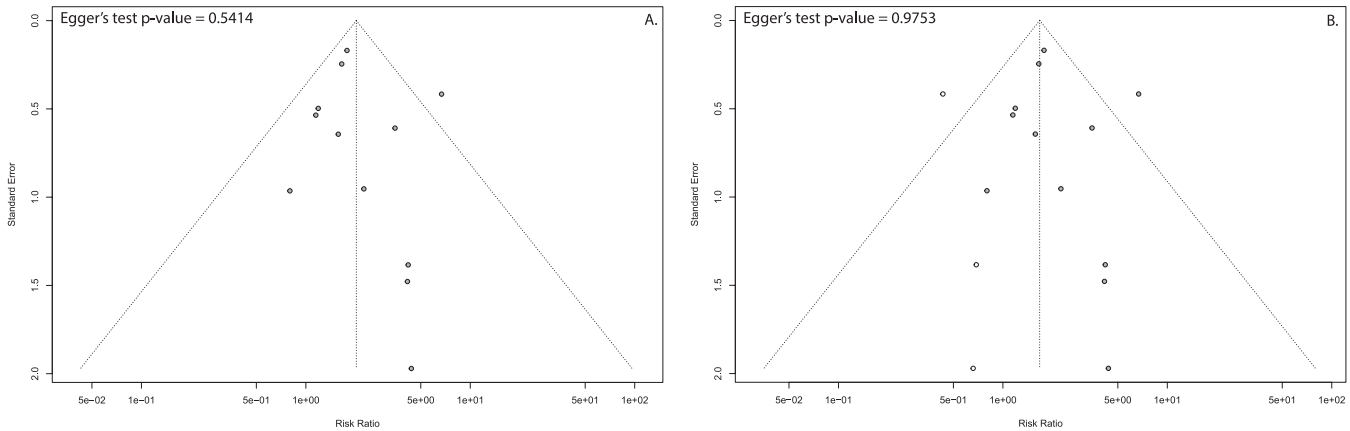

FIGURE 6 | Funnel plot of the risk of failure in irradiated patients comparing grafted bone to native bone. (A) Baseline meta-analysis; (B) trim-and-fill method.

practices. The present study reviewed the current status of this topic, revealing that overall implant survival in HNC patients receiving radiotherapy or radiochemotherapy is high; however, radiotherapy and radiochemotherapy should still be considered risk factors for implant loss.

Regarding the impact of radiation dose on dental implant survival, a consistent pattern emerges regarding the detrimental effects of high-dose radiation in 3 studies (Alberga et al. 2023; Lee et al. 2022; Wolf et al. 2021). Lee et al. (2022) identified that radiation doses exceeding 40 Gy were associated with significantly decreased implant success. Similarly, Alberga et al. (2023) found that implants exposed to doses greater than 40 Gy had a higher risk of failure, with doses above 50 Gy correlating with increased peri-implant bone loss and implant loss. Wolf et al. (2021) found that higher site-specific radiation doses were associated with increased implant failure rates and higher incidences of sinusitis. Specifically, patients who received radiation doses greater than 60 Gy had a significantly higher rate of implant failure. Despite some variations, the threshold radiation dose above which implant survival decreases significantly was consistently found to be around 40–60 Gy across the studies, each of which emphasized the importance of managing radiation exposure to improve implant outcomes in HNC patients. These results are in agreement with a recent systematic review (Sriram et al. 2024) indicating that pooled survival rates for implants receiving > 60 Gy were significantly lower than implants receiving < 60 Gy (82.8% vs. 90.1%, $p = 0.035$) in the fibula-free flap. The present study aimed to explore the potential value of a dose–response meta-analysis with methodological precision. However, the included studies demonstrate substantial variability in radiotherapy modalities and inconsistencies in reporting radiotherapy doses, leading to significant heterogeneity. Future research should prioritize standardized reporting of radiation exposure and implant site-specific doses to enhance the reliability and clinical applicability of dose–response analyses.

Across the 5 included studies evaluating, a consistent pattern emerged regarding the survival rates of implants placed in grafted bone versus native bone (Khadembaschi et al. 2021; Lee et al. 2022; Mattila et al. 2024; Schiegnitz et al. 2021; Wüster et al. 2023). Two out of these, Khadembaschi et al. (2021) and

Schiegnitz et al. (2021) reported significantly lower survival rates for implants in grafted bone, emphasizing the negative impact of radiotherapy. Similarly, Wüster et al. (2023) and Lee et al. (2022) found that implants in the grafted bone had poorer outcomes, with radiation dose and chemotherapy identified as additional risk factors. Regarding soft tissue, Mattila et al. (2024) highlighted that mucosal overgrowth is a more common issue in grafted areas, leading to implant failure. Wüster et al. (2023) pointed out that patients who underwent vestibuloplasty showed a 100% cumulative survival rate with significantly lower peri-implant bone resorption compared to those who did not undergo the procedure. Similar results were reported by Khadembaschi et al. (2021), with significantly lower peri-implant bone resorption rates and a cumulative implant survival rate of 100% after 5 years for patients with vestibuloplasty, compared to 93.1% for those without it. The present meta-analysis indicates that implants placed in grafted bone have a higher failure risk than those in native bone (RR = 2.03, 95% CI: 1.39–2.96, $p = 0.0018$). Due to non-standardized reporting and high heterogeneity ($I^2 = 47.4\%$), further subgroup analysis on vascularized versus non-vascularized bone was not feasible.

Bone loss adversely affects implant survival and overall treatment success (Albrektsson et al. 1986). Seven studies consistently showed that higher radiation doses, particularly those exceeding 40 Gy, were significantly associated with increased peri-implant bone loss in HNC patients (Alberga et al. 2023; Lee et al. 2022; Li et al. 2022; Mattila et al. 2024; Schiegnitz

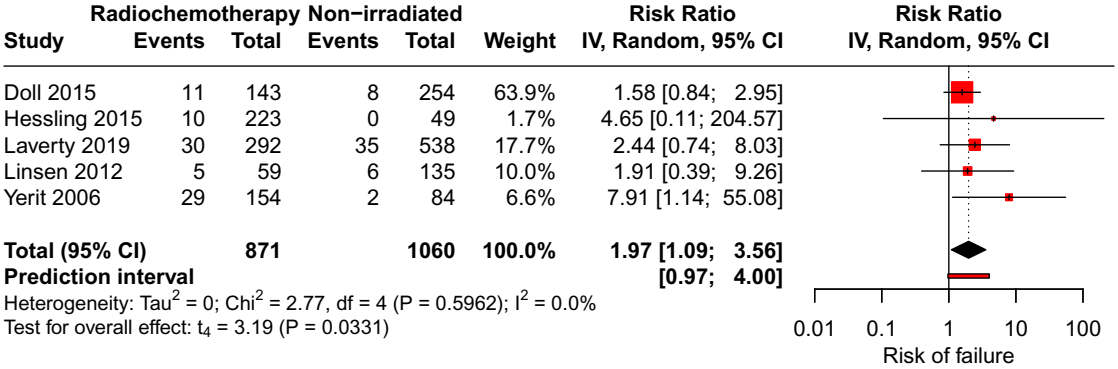

FIGURE 7 | Forest plot of the risk of implant failure in patients treated with radiochemotherapy compared to non-irradiated patients.

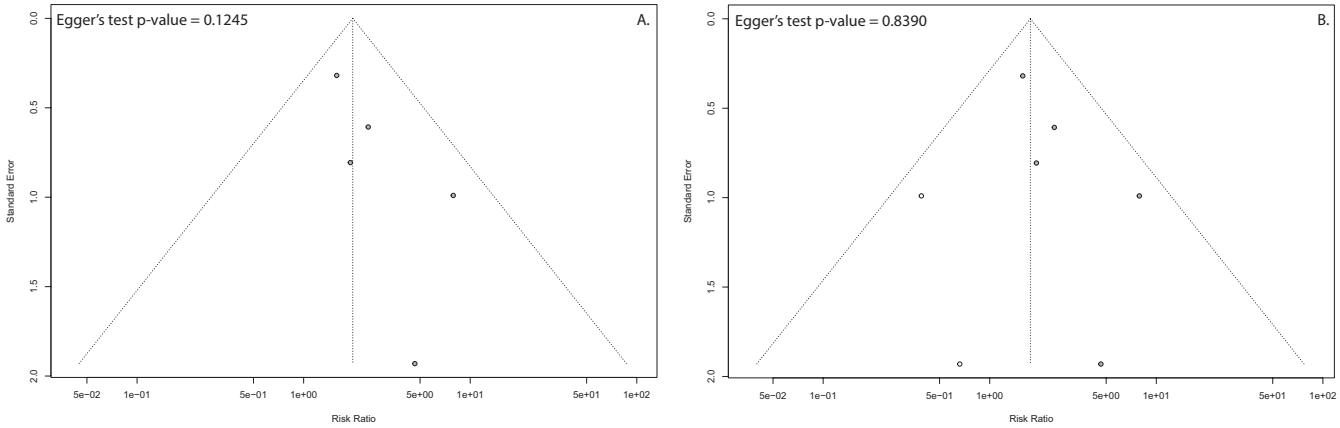

FIGURE 8 | Funnel plot of the risk of failure in patients treated with radiochemotherapy. (A) Baseline meta-analysis; (B) trim-and-fill method.

TABLE 5 | GRADE assessment of evidence quality.

Outcomes	Studies (*n*)	Implants (*n*)	Relative risk (95% CI)	Heterogeneity (I^2)	GRADE certainty
Irradiated bone vs. non-irradiated bone	24	7579 (3800 irradiated, 3779 non-irradiated)	RR = 1.62 (1.33–1.98)	0.2%	Moderate
Grafted bone vs. native bone	12	2290 (577 grafted, 1713 native)	RR = 2.03 (1.39–2.96)	21.9%	Moderate
Radiochemotherapy vs. non-irradiated	5	1931 (871 radiochemotherapy, 1060 non-irradiated)	RR = 1.97 (1.09–3.56)	0%	Moderate

et al. 2021; Wolf et al. 2021; Wüster et al. 2023). Li et al. (2022) reported substantial peri-implant bone resorption, with average bone losses of up to 1.5 mm after 3 years. Alberga et al. (2023) and Wolf et al. (2021) also noted that higher site-specific radiation doses led to increased bone loss. Schiegnitz et al. (2021) highlighted that irradiated patients experienced greater bone loss, which negatively affected implant survival. Wüster et al. (2023) found that radiochemotherapy exacerbated peri-implant mesial bone loss after 3 years compared to radiotherapy alone, which stresses the detrimental effects of combined treatments. For implant survival, the present meta-analysis emphasizes the significant impact of radiation on implant survival, confirming a higher failure risk in irradiated bone (RR = 1.62, 95% CI: 1.33–1.98, $p < 0.0001$) with strong consistency across studies ($I^2 = 0.2\%$).

The opinions on the timing of implant placement in HNC patients generally vary (Koudougou et al. 2020). The findings from the included studies indicate that the optimal timing for implant placement might be either before the onset of radiotherapy or during ablative surgery. Li et al. (2022) and Mahendran et al. (2022) emphasized reduced complications and better initial osseointegration with pre-radiotherapy placement. Alberga et al. (2023) and Wolf et al. (2021) noted the benefits of simultaneous placement with ablative surgery, citing improved oral function and osseointegration before radiotherapy begins. Similarly, Schiegnitz et al. (2021) observed that implants placed during ablative surgery showed slightly higher survival rates compared to those placed after oncological treatments. Additionally, Wüster et al. (2023) reported high cumulative survival rates of 99.1% after 1 year and 93.1% after 5 years, demonstrating the feasibility of immediate placement under specific conditions. These results align with previous studies (In't Veld et al. 2021; Panchal et al. 2020; Schepers et al. 2006), which also found that immediate implant placement offers the benefit of implant healing and osseointegration in non-irradiated bone. On the other hand, Mattila et al. (2024) suggested that implant survival is less affected by timing but recognized higher complication risks with early placements. Regarding a current systematic review by Pitorro et al. (2022), the survival rates of implants were described as follows: 89.4% to 97% for pre-radiotherapy, 80% to 100% for post-radiotherapy, and 92.2% to 100% for non-irradiated patients. The optimal timing for implant placement in HNC patients remains inconclusive based on the current data. Future research should aim to improve the understanding of implant placement timing.

The use of IMRT is highlighted in several studies for its benefits in HNC patients undergoing implant procedures (Chrcanovic et al. 2010; Raj et al. 2022). Li et al. (2022) noted reduced peri-implant bone loss and lower peri-implant inflammation with IMRT. Schiegnitz et al. (2021) and Wüster et al. (2023) found that IMRT, along with volume-modulated arc therapy (VMAT), resulted in better peri-implant health and higher implant survival rates. Khadembaschi et al. (2021) reported that IMRT was effective in minimizing radiation-induced complications and preserving implant stability, while Lee et al. (2022) associated IMRT with better implant survival rates and reduced bone loss. However, due to inconsistent data, no solid evidence on the influence of different modalities of IMRT or VMAT could be drawn within this research.

Definitive and adjuvant radiotherapy were both utilized in HNC patients depending on the clinical scenario. Early tumors (stage I and II) are typically treated with primary surgery or definitive radiation therapy, whereas stage III and IV (locoregionally advanced) tumors are managed with surgery followed by adjuvant radiation therapy, with or without concurrent chemoradiotherapy (Anderson et al. 2021). Li et al. (2022) reported that 6.9% of patients received definitive radiotherapy, while 93.1% received adjuvant radiotherapy. The study found higher implant failure rates in the mandible (median dose 45.9 Gy) compared to the maxilla (median dose 35.0 Gy), highlighting the impact of radiation dose and anatomical site on implant success. Wolf et al. (2021) included 121 patients, with 25.6% receiving definitive radiotherapy and 74.4% receiving adjuvant radiotherapy with a mean dose of 62.6 Gy. This study noted that maxillary implants were more prone to complications and that adjuvant radiotherapy was associated with higher rates of sinusitis than definitive radiotherapy.

The meta-analysis from the present study demonstrates that implants placed in radiochemotherapy-treated bone have a significantly higher failure risk compared to those in non-irradiated bone (RR = 1.97, 95% CI: 1.09–3.56, $p = 0.0331$), indicating consistent findings across studies. Consistent results were also reported from the systematic review by Chrcanovic et al. (2016). Two studies (Schiegnitz et al. 2021; Lee et al. 2022) identified chemotherapy as a significant risk factor, noting lower implant survival rates in patients who underwent radiochemotherapy compared to those receiving radiotherapy alone. Li et al. (2022) and Alberga et al. (2023) also reported that combined radiochemotherapy led to decreased implant success rates, with higher doses correlating with increased peri-implant bone loss and higher failure rates. However, Mattila et al. (2024) suggested that short-term implant survival was not significantly affected by chemotherapy, as observed in the study from Kovács (2001). Studies like Khadembaschi et al. (2021), Mahendran et al. (2022), and Wolf et al. (2021) did not focus extensively on the isolated effects of chemotherapy but noted the combined adverse effects of cancer treatments on implant survival.

Besides radiotherapy and chemotherapy, other risk factors affecting implant survival in HNC patients include pre-existing dental issues, such as periodontal disease and poor oral hygiene (Li et al. 2022), systemic diseases like diabetes and cardiovascular conditions (Schiegnitz et al. 2021). Two studies (Schiegnitz et al. 2021; Wolf et al. 2021) identified smoking as a significant risk factor, with higher rates of peri-implant inflammation, bone loss, and implant failure among smokers. Additionally, both bleeding and plaque indices were identified as risk factors affecting implant survival and peri-implant health. A study (Schiegnitz et al. 2021) reported that 79% of implants showed satisfactory bleeding indices and 60.6% had satisfactory plaque indices, with higher scores associated with increased peri-implant inflammation and bone loss. Similarly, Neckel et al. (2021) found that higher bleeding and plaque indices were linked to increased peri-implant inflammation and bone loss.

With respect to implant failure timing, only the study by Wolf et al. (2021) provided detailed longitudinal data, reporting failures as early as 1 month after functional loading and extending up to 113 months. These findings suggest that early post-loading monitoring may be critical in irradiated patients.

The reported causes of failure included peri-implantitis, ORN, and inadequate osseointegration. Given the limited data on failure timing across the included studies, future research is needed to evaluate the influence of different loading protocols and implant placement timing on implant survival in irradiated populations.

Limitations of this review include the limited number of studies within the 4-year updated period and considerable variations in design, radiotherapy protocols, and follow-up periods. Moreover, inconsistent reporting of outcomes, such as differing measures of implant success, bone loss, and complications, further complicates direct comparisons. Publication bias should also be considered in light of the low number of studies included. Even thoughseveral methods to assess publication bias and small study effects were used (Lin et al. 2018), it did not display statistical evidence that supports its existence; there is uncertainty about the potential impact of this issue on the effect estimates. Additionally, it was not possible to conduct a multivariate analysis due to missing data on other potential risk factors. Consequently, the results should be interpreted with caution.

5 | Conclusion

This study integrates the latest research findings to support current practices in implant treatment for HNC patients. While implant survival is relatively high, the adverse effects of irradiation negatively impact outcomes in patients treated with radiotherapy/chemotherapy. Particularly, implants placed in grafted irradiated bone present a higher risk than those in native bone. Treatment with higher radiation doses appears to be associated with increased peri-implant bone loss. Based on these findings, implant placement in HNC patients necessitates comprehensive pre-treatment planning, incorporating radiation dose, optimal timing, and placement site selection.

Author Contributions

Shengchi Fan: conceptualization, methodology, investigation, writing – original draft, data curation, project administration, supervision, writing – review and editing. **Leonardo Diaz:** investigation, methodology, validation, data curation, writing – original draft, writing – review and editing. **Gustavo Sáenz-Ravello:** methodology, visualization, writing – original draft, investigation, formal analysis. **Eduard Valmaseda-Castellon:** investigation, writing – review and editing, supervision. **Bilal Al-Nawas:** supervision, writing – review and editing, project administration. **Eik Schiegnitz:** supervision, writing – review and editing, project administration.

Acknowledgments

The authors have nothing to report.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data sets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.