

A Systematic Review and Meta-Analysis of Peak Skin Dose Determination Methods during Standard and Complex Endovascular Aortic Aneurysm Repair Procedures

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Background: Endovascular aneurysm repair (EVAR) is performed under real-time fluoroscopic guidance. Complex fenestrated and branched EVAR procedures may result in substantial localized radiation exposure to the patient's skin, with peak skin dose (PSD) being the most relevant metric for assessing deterministic radiation risk. Despite advances in dose monitoring technologies, no comprehensive synthesis of PSD during EVAR procedures exists.

Methods: A systematic review and meta-analysis was conducted according to PRISMA guidelines. PubMed, Scopus, and the Cochrane Library were searched without date restrictions for articles reporting PSD during EVAR. Risk-of-bias was assessed using Risk-of-Bias in Non-randomized Studies of Interventions, and publication bias was evaluated with Egger's test. A random-effects model pooled mean PSD. Subgroup analyses compared PSD by determination method (direct versus indirect) and EVAR technique (standard versus complex).

Results: Eleven articles comprising 19 study cohorts were included. Direct measurement methods (radiochromic films or thermoluminescent dosimeters) were used in $\approx 57.9\%$ of reported PSD values, indirect methods (dose-area product (DAP) or reference air kerma (RAK) estimations) in $\approx 26.3\%$, and hybrid approaches in $\approx 15.8\%$. Reported PSD ranged from 63 mGy to 6,600 mGy. Meta-analysis showed that indirect methods yielded significantly higher pooled mean PSD than direct methods (3,115 mGy vs. 558 mGy; $P < 0.001$). No significant difference was observed between standard and complex EVAR (1,326 mGy vs. 2,719 mGy; $P = 0.33$). Heterogeneity was substantial ($I^2 \geq 94.9\%$).

Conclusion: A substantial discrepancy between indirect and direct PSD measurement methods during EVAR has been revealed. Indirect DAP- or RAK-based estimations yield significantly higher PSD values than direct measurements. No significant difference in PSD was observed between standard and complex EVAR procedures. Future research should prioritize prospective, multi-center studies with standardized, directly validated PSD measurement protocols.

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INTRODUCTION

Compared to traditional open surgery, endovascular aneurysm repair (EVAR) has emerged as a minimally invasive alternative for treating progressive aortic dilatations.¹ Accurate stent-graft deployment and complete exclusion of the aneurysm sac require EVAR procedures to be performed under real-time fluoroscopic guidance. Nevertheless, reliance on ionizing radiation raises concerns, as it poses potential health risks to both patients and the operating room staff.^{2–6}

Fluoroscopy in lengthy or complex fenestrated/branched EVAR (F/BEVAR) procedures can result in substantial localized radiation exposure to the patient's skin, potentially causing deterministic effects such as transient erythema, epilation, or, in extreme cases, necrosis.^{7,8} Deterministic radiation effects, or tissue reactions, occur only above a threshold dose, with severity increasing with dose. In fluoroscopically guided procedures, peak skin dose (PSD) is the most relevant metric for assessing skin tissue reaction risk, as it reflects localized energy deposition. The National Council on Radiation Protection and Measurements and the International Atomic Energy Agency recommend that PSD should be determined and monitored to guide follow-up and improve radiation safety.^{9,10} The magnitude of PSD during endovascular interventions is influenced by multiple factors, including patient-specific characteristics, procedure duration and complexity, field size, beam angulation, and overlapping projections.^{7,11}

PSD has been typically assessed using either direct or indirect methods. Direct measurement techniques include thermoluminescent dosimeters (TLDs) and radiochromic films, the latter often considered the gold standard due to their high spatial resolution and acceptable uncertainty.¹² However, routine clinical use of direct methods is limited by practical constraints including calibration, handling, and time requirements.^{7,12} Indirect methods, on the other hand, rely on surrogate dose metrics such as dose-area product (DAP) or reference air kerma (RAK), which are automatically reported by modern fluoroscopy systems. Advanced software integrated into modern C-arm systems enables PSD estimation and mapping using radiation dose structured report data and geometric parameters.^{7,8,11} These systems provide either real-time feedback or retrospective analysis, supporting intra-operative dose optimization and postprocedural assessment.^{7,13,14} Their accuracy, however, depends on appropriate calibration, patient modeling, and the quality of recorded dose data, requiring

independent verification prior to clinical implementation.^{7,13} Monte Carlo-based radiation transport simulations, which are widely recognized as a high-fidelity approach for dose modeling, have increasingly been used as a benchmark for evaluating clinically implemented dose estimation algorithms.¹⁵

Despite the increasing recognition of skin dose as an important parameter for patient safety, there is no comprehensive synthesis of the existing evidence on PSD in EVAR procedures. The current work represents the first systematic review and meta-analysis focused specifically on PSD during standard and complex EVAR interventions, aiming to summarize the reported PSD values, evaluate and compare PSD determination methods, identify key contributors to radiation exposure, and highlight strategies to minimize deterministic radiation effects while maintaining procedural effectiveness.

MATERIALS AND METHODS

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, the peer-reviewed literature on PSD in standard and complex EVAR procedures was systematically assessed.¹⁶

Electronic Databases and Search Strategy

A comprehensive search strategy was employed to identify articles, combining electronic database searches with manual screening of reference lists from relevant work. The following databases were searched: the National Library of Medicine's MEDLINE database (via PubMed), the Cochrane Library, and Scopus. No date restrictions were applied, and the final search was executed on April 1, 2026. No language restrictions were imposed during the initial screening phase to ensure broad coverage. The search strategy incorporated database-specific controlled vocabularies, including Medical Subject Headings (MeSH) for PubMed and the Cochrane Library, as well as both MeSH and Emtree terms for Scopus. A combination of exploded MeSH terms and free-text keywords was used, with terms linked using the Boolean operators "AND" and "OR" to optimize retrieval of relevant records. The complete search syntax for each of the 3 databases is presented in [Table I](#). The review protocol was developed a priori, specifying the research question, search strategy, eligibility criteria, data extraction items, and statistical analysis plan. The protocol was registered in an International Prospective Registry of Systematic Reviews prior to initiation to ensure methodological

Table I. Systematic search strategy and retrieved records.

Search strategy		Results
MEDLINE (PubMed)		
1	("Aortic Aneurysm, Abdominal"[Mesh] OR "Aortic Aneurysm, Thoracic"[Mesh] OR "Aortic Diseases"[Mesh] OR aortic[All Fields] OR aorta[All Fields] OR aortoiliac[All Fields] OR thoracoabdominal[All Fields])	414,603
2	("Endovascular Procedures"[Mesh] OR endovascular[All Fields] OR EVAR[All Fields] OR TEVAR[All Fields] OR FEVAR[All Fields] OR BEVAR[All Fields] OR fenestrated[All Fields] OR branched[All Fields] OR "stent graft"[All Fields] OR stent-graft[All Fields] OR endograft[All Fields])	713,601
3	("Radiation Dosage"[Mesh] OR "Fluoroscopy"[Mesh] OR "Radiography, Interventional"[Mesh] OR fluoroscopy[All Fields] OR radiation[All Fields] OR dosimetry[All Fields] OR dose[All Fields] OR "air kerma"[All Fields] OR "reference air kerma"[All Fields] OR "cumulative air kerma"[All Fields] OR "dose area product"[All Fields] OR "dose-area product"[All Fields] OR "kerma area product"[All Fields]) AND ("Radiodermatitis"[Mesh] OR "Radiation Injuries"[Mesh] OR "peak skin dose"[All Fields] OR "skin dose"[All Fields] OR "entrance skin dose"[All Fields] OR "equivalent skin dose"[All Fields] OR "reference air kerma"[All Fields] OR "cumulative air kerma"[All Fields] OR "air kerma"[All Fields] OR "dose area product"[All Fields] OR "kerma area product"[All Fields] OR "deterministic effect"[All Fields] OR "deterministic effects"[All Fields] OR "radiation skin injury"[All Fields] OR "radiation-induced skin injury"[All Fields])	85,786
4	#1 AND #2	66,600
5	#1 AND #2 AND #3	247
Scopus		
1	TITLE-ABS-KEY: (skin dose OR PSD OR peak skin dose OR radiation)	371,915
2	TITLE-ABS-KEY: aortic aneurysm	25,616
3	#1 AND #2	286
Cochrane Library		
1	aortic aneurysm (All text)	2,422
2	skin dose (All text)	20,117
3	#1 AND #2	39

transparency and avoid effort duplication (PROSPERO registration number: CRD420261348100).

third senior reviewer (K.M.) was consulted to adjudicate and provide the final decision.

Record Selection Process

All records retrieved from the database search were imported into a reference management software (Mendeley; Elsevier B.V., Amsterdam, The Netherlands). Duplicate entries were identified and removed using a dedicated tool (Ablebits Duplicate Remover, 4Bits Ltd, Gomel, Belarus) within spreadsheet software (Microsoft Excel; Microsoft Corp., Redmond, WA, USA). Article selection was conducted independently by 2 reviewers (F.E. and C.P.) following a standardized, unblinded approach. Initially, titles and abstracts were screened to identify potentially relevant articles, followed by full-text evaluation to confirm eligibility. Any disagreements arising during the selection process were resolved through discussion between the 2 reviewers. When consensus could not be reached, a

Risk-of-Bias and Publication Bias Appraisal

The methodological quality and risk-of-bias (ROB) of the included articles were assessed using the Risk-of-Bias in Non-randomised Studies of Interventions (ROBINS-I)¹⁷ tool and graphically represented using the robvis visualization tool.¹⁸ The presence of small-study effects and potential publication bias was evaluated by visual inspection of funnel plot asymmetry and statistically assessed using Egger's regression test. Egger's regression test was used to quantify small-study effects by regressing the standardized effect estimate against its standard error (SE), where the beta coefficient (β) represented the slope of this regression line (indicating the direction and magnitude of bias) and the z-statistic (z) tested

Table II. Inclusion and exclusion criteria applied during study selection.

Category	Criteria
Inclusion criteria	Population: Studies involving human subjects undergoing standard or complex endovascular aortic repair (including EVAR, EVARib, FEVAR, BEVAR, TEVAR), as well as phantom-based experiments or computational simulations (e.g., Monte Carlo modeling) relevant to these procedures. Outcome: Studies that report PSD, including methods for its calculation, measurement, or estimation. Study characteristics: Full-text original research articles published in English, with no restriction on publication date, providing sufficient quantitative or methodological data for analysis.
Exclusion criteria	Animal studies: Preclinical or experimental studies conducted on non-human subjects were excluded due to limited clinical applicability. Insufficient or non-extractable data: Studies lacking useable or clearly reported data on PSD, preventing meaningful extraction or analysis. Irrelevant procedure type: Studies not involving aorta-related endovascular repair (e.g., coronary, carotid, peripheral, or neurointerventional procedures). Nondisaggregated EVAR data: Studies where EVAR results were combined with those of other procedures and could not be analyzed separately. Nonprimary research formats: Letters to the editor, editorials, conference abstracts, presentations and unpublished studies lacking sufficient methodological detail. Language restriction: Studies not published in English.

EVAR, endovascular aneurysm repair; EVARib, endovascular aneurysm repair with iliac branch; FEVAR, fenestrated endovascular aneurysm repair; BEVAR, branched endovascular aneurysm repair; TEVAR, thoracic endovascular aneurysm repair; PSD, peak skin dose.

the null hypothesis that β equaled zero (i.e., no asymmetry).

Inclusion and Exclusion Criteria

The predefined inclusion and exclusion criteria applied during the article selection process are summarized in detail in Table II. Review articles were excluded from the final analysis; however, their reference lists were screened to identify additional pertinent research.

Radiation Dose Metrics and EVAR Classification

PSD, defined as the maximum absorbed dose (D) to a localized area of the patient’s skin during a single procedure, was used as the primary dosimetric endpoint. PSD (also known as $D_{\text{skin, max}}$) was reported in units of gray (Gy). Additional radiation dose metrics reported herein included DAP (also referred to as kerma-area product, KAP) and RAK. DAP represents the integral of air kerma over the area of the X-ray beam and provides an estimate of total radiation energy delivered to the patient, with units of $\text{Gy}\cdot\text{cm}^2$.² RAK (also referred to as cumulative air kerma or reference air kerma, $K_{a,r}$), reported in Gy, corresponds to the air kerma accumulated at the interventional reference point under standardized geometric conditions and is

commonly used as a surrogate for patient radiation exposure and for triggering skin dose alerts in interventional suites.¹⁰

EVAR procedures were categorized into standard and complex techniques. Standard EVAR included conventional infrarenal EVAR and thoracic endovascular aortic repair (TEVAR). TEVAR was classified as a standard procedure based on its relatively low technical complexity, straightforward endograft deployment, and short fluoroscopy times (FTs), as supported by findings from a recent work.⁵ Complex EVAR comprised F/BEVAR procedures.

Data Synthesis and Statistical Analysis

Data extraction was performed using a standardized approach, capturing article characteristics (first author, year of publication and study type), EVAR technique, PSD values and PSD assessment approach. All PSD values were extracted directly from the original articles as reported by the study investigators; no conversions to PSD were performed by the review authors. When articles reported multiple cohorts, each cohort was treated as an independent study. Given the heterogeneity in reporting of PSD values across articles, several datasets were not presented as mean $\pm$ standard deviation (SD), but instead as medians with ranges (minimum-maximum) or interquartile ranges (IQRs). To enable

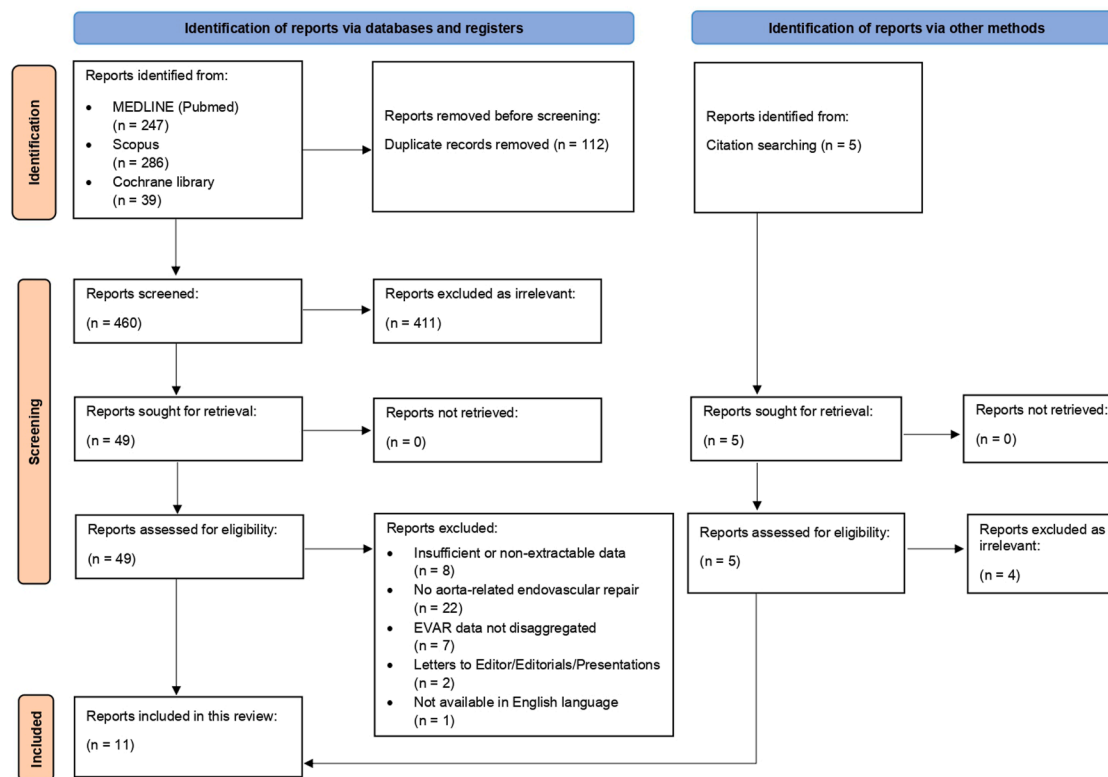


Fig. 1. PRISMA flow diagram of article selection for publications reporting peak skin dose in EVAR procedures.

inclusion in the meta-analysis, these data were converted to approximate mean and SD values using established methods proposed by Wan et al.¹⁹ The choice of the conversion method was based on the type of the available summary statistics and the corresponding sample size. Pooled mean PSD estimates with corresponding 95% confidence intervals (CIs) were calculated using a random-effects model with restricted maximum likelihood estimation. Sub-group analysis was performed to compare PSD values between direct and indirect determination methods as well as between standard and complex EVAR techniques. Articles reporting a single PSD value derived using both direct and indirect methods were classified as hybrid. These articles were included in the qualitative synthesis but excluded from the quantitative meta-analysis to minimize methodological heterogeneity. Similarly, research reporting a single PSD value derived from both standard and complex EVAR procedures were excluded from the meta-analysis. All statistical analyses and forest plot generation were performed using Stata software (version 18; StataCorp LP, USA). Statistical significance was defined as a two-sided $P < 0.05$.

RESULTS

Literature Search and Cohort Overview

A systematic search of the peer-reviewed literature identified 572 records, of which 11 articles met the predefined inclusion criteria by reporting PSD during standard or complex EVAR procedures, forming the core evidence base for the present analysis (Fig. 1). A total of 19 distinct PSD study cohorts were extracted from the 11 included articles, with publication dates ranging from 2008 to 2024 (Table III). Among the 19 reported PSD values, 11 (approximately 57.9%) were obtained using direct measurement methods,^{20,24–26,28–30} specifically passive dosimeters (radiochromic films and/or TLDs placed on the patient's back); no optically stimulated luminescence dosimeters (OSLDs) or active real-time dosimeters were employed. Indirect determination methods, based on DAP or RAK estimations, accounted for 5 values (approximately 26.3%),^{23,24,26} while the remaining 3 values (approximately 15.8%) were derived using a hybrid approach (combination of direct and indirect techniques).^{22,23,27} Regarding procedural complexity, 11 PSD values

Table III. EVAR studies reporting PSD values.

Author (year of publication)	Dosimetry method (assessment approach)	EVAR technique (sample)	PSD (mGy)
Clauss et al. ²⁰ (2024) ^a	Direct (Radiochromic films on patient)	Standard EVAR (<i>n</i> = 24) EVARib (<i>n</i> = 7) F/BEVAR (<i>n</i> = 8) TEVAR (<i>n</i> = 2)	<RT – 375 150–750 480–975 <RT – 350
Kirkwood et al. ²¹ (2015) ^b	Indirect (RAK-derived estimation)	FEVAR (<i>n</i> = 21)	4,800 ± 2,000 (2,300–10,400)
Hertault et al. ²² (2014) ^c	Hybrid Direct (Radiochromic films on patient) Indirect (DAP-derived estimation)	Standard EVAR (<i>n</i> = 44)	63 (44–103)
Kirkwood et al. ²³ (2014) ^b	Hybrid Direct (Radiochromic films on patient) Indirect (RAK-derived estimation)	FEVAR (<i>n</i> = 50)	6,600 ± 3,600 (3,700–18,000)
Howells et al. ²⁴ (2012) ^d	Direct (Radiochromic films on patient) Indirect (DAP-derived estimation)	Standard EVAR (<i>n</i> = 9) F/BEVAR (<i>n</i> = 1) Standard EVAR (<i>n</i> = 630) TEVAR (<i>n</i> = 232) F/BEVAR (<i>n</i> = 53)	600 (500–850) 710 (440–13,700) 800 (460–1,440) 1,300 (710–8,700)
Maurel et al. ²⁵ (2012) ^e	Direct (Radiochromic films on patient)	Standard EVAR (<i>n</i> = 10) F/BEVAR (<i>n</i> = 4)	110 (30–230) 430 (150–750)
Walsh et al. ²⁶ (2012) ^e	Direct (Radiochromic films on patient)	Standard EVAR (<i>n</i> = 8)	1,010 (650–1,990)
Kalef-Ezra et al. ²⁷ (2011) ^e	Indirect (DAP-derived estimation)	Standard EVAR (<i>n</i> = 111)	690 (NA – 3,150)
	Hybrid Direct (Radiochromic films and TLDs on patient) Indirect (DAP-derived estimation)	Standard EVAR (<i>n</i> = 91)	226 (56–1,066)
Panuccio et al. ²⁸ (2011) ^f	Direct (Radiochromic films on patient)	BEVAR (<i>n</i> = 47)	2,500
Kalef-Ezra et al. ²⁹ (2009) ^e	Direct (TLDs on patient)	Standard EVAR (<i>n</i> = 5)	227 (NA – 773)
Weiss et al. ³⁰ (2008) ^e	Direct (Radiochromic films on patient)	Standard EVAR (<i>n</i> = 12)	750 (270–1,250)

PSD, peak skin dose; EVAR, endovascular aneurysm repair; EVARib, endovascular aneurysm repair with iliac branch; F/BEVAR, Fenestrated/branched endovascular aneurysm repair; TEVAR, thoracic endovascular aneurysm repair; RT, reading threshold ≈ 100 mGy; RAK, reference air kerma; DAP, dose-area product; NA, not available; TLD, thermoluminescent dosimeter.

^aPSD reported as range.

^bPSD reported as mean ± standard deviation (range).

^cPSD reported as median (interquartile range).

^dPSD reported as median (range).

^ePSD reported as mean (range).

^fPSD reported as mean.

(approximately 57.9%) corresponded to standard EVAR (infrarenal and TEVAR),^{20,22,24–27,29,30} 6 (approximately 31.5%) to complex EVAR (F/BEVAR),^{20,21,23–25,28} 1 (approximately 5.3%) to EVAR with an iliac branch device,²⁰ and 1 (approximately 5.3%) to a combined standard and complex EVAR.²⁴ Across all included cohorts, reported PSD values ranged from 63 mGy to 6,600 mGy.

Risk-of-Bias

ROB was evaluated at the article level (*n* = 11), even when multiple study cohorts were extracted from a single publication. The results are graphically represented as "traffic light" plots (Fig. 2) and weighted summary bar charts (Fig. 3). The majority of studies exhibited serious overall ROB (Fig. 2). Specifically, 7 out of 11 articles (approximately 63.6%) were rated

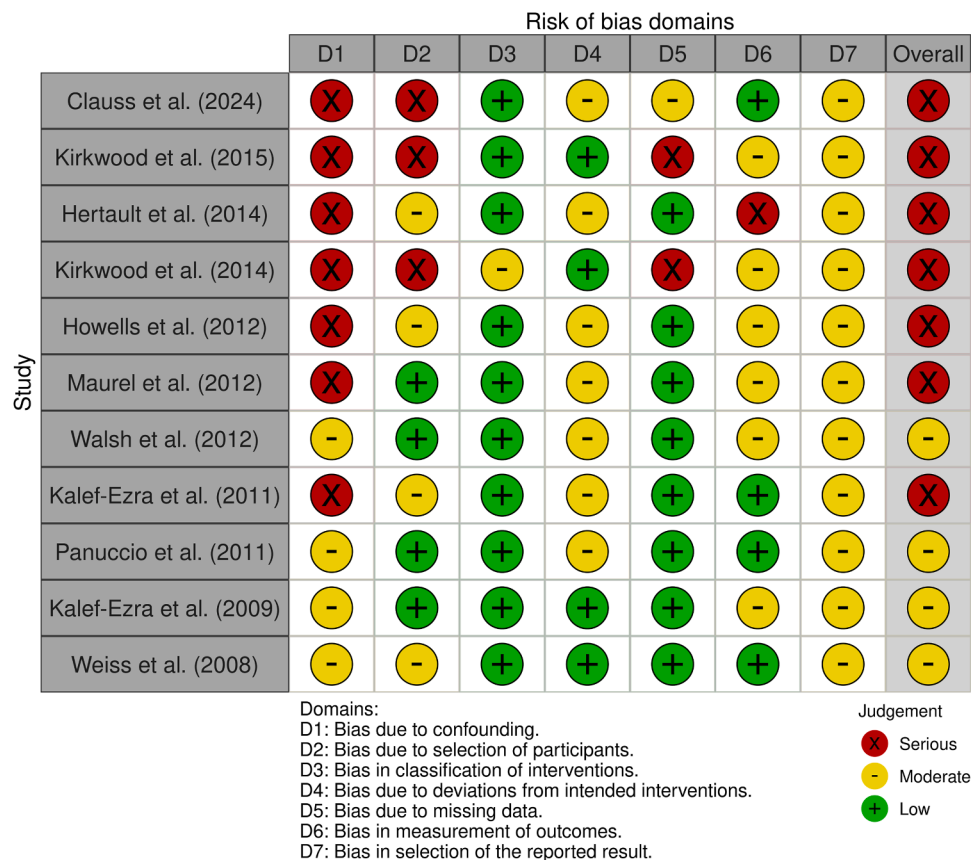


Fig. 2. Per-record risk-of-bias assessment across domains, displayed as a “traffic light” plot.

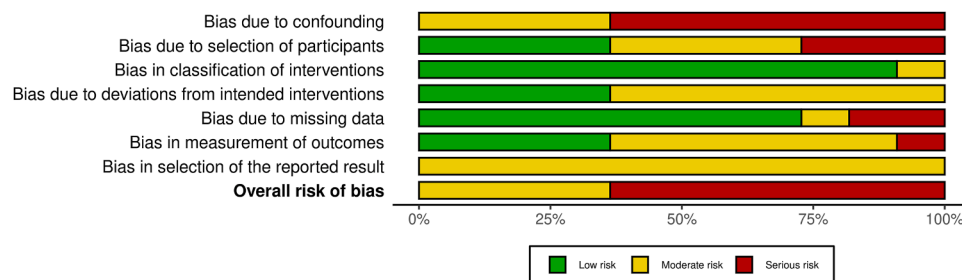


Fig. 3. Distribution of risk-of-bias judgments across domains, presented as a weighted bar plot.

as having serious overall ROB,^{20–25} while the remaining 4 articles (approximately 36.4%) were rated as having moderate overall ROB.^{26,28–30} No study was judged to have low or critical overall ROB. Across individual domains, bias due to confounding, and bias due to selection of participants were the most common sources of serious ROB, each affecting 7 studies (approximately 63.6%).^{20–25} In contrast, bias in classification of interventions was consistently rated as low across all

studies. A detailed breakdown of domain-specific ROB is presented in the weighted summary bar chart (Fig. 3).

Publication Bias

The funnel plot for PSD (Fig. 4) exhibited asymmetry, with points scattered beyond the pseudo-95% CIs, particularly at higher SEs, suggesting potential under-reporting of smaller or nonsignificant effects.

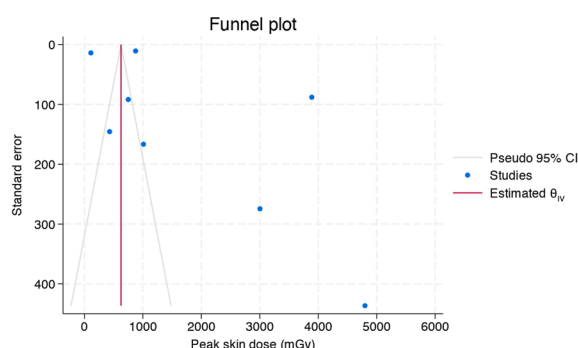


Fig. 4. Funnel plot of peak skin dose values across included studies.

Egger's test confirmed the presence of significant small-study effects ($\beta = 8.96$, $SE = 3.601$, $z = 2.49$, $P = 0.0129$), providing evidence of publication bias across the included studies.

Meta-Analysis and Forest Plots

A total of 8 individual studies from 5 articles^{21,24–26,30} were included in the meta-analysis, whereas the remaining 11 studies from 8 articles^{20,22–24,26–29} were excluded due to insufficient reporting of summary statistics, as the mean and/or SD could not be reliably estimated from the available data. Subgroup analysis was performed according to PSD determination method (direct versus indirect), with the corresponding forest plot shown in Figure 5. Studies employing indirect dosimetry (DAP- or RAK-derived estimations)^{21,24} reported a significantly higher pooled mean PSD compared with those using direct measurement (radiochromic films or TLDs)^{25,26,30}: 3,115 mGy (95% CI: 1,465–4,765) versus 558 mGy (95% CI: 171–945). The difference between the 2 groups was statistically significant ($Q_b = 8.74$, $P < 0.001$). A second subgroup analysis compared PSD between standard and complex EVAR procedures, with the forest plot presented in Figure 6. No statistically significant difference was observed between standard EVAR^{24–26,30} (pooled mean PSD: 1,326 mGy; 95% CI: 33–2,619) and complex EVAR^{21,24,25} (pooled mean PSD: 2,719 mGy; 95% CI: 234–5,205), with a test for subgroup differences yielding $Q_b = 0.95$, $P = 0.33$.

DISCUSSION

Novelty and Key Findings

To our knowledge, no previous report has appraised the methodologies for PSD determination during EVAR procedures, nor has any meta-

analysis compared PSD values derived from direct versus indirect dosimetry approaches in this setting. The present work addresses this gap by systematically evaluating the available evidence, guided by the established framework provided by the Society of Interventional Radiology (SIR) guidelines on patient radiation dose management.³¹ According to these guidelines, PSD represents the most relevant metric for assessing deterministic skin injury risk. The SIR explicitly cautions that estimated skin doses may differ from actual PSD by a factor of 2 or more. With this authoritative context in mind, the present meta-analysis quantitatively assessed the discrepancy between direct and indirect PSD determination methods in EVAR procedures.

Impact of Dosimetry Method and Procedure Type on PSD

The most important finding is the substantial discrepancy between PSD values obtained through indirect estimation methods versus direct measurements. Indirect methods produced a pooled mean PSD nearly 6 times higher than that derived from radiochromic films or TLDs (3,115 mGy vs. 558 mGy; $P < 0.001$). According to the SIR guidelines, the threshold for patient follow-up is 3,000 mGy. The pooled mean PSD from indirect methods exceeds this threshold, whereas the mean from direct measurements remains well below it. This suggests that reliance on surrogates such as DAP or RAK may systematically overestimate the risk of deterministic skin effects in EVAR patients, potentially leading to unnecessary clinical follow-up and patient anxiety. One explanation is that indirect methods rely on conversion factors and assumptions regarding beam geometry, patient positioning, and backscatter that may not fully capture the dynamic nature of EVAR procedures. Direct dosimetry measures actual skin dose, whereas indirect methods may provide conservative overestimates. The extreme heterogeneity observed ($I^2 \geq 94.9\%$) further supports this concern, reflecting variability in dosimetry protocols, patient characteristics, procedural factors, and equipment configurations.

Regarding procedure type, standard and complex EVAR did not differ significantly in terms of pooled mean PSD (1,326 mGy vs. 2,719 mGy; $P = 0.33$). However, this finding must be interpreted with caution. The CIs for both groups were extremely wide, and heterogeneity was near-complete. Other factors, such as steep beam angulation, number of digital subtraction angiography (DSA) runs,

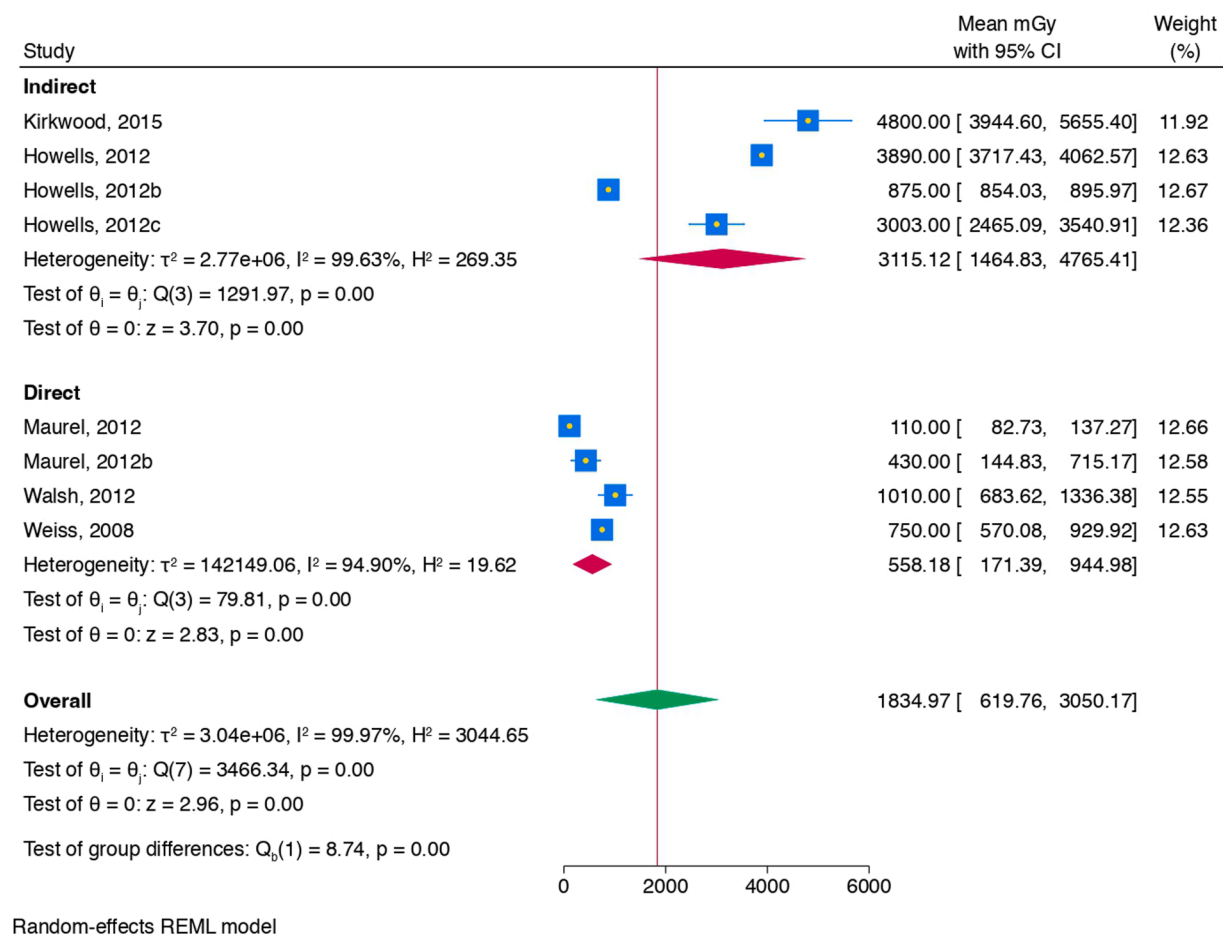


Fig. 5. Forest plot of peak skin dose stratified by direct versus indirect determination methods.

operator experience, body mass index (BMI), and dose-reduction techniques, may be more influential determinants of PSD than procedural complexity alone.

PSD Range and Implications for Deterministic Risk

The reported PSD values across the included studies ranged from 63 mGy to 6,600 mGy, representing a nearly 100-fold difference. Understanding the factors that contributed to these extremes is essential for interpreting the findings of this report. The minimum reported PSD of 63 mGy was documented by Hertault et al.²² in a cohort of 44 standard EVAR procedures. This remarkably low value can be attributed to several factors: the exclusive use of standard infrarenal EVAR procedures (which are associated with shorter FT and fewer DSAs), the implementation of strict dose optimization protocols, and the fact that the reported value was

primarily derived from indirect PSD-to-DAP ratio estimations rather than direct film measurements on all patients. Additionally, the study was conducted using a modern C-arm system with advanced dose reduction features, and the operators were experienced in radiation-saving techniques.

In contrast, the maximum reported PSD of 6,600 mGy was reported by Kirkwood et al.²³ in a cohort of 50 FEVAR procedures. This substantially higher value reflects the inherent complexity of FEVAR procedures, which requires prolonged FTs, multiple DSA runs, and frequent use of steep beam angulations (particularly left anterior oblique projections) for cannulation of target vessels. Furthermore, the majority of patients in this cohort were obese (BMI: 31 ± 6), which increases radiation dose due to greater X-ray attenuation. The PSD values in this study were derived from custom software calculations validated against Gafchromic film measurements on only 5 patients, and the authors themselves reported a mean PSD of 6.6 Gy with a

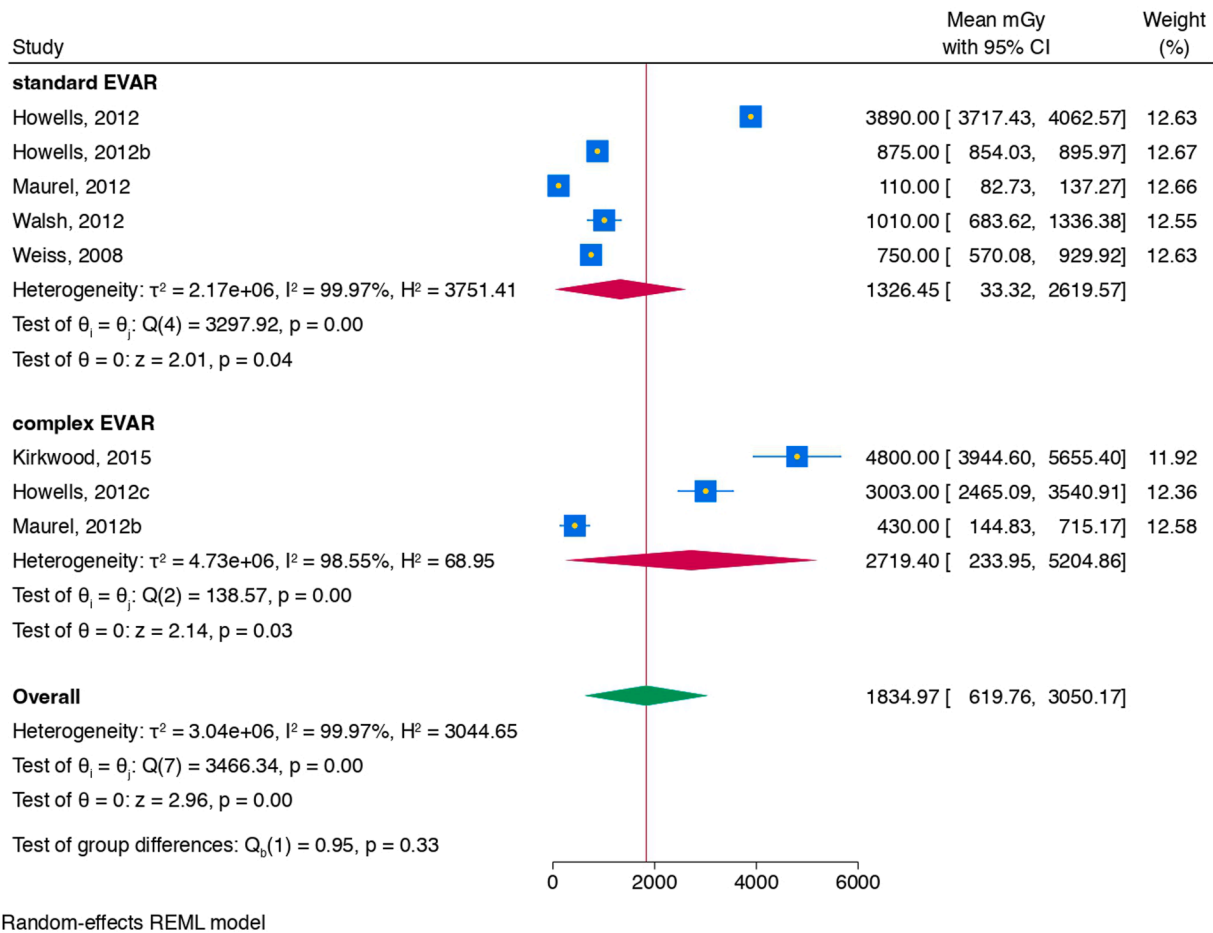


Fig. 6. Forest plot of peak skin dose stratified by standard versus complex EVAR technique.

wide range (3.7–18 Gy), reflecting substantial inter-patient variability. Notably, the mean PSD of 6.6 Gy exceeds the established threshold for transient erythema (2 Gy) and falls within the range for temporary epilation (3–6 Gy), while the maximum value of 18 Gy exceeds even the threshold for desquamation (>10 Gy) and necrosis (>15 Gy).³¹ Based on these dose distributions, the authors acknowledged that they would have expected to observe grade 1 to grade 3 skin injuries. Remarkably, however, no radiation-induced skin injuries were documented in any patient, despite rigorous follow-up including clinical examinations at 2 and 6 weeks, 3 and 6 months, and 1 year, as well as telephone interviews. Several explanations may account for this discrepancy, including individual biologic variation in radiation sensitivity, the protraction of exposure over time allowing for partial skin recovery, and the possibility that minor skin injuries were underrecognized or misdiagnosed. These findings suggest that current PSD threshold-based

predictions may overestimate the actual risk of clinically significant skin injury in complex endovascular procedures.

Surrogate Skin Dose Metrics

A notable finding of the present systematic review is that certain studies which addressed the risk of deterministic skin effects during EVAR procedures did not employ PSD as their primary dosimetric endpoint, instead relying on alternative quantities such as entrance surface dose (ESD), entrance surface air kerma (ESAK), or $K_{a,r}$. This practice raises concerns because these surrogates do not accurately reflect the maximum dose absorbed at a single point on the patient’s skin, which is the critical determinant of tissue reactions. Fossaceca et al.³² calculated ESD from DAP values for 153 EVAR procedures and discussed the risk of skin injuries, noting that the 2 Gy threshold for transient erythema was exceeded in 42% of patients when using mobile angiography

and in 56% when using fixed angiography, while explicitly acknowledging that their ESD estimates were neither precisely measured nor specific to individual patients. Similarly, Weerakkody et al.³³ calculated ESD from DAP values for 96 patients and reported that the 2 Gy threshold for possible skin damage was exceeded in 29% of procedures. Efthymiou et al.³⁴ calculated ESD from KAP values and reported that the 2 Gy threshold for skin erythema was exceeded in up to 66 procedures depending on the assumed focus-to-skin distance. Likewise, Blaszkak and Juszkat³⁵ reported ESAK values of 517 mGy for males and 374 mGy for females, using ESAK as a surrogate for skin dose without direct PSD measurement. Bannazadeh et al.³⁶ reported "estimated skin dose" values calculated from FT using an assumed dose rate of 30 mGy/min, acknowledging that direct skin dose monitoring would be a stronger approach. Rolls et al.³⁷ reported a reduction in $K_{a,r}$ - which they referred to as "skin dose" - from 4.4 Gy to 1.6 Gy after introducing a team-based approach to radiation safety. Haga et al.³⁸ reported that 6% of patients undergoing TEVAR or EVAR in a hybrid operating room received $K_{a,r}$ values exceeding 2 Gy, yet relied on this surrogate metric rather than PSD to assess deterministic risk. Budtz-Lilly et al.³⁹ reported "accumulated skin dose" values ranging from 0.97 Gy to 7.63 Gy for standard and complex EVAR procedures; however, their methods provide no description of how this quantity was obtained.

Methodological Limitations and Gaps in the Literature

In hybrid studies combining direct and indirect methods, direct measurements were performed on only a small subset of patients, with results extrapolated to the larger cohort.^{22,23,27} This raises concerns about accuracy and generalizability. Beyond this, no included studies employed physical phantoms, Monte Carlo simulations, OSLDs, or MOSFETs for PSD determination during EVAR. Physical phantoms and Monte Carlo approaches could serve as valuable benchmarks for validating dose estimation algorithms, while OSLDs and MOSFETs offer practical advantages including reusability and real-time readout. Notably, Nasr et al.⁴⁰ recently employed OSLDs during EVAR, though their study focused on Monte Carlo validation rather than PSD reporting, and measurements were limited to 4 anatomical points without full skin mapping. The absence of these complementary methodologies represents a significant gap. Future research should explore

these approaches to enhance accuracy, standardization, and comparability of PSD assessment in EVAR.

Commercial and Open-Source Dose Management Software

Several commercial dose management systems have incorporated PSD estimation and skin dose mapping, reflecting growing recognition of this quantity as a critical safety metric.^{41–44} Commercial platforms such as DoseWatch, DoseWise Portal, Radiation Dose Monitor (RDM), and NovaDose offer automated skin dose mapping and outlier detection.^{41–44} Hadid-Beurrier et al.⁴⁵ validated RDM against film measurements in cardiac (−4.5%), abdominal (−21.9%), and neurologic (−10.2%) procedures, but no EVAR-specific data were reported. Similarly, the vendor-independent application SkinCare demonstrated PSD accuracy within 16–17% in non-EVAR settings.⁴⁶ Open-source alternatives, including PySkinDose,⁴⁷ OpenREM with OpenSkin,^{48,49} PyMCGPU-IR,⁵⁰ and the FDA's Virtual Dosimeter,⁵¹ provide customizable options, though validation has been limited to general angiography or laboratory setups.^{50,52}

Importantly, none of these tools have been specifically validated for EVAR procedures, which involve unique challenges including prolonged FT, steep beam angulations, and variable patient body habitus.^{45,46,52} Future research should prioritize prospective validation against gold-standard direct measurements during EVAR. Until then, clinical users should interpret software-generated PSD estimates with caution and corroborate them with direct dosimetry in a subset of patients.

The 8-Year Gap and Emerging Protocols

A notable gap in published PSD data occurred between 2016 and 2023, possibly due to the labor-intensive nature of direct measurements, ethical challenges, or a shift toward validating indirect methods. Del Carmen et al.⁵³ recently published a prospective protocol for monitoring radiation exposure during endovascular procedures, relying exclusively on indirect PSD determination without direct validation. Given that the present meta-analysis found indirect methods yield significantly higher PSD than direct methods, continued validation of software-based estimates remains necessary.

Practical Recommendations for Skin Dose Reduction and Emerging Strategies

Based on the findings and existing literature, several practical strategies can reduce PSD during EVAR

without compromising efficacy. Operators should optimize technical factors: increase table height, utilize tight collimation, employ C-arm angulation to spread skin dose, use DSA sparingly, and select the lowest possible frame rates.⁵⁴ Removing the anti-scatter grid for low-to-medium BMI patients may reduce PSD by up to 54%, though this has not been specifically examined in EVAR.^{55–57} Modern C-arm systems and dose management software offer 4D skin dose mapping and automated outlier detection; establishing PSD-specific alert criteria (e.g., >3 Gy) enables systematic follow-up.^{11,58} Monte Carlo approaches using ICRP voxel phantoms can estimate organ and skin doses with improved accuracy.^{15,59} Institutional protocols, staff education,¹⁰ patient-specific simulation training,⁶⁰ and emerging X-ray-free navigation technologies^{61,62} represent additional strategies. Until these are fully validated, adherence to directly validated PSD measurement protocols remains the most effective approach.

Limitations

Several limitations of the current work should be acknowledged. Substantial statistical heterogeneity was observed across all analyses, which limits the generalizability of the pooled estimates and reflects considerable variability in patient populations, dosimetry protocols, and equipment configurations across the included studies. Significant publication bias was also detected, suggesting that studies with null or negative findings may be underrepresented in the literature, potentially inflating the pooled PSD estimates. The use of validated statistical methods to estimate means and SDs may have introduced bias, particularly for studies with small sample sizes or skewed PSD distributions, although such approaches are generally accepted in meta-analyses of heterogeneous data. The majority of included studies exhibited serious ROB, particularly in domains related to confounding and participant selection, limiting the ability to draw causal inferences. Furthermore, the predominance of single-center studies restricts the generalizability of the findings to broader clinical practice. Finally, 11 of the 19 identified cohorts were excluded from the quantitative synthesis due to insufficient reporting of summary statistics, highlighting the need for more standardized PSD reporting in future studies.

CONCLUSION

This first systematic review and meta-analysis on PSD during EVAR procedures reveals a substantial discrepancy between indirect and direct

measurement methods. Indirect DAP- or RAK-based estimations yield significantly higher PSD values than direct measurements with radiochromic films or TLDs. No significant difference in PSD was observed between standard and complex EVAR procedures. Critical gaps in the literature include an 8-year publication hiatus and the absence of studies employing phantoms, Monte Carlo simulations, or active dosimeters. Future research should prioritize prospective, multicenter studies with standardized, directly validated PSD measurement protocols.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used an AI-assisted tool (DeepSeek) for language editing and improvement of readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Fotios O. Efthymiou: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vasileios I. Metaxas:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Christos F. Pitros:** Writing – original draft, Data curation. **Constantine N. Antonopoulos:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Christos P. Dimitroukas:** Writing – review & editing, Methodology. **Konstantinos G. Moulakakis:** Supervision. **John D. Kakisis:** Supervision. **Stavros K. Kakkos:** Supervision. **George S. Panayiotakis:** Project administration.

REFERENCES

- England A, McWilliams R. Endovascular aortic aneurysm repair (EVAR). *Ulster Med J* 2013;82:3–10.
- Valentin J. Avoidance of radiation injuries from medical interventional procedures. *Ann ICRP* 2000;30:7–67.
- Jaschke W, Schmuth M, Trianni A, et al. Radiation-induced skin injuries to patients: what the interventional radiologist needs to know. *Cardiovasc Intervent Radiol* 2017;40:1131–40.
- Efthymiou FO, Pitros CF, Metaxas VI, et al. A systematic review and meta-analysis of intraoperative patient dosimetric data in standard endovascular repair for infrarenal abdominal aortic aneurysms versus fenestrated and branched endovascular procedures for thoracoabdominal aortic

- aneurysms. *J Endovasc Ther* 2025;. <https://doi.org/10.1177/15266028251380519>.
5. Efthymiou FO, Pitros CF, Antonopoulos CN, et al. Fluoroscopy time and radiation exposure in TEVAR versus EVAR: a systematic review and meta-analysis. *Ann Vasc Surg* 2026;126:84–99.
 6. Efthymiou FO, Pitros CF, Metaxas VI, et al. A systematic review on occupational radiation exposure during standard and complex endovascular aortic aneurysm repair procedures. *J Endovasc Ther* 2026;. <https://doi.org/10.1016/j.avsg.2026.06.005>.
 7. International Commission on Radiological Protection ICRP. The 2007 Recommendations of the International Commission on Radiological Protection (ICRP Publication 103). *Ann ICRP* 2007;37:1–332.
 8. Greffier J, Goupil J, Larbi A, et al. Assessment of patient's peak skin dose during abdominopelvic embolization using radiochromic (Gafchromic) films. *Diagn Interv Imaging* 2018;99:321–9.
 9. National Council on Radiation Protection and Measurements. Radiation Dose Management for Fluoroscopically-Guided Interventional Medical Procedures. Bethesda, MD: NCRP, 2011. NCRP Report No. 168.
 10. International Atomic Energy Agency IAEA. Patient Dose Optimization in Fluoroscopically Guided Interventional Procedures. Vienna: IAEA, 2010. IAEA-TECDOC-1641.
 11. Greffier J, Moliner G, Pereira F, et al. Assessment of patient's peak skin dose using Gafchromic films during interventional cardiology procedures: routine experience feedback. *Radiat Prot Dosimetry* 2017;174:395–405.
 12. Greffier J, Dabli D, Frandon J, et al. Skin dose assessment in interventional radiology. *Phys Med* 2021;81:170–2.
 13. Jones AK, Ensor JE, Pasciak AS. How accurately can the peak skin dose in fluoroscopy be determined using indirect dose metrics? *Med Phys* 2014;41:071913.
 14. Jones AK, Pasciak AS. Calculating the peak skin dose resulting from fluoroscopically guided interventions. Part I: methods. *J Appl Clin Med Phys* 2011;12:3670.
 15. Johnson PB, Borrego D, Balter S, et al. Skin dose mapping for fluoroscopically guided interventions. *Med Phys* 2011;38:5490–9.
 16. Moher D, Liberati A, Tetzlaff J, et al., PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Plos Med* 2009;6:e1000097.
 17. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ* 2016;355:i4919.
 18. McGuinness LA, Higgins JPT. Risk-of-bias VISualization (robvis): an R package and shiny web app for visualizing risk-of-bias assessments. *Res Synth Methods* 2021;12:55–61.
 19. Wan X, Wang W, Liu J, et al. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Med Res Methodol* 2014;14:135.
 20. Clauss N, Kuntz S, Colvard B, et al. Intraoperative Staff radiation exposure during aortic endovascular procedures. *Ann Vasc Surg* 2024;106:16–24.
 21. Kirkwood ML, Arbique GM, Guild JB, et al. Deterministic effects after fenestrated endovascular aortic aneurysm repair. *J Vasc Surg* 2015;61:902–6.
 22. Hertault A, Maurel B, Sobocinski J, et al. Impact of hybrid rooms with image fusion on radiation exposure during endovascular aortic repair. *Eur J Vasc Endovasc Surg* 2014;48:382–90.
 23. Kirkwood ML, Arbique GM, Guild JB, et al. Radiation-induced skin injury after complex endovascular procedures. *J Vasc Surg* 2014;60:742–8.
 24. Howells P, Eaton R, Patel AS, et al. Risk of radiation exposure during endovascular aortic repair. *Eur J Vasc Endovasc Surg* 2012;43:393–7.
 25. Maurel B, Sobocinski J, Perini P, et al. Evaluation of radiation during EVAR performed on a mobile C-arm. *Eur J Vasc Endovasc Surg* 2012;43:16–21.
 26. Walsh C, O'Callaghan A, Moore D, et al. Measurement and optimization of patient radiation doses in endovascular aneurysm repair. *Eur J Vasc Endovasc Surg* 2012;43:534–9.
 27. Kalef-Ezra JA, Karavasili S, Kouvelos G, et al. Endovascular abdominal aortic aneurysm repair: methods of radiological risk reduction. *J Cardiovasc Surg (Torino)* 2011;52:769–78.
 28. Panuccio G, Greenberg RK, Wunderle K, et al. Comparison of indirect radiation dose estimates with directly measured radiation dose for patients and operators during complex endovascular procedures. *J Vasc Surg* 2011;53:885–94.
 29. Kalef-Ezra JA, Karavasili S, Ziogas D, et al. Radiation burden of patients undergoing endovascular abdominal aortic aneurysm repair. *J Vasc Surg* 2009;49:283–7.
 30. Weiss DJ, Pipinos II, Longo GM, et al. Direct and indirect measurement of patient radiation exposure during endovascular aortic aneurysm repair. *Ann Vasc Surg* 2008;22:723–9.
 31. Stecker MS, Balter S, Towbin RB, et al. Guidelines for patient radiation dose management. *J Vasc Interv Radiol* 2009;20:S263–73.
 32. Fossaceca R, Brambilla M, Guzzardi G, et al. The impact of radiological equipment on patient radiation exposure during endovascular aortic aneurysm repair. *Eur Radiol* 2012;22:2424–31.
 33. Weerakkody RA, Walsh SR, Cousins C, et al. Radiation exposure during endovascular aneurysm repair. *Br J Surg* 2008;95:699–702.
 34. Efthymiou FO, Metaxas VI, Dimitroukas CP, et al. KERMA-AREA product, entrance surface dose and effective dose in abdominal endovascular aneurysm repair. *Radiat Prot Dosimetry* 2021;194:121–34.
 35. Blaszk MA, Juszkat R. Monte Carlo simulations for assessment of organ radiation doses and cancer risk in patients undergoing abdominal stent-graft implantation. *Eur J Vasc Endovasc Surg* 2014;48:23–8.
 36. Bannazadeh M, Altinel O, Kashyap VS, et al. Patterns of procedure-specific radiation exposure in the endovascular era: impetus for further innovation. *J Vasc Surg* 2009;49:1520–4.
 37. Rolls AE, Rosen S, Constantinou J, et al. Introduction of a team based approach to radiation dose reduction in the enhancement of the overall radiation safety profile of FEVAR. *Eur J Vasc Endovasc Surg* 2016;52:451–7.
 38. Haga Y, Chida K, Sota M, et al. Hybrid operating room System for the treatment of thoracic and abdominal aortic aneurysms: evaluation of the radiation dose received by patients. *Diagnostics (Basel)* 2020;10:846.
 39. Budtz-Lilly J, Liungman K, Wanhainen A, et al. Correlations between branch vessel catheterization and procedural complexity in fenestrated and branched endovascular aneurysm repair. *Vasc Endovascular Surg* 2019;53:277–83.
 40. Nasr B, Villa M, Benoit D, et al. Monte Carlo dosimetry validation for X-Ray guided endovascular procedures. *Ann Vasc Surg* 2024;99:186–92.

41. GE HealthCare, DoseWatch™ dose monitoring software, Available at: <https://www.gehealthcare.com.au/en-au/products/dose-management/dosewatch-dose-monitoring-software-ge-healthcare>. Accessed 09/02/2026.
42. Philips Healthcare, DoseWise portal 2.0 Radiation dose management solution, Available at: https://images.philips.com/is/content/PhilipsConsumer/Campaigns/HC20140401_DG/Documents/HC20200630_DoseWise_Portal_Product_Brochure.pdf. Accessed 09/02/2026.
43. Assistance Publique - Hôpitaux de Paris, Dose de peau du patient en radiologie interventionnelle (DPPRI). ClinicalTrials.gov identifier: NCT04246125. Updated 2023, Available at: <https://clinicaltrials.gov/ct2/show/NCT04246125>. Accessed 09/02/2026.
44. Novarad, NovaDose radiation dose exposure monitoring & Medical Imaging, Available at: <https://www.novarad.net/dose>. Accessed 09/02/2026.
45. Hadid-Beurrier L, Geryes BH, Jean-Pierre A, et al. Clinical benchmarking of a commercial software for skin dose estimation in cardiac, abdominal, and neurology interventional procedures. *Med Phys* 2024;51:3687–97.
46. Krajinovic M, Krzanovic N, Ciraj-Bjelac O. Vendor-independent skin dose mapping application for interventional radiology and cardiology. *J Appl Clin Med Phys* 2021;22:145–57.
47. Hellström M, Granberg C, Lundman J, et al. Introducing PySkinDose, a novel framework for patient peak skin dose estimation in interventional radiology. Vienna, Austria: EuroSafe Imaging, 2020. ESI-00814.
48. McDonagh E, Platten D. OpenREM: radiation Exposure Monitoring for physicists. Available at: <https://openrem.org>. Accessed February 9, 2026.
49. Platten D. Monte Carlo simulation of skin dose distribution from interventional cardiology procedures. Available at: <https://research.manchester.ac.uk/en/studentTheses/monte-carlo-simulation-of-skin-dose-distribution-from-interventio/>; 2023. Accessed February 2, 2026.
50. Fernández-Bosman D, von Barnekow A, Dabin J, et al. Validation of organ dose calculations with PyMCGPU-IR in realistic interventional set-ups. *Phys Med* 2022;93:29–37.
51. Lee H, Badal-Soler A. Virtual dosimeter for interventional fluoroscopy. U.S. Food and Drug Administration, Center for Devices and Radiological Health. Available at: <https://www.fda.gov/science-research/fda-stem-outreach-education-and-engagement/virtual-dosimeter-interventional-fluoroscopy>; 2021. Accessed February 9, 2026.
52. Balboni E, Nocetti L, Guidi G. Configuration and validation of pyskindose for the calculus of peak skin dose for an angiography equipment. *Phys Med* 2026;142(Suppl 105252).
53. Martinez Del Carmen DT, Saldaña Gutierrez P, Vila Coll R, et al. Radiation exposure in endovascular surgery according to complexity: protocol for a prospective observational Study. *Methods Protoc* 2023;6:49.
54. Kirkwood ML, Arbique GM, Guild JB, et al. Surgeon education decreases radiation dose in complex endovascular procedures and improves patient safety. *J Vasc Surg* 2013;58:715–21.
55. Hartmann K, Techt L, Zinkl T. Pulmonary vein isolation: influence of the scattered radiation grid on patient dose. *Radiopraxis* 2024;17:84–93.
56. Roy JR, Sun P, Ison G, et al. Selective anti-scatter grid removal during coronary angiography and PCI: a simple and safe technique for radiation reduction. *Int J Cardiovasc Imaging* 2017;33:771–8.
57. Manzo L, Di Maggio L, Castellano D, et al. An efficient strategy to reduce patient X-Ray exposure during upper and lower extremity revascularization procedures: removal of antiscatter grid. *Cardiovasc Intervent Radiol* 2023;46:815–8.
58. Sas N, Lacroix JB, Dedieu V, et al. Optimized radiological alert thresholds based on device-dosimetric information to predict peak skin dose between 2 and 4 Gy during vascular fluoroscopically guided intervention. *Eur Radiol* 2023;33:5707–16.
59. Harbron RW, Abdelhalim M, Ainsbury EA, et al. Patient radiation dose from x-ray guided endovascular aneurysm repair: a Monte Carlo approach using voxel phantoms and detailed exposure information. *J Radiol Prot* 2020;40:704–26.
60. German Research FoundationDFG. Patient-specific, low-radiation training setup for aortic aneurysm repair (Project No. 551593073). Bonn, Germany: Deutsche Forschungsgemeinschaft, 2025.
61. Timaran LI, Timaran CH, Scott CK, et al. Dual fluoroscopy with live-image digital zooming significantly reduces patient and operating staff radiation during fenestrated-branched endovascular aortic aneurysm repair. *J Vasc Surg* 2021;73:601–7.
62. Panuccio G, Torrealba J, Rohlfes F, et al. Fiber optic RealShape (FORS) technology for endovascular navigation in severe tortuous vessels. *J Endovasc Ther* 2023;30:29–33.