Review

Radiation Safety in Prostatic Artery Embolization: A Review of Current Evidence and Best Practices

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Radiation Safety in Prostatic Artery Embolization: A Review of Current Evidence and Best Practices

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Simple Summary

Prostatic artery embolization (PAE) is a minimally invasive procedure that helps relieve urinary symptoms caused by an enlarged prostate, a common condition in older men. Because PAE is performed using live X-ray imaging, it exposes both the patient and the medical team to radiation. This article reviews the existing scientific research to understand how much radiation is typically used during PAE and why this amount can vary so much between procedures. Most importantly, this review provides a clear guide of best practices—specific techniques and technologies that doctors can use to significantly reduce radiation exposure, making this effective procedure as safe as possible for everyone involved.

Abstract

Prostatic artery embolization (PAE) is increasingly used as a primary minimally invasive treatment modality for lower urinary tract symptoms associated with benign prostatic hyperplasia. As a complex, fluoroscopic-guided endovascular procedure, PAE necessitates a significant use of ionizing radiation, raising important safety considerations for both patients and medical personnel. The objective of this review is to first summarize the procedural and anatomic fundamentals of PAE, and then to provide a comprehensive overview of the current literature on radiation dosimetry, establish contemporary benchmarks for dose metrics, and present an evidence-based guide to practical dose optimization strategies. Through a thorough review of published clinical studies, this article synthesizes reported values for key radiation indices, including Dose Area Product (DAP), Cumulative Air Kerma (CAK), and Fluoroscopy Time (FT). Furthermore, we will critically examine factors influencing dose variability—including patient complexity, procedural technique, and imaging technology—and will provide a practical, clinically-oriented guide to implementing dose-saving measures. Ultimately, this review concludes that while PAE involves a non-trivial radiation burden, a thorough understanding and application of optimization principles can ensure the procedure is performed safely, reinforcing its role as a valuable therapy for BPH.

Keywords: prostatic artery embolization; radiation safety; dosimetry; dose reduction; interventional radiology; benign prostatic hyperplasia; ALARA; occupational exposure

1. Introduction

Benign prostatic hyperplasia (BPH) represents a significant clinical and quality-of-life burden for the aging male population, with lower urinary tract symptoms (LUTS) affecting up to 30-40% of men by the age of 50, and its prevalence increases almost linearly to 70-80% of those older than 80 years [1,2]. While traditional surgical interventions such as transurethral resection of the prostate (TURP) have long been the standard of care, they are associated with notable risks, including sexual dysfunction and complications requiring hospitalization [3]. In this context, Prostatic artery embolization (PAE) has emerged as a paradigm-shifting, minimally invasive therapy. By offering durable symptomatic relief with a lower risk of adverse events, particularly the preservation of sexual

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function, PAE has gained rapid and widespread adoption in urological and interventional radiology practices worldwide [4,5].

The efficacy and precision of PAE are fundamentally dependent on advanced, fluoroscopic-guided endovascular techniques. Real-time visualization of the complex and variable pelvic arterial anatomy using digital subtraction angiography (DSA) and fluoroscopy is essential for the successful catheterization and embolization of prostatic arteries. Consequently, an inherent and unavoidable component of every PAE procedure is the use of ionizing radiation. This exposure applies not only to the patient but also to the entire procedural team, including the interventional radiologist, technologists, and nursing staff. As the volume and complexity of PAE procedures continue to grow, a comprehensive understanding of the associated radiation burden has become a critical patient and occupational safety imperative.

The guiding philosophy of radiation safety in modern medicine is the ALARA (As Low As Reasonably Achievable) principle [6]. This tenet mandates that clinical procedures utilize the lowest possible radiation dose necessary to achieve the required diagnostic or therapeutic objective without compromising procedural quality. For a technically demanding procedure like PAE, adhering to the ALARA principle requires a sophisticated understanding of the factors that influence radiation dose and a diligent application of dose-reduction strategies.

Therefore, the aims of this review are threefold: first, to synthesize the current evidence on patient and operator radiation doses reported during PAE; second, to critically examine the patient-, operator-, and technology-related factors that contribute to dose variability; and third, to establish a practical, evidence-based framework of best practices for dose optimization. By consolidating this knowledge, this article will serve as a definitive guide for clinicians to benchmark their practice, enhance safety protocols, and ensure the continued safe application of this valuable therapy.

2. Materials and Methods

2.1. The PAE Procedure

PAE has rapidly evolved into a cornerstone minimally invasive therapy for men suffering from the effects of BPH. A comprehensive understanding of the clinical problem, the complex vascular anatomy of the prostate, and the procedural techniques is essential before delving into the specifics of radiation safety.

2.1.1. BPH and LUTS

BPH is a common, non-malignant enlargement of the prostate gland that primarily affects aging men. Its prevalence is striking, affecting approximately 80% of men over the age of 70 [7]. The progressive growth of the prostate, particularly in the transitional zone, can compress the urethra, leading to a constellation of debilitating Lower Urinary Tract Symptoms (LUTS). These symptoms are broadly categorized into storage issues (frequency, urgency, nocturia) and voiding issues (hesitancy, weak stream, incomplete emptying). The impact of moderate to severe LUTS on a patient's quality of life (QoL) is significant, prompting many to seek treatment beyond medical management. PAE offers a less invasive alternative to surgical procedures, such as TURP, demonstrating comparable improvements in symptom scores and QoL with lower complication rates and hospital stays [4,5].

2.1.2. Prostatic Arterial Anatomy

The technical success of PAE hinges on the interventional radiologist's ability to navigate the complex and highly variable male pelvic arterial anatomy [8]. The prostatic artery (PA) typically originates from the anterior division of the internal iliac artery. However, its exact origin can vary substantially, making each procedure unique. According to a comprehensive review by Bilhim (2023), the four most frequent origins account for approximately 90% of cases: the superior vesical

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artery and the internal pudendal artery each contribute around 30%, while the common gluteal-pudendal trunk and the obturator artery are responsible for about 15% each [9].

The prostate gland itself has a dual blood supply, with distinct arteries feeding the central and peripheral glands. The primary target for embolization is the artery supplying the central gland, as this is the region responsible for BPH. In about 40% of patients, these arteries arise independently, requiring precise identification to ensure effective treatment and avoid non-target embolization [9]. Furthermore, extensive anastomoses with arteries supplying the bladder, rectum, and penis are present in over half of patients, necessitating careful angiographic evaluation to prevent ischemic complications.

2.1.3. The PAE Technique

The PAE procedure begins with a thorough pre-procedural assessment, often including MR or CT angiography to map the patient's specific pelvic vascular anatomy. This pre-procedural planning can reduce procedural time and radiation exposure by guiding the initial catheterization [9,10]. Vascular access is typically gained via the femoral or, increasingly, the radial artery [11–14].

Using a diagnostic catheter, an initial pelvic angiogram is often performed. Subsequently, a microcatheter (typically 1.7–2.4 F) is navigated into the internal iliac artery. The operator then meticulously identifies and selectively catheterizes the PA on one side. Steep ipsilateral oblique angiographic projections are crucial for visualizing the PA origin. Once the microcatheter is confirmed to be in the artery supplying the prostatic central gland—a step greatly aided by CBCT—the embolic agent is slowly injected until stasis is achieved. The process is then repeated on the contralateral side to ensure complete devascularization of the hyperplastic tissue. A key procedural goal is achieving complete bilateral embolization, as unilateral treatment is a known predictor of clinical failure [5,9].

2.1.4. Embolic Agents

A variety of embolic agents are used in PAE, with the choice often guided by operator preference and the specific vascular anatomy encountered during the procedure. To date, no single agent has demonstrated superior clinical outcomes [9]. Among the most commonly used agents are microspheres, which are available in various materials and sizes. Spherical options such as tris-acryl gelatin microspheres and polyzene-coated hydrogel microspheres are typically used in the 300–500 μm range. Notably, smaller microspheres (less than 300 μm) have been associated with a higher incidence of adverse events without offering additional clinical benefit. Non-spherical polyvinyl alcohol (PVA) particles, usually in the 100–300 μm range, are another frequently employed option. More recently, liquid embolic agents such as n-butyl cyanoacrylate (nBCA) have been introduced, offering rapid action and potential advantages in procedural efficiency [9,15].

2.2. Fundamentals of Radiation Measurement in PAE

A meaningful discussion of radiation safety in PAE requires a clear understanding of the specific metrics used to quantify radiation exposure. These dosimetric quantities are not interchangeable; each provides a different and crucial piece of information about the potential risks to the patient and staff.

2.2.1. Key Dosimetric Quantities and Their Clinical Relevance

- **Fluoroscopy Time (FT):** Measured in minutes, this is the total duration the X-ray beam is active during fluoroscopic guidance [16]. While simple to record, FT is an incomplete and often poor proxy for total radiation dose, as it does not account for radiation intensity (dose rate) or the use of higher-dose acquisition modes like DSA and CBCT.
- **Dose Area Product (DAP) or Kerma-Area Product (KAP):** Reported in Gray-centimeters squared (Gy·cm2) or a variant thereof, DAP is a measure of the total radiation energy delivered

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to the patient. It is calculated by multiplying the air kerma (dose) by the area of the X-ray beam. DAP is considered a robust indicator of the overall radiation burden and is the primary metric used for estimating the stochastic risk of cancer induction.

- **Cumulative Air Kerma (CAK):** Measured in milligrays (mGy), CAK represents the cumulative radiation dose delivered to a specific point in space, known as the interventional reference point. This metric is crucial for monitoring and predicting the risk of deterministic skin injuries, such as erythema or epilation, as it approximates the dose delivered to the patient's skin at the beam's entry point.
- **Peak Skin Dose (PSD):** Also measured in mGy, PSD is the highest radiation dose received by any single area of the patient's skin. It is the most accurate predictor of deterministic skin injury. While direct measurement can be complex, values are often estimated from CAK and procedural geometry or measured directly using radiochromic film, as demonstrated in early PAE safety studies [17,18].
- **Effective Dose (ED):** Reported in millisieverts (mSv), ED is a calculated, whole-body equivalent dose that accounts for the varying radiosensitivity of different organs. It allows for the comparison of long-term stochastic risk across different types of radiologic procedures. ED is typically calculated by multiplying the DAP value by an established conversion coefficient specific to the anatomic region being imaged [19].

2.2.2. Deterministic vs. Stochastic Radiation Effects

The metrics above are used to assess two distinct types of biological effects:

- **Deterministic Effects:** These are direct tissue reactions that occur only after a certain threshold dose is exceeded. The severity of the effect increases with the dose. In PAE, the primary concern is skin injury, which can range from transient erythema to, in extreme cases, necrosis. CAK and PSD are the most relevant metrics for preventing these effects.
- **Stochastic Effects:** These are probabilistic effects, primarily radiation-induced cancer, for which no safe dose threshold is assumed. The probability of the effect occurring increases with dose, but the severity of the potential cancer is independent of the dose. DAP and ED are the key metrics used to quantify and manage this risk.

2.2.3. Radiation Contribution from Different Imaging Modalities

The total radiation dose in a PAE procedure is a composite of three primary imaging modes. While fluoroscopy often constitutes the longest duration, it is frequently not the largest contributor to the total dose. A detailed analysis by Schott et al. (2019) found that in their PAE protocol, DSA accounted for the largest portion of the total DAP (43.3%), followed by CBCT (30.3%), with fluoroscopy contributing the remaining 26.4% [20]. Similarly, a prospective study by Andrade et al. (2017) reported that DSA was the main source of radiation, responsible for 71.5% of the total DAP, followed by fluoroscopy (19.9%) and cone-beam CT (8.6%) [17]. In contrast, an earlier study by Garzon et al. (2016), which used CBCT more sparingly, reported a different distribution, with DSA responsible for the vast majority of the dose (79.8%), followed by fluoroscopy (17.2%) and CBCT (3%) [18]. This highlights how different institutional protocols, particularly regarding CBCT utilization, can dramatically alter the dose distribution.

3. Results

3.1. Current Evidence

Having established the fundamental metrics of radiation measurement, this section reviews the current body of literature to quantify the typical radiation doses associated with PAE. The published data show a wide range of values, reflecting variations in patient populations, operator experience, and, most notably, procedural techniques and technology (Table 1).

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Table 1. Summary of Selected Studies Reporting Radiation Doses in Prostatic Artery Embolization (PAE).

Author, Year	Study Design	No. of Patients (n)	Embolic Agents	Primary Radiation Metrics (Mean or Median)	FT (min)
Ayyagari et al. (2024) [19]	Retrospective Multicenter	1476	No specified	**CAK:** 1177 mGy (Fixed System)	35
Sajan et al. (2024) [23]	Retrospective Single-Center	53	No specified	**DAP:** 72.7–259.3 Gy·cm² **CAK:** 490–2020 mGy	32.1-37.3
Sanghvi et al. (2024) [15]	Retrospective Single-Center	98	Microspheres vs. nBCA	**DAP:** 124.2–135.8 Gy·cm² **CAK:** 544–586.3 mGy	19.8-30.0
Barral et al. (2024) [21]	Retrospective Comparative	77 (VIS Group)	300-500 µm Microspheres	**DAP:** 110.4 Gy·cm² **CAK:** 642 mGy	35.6
Ngov et al. (2023) [25]	Retrospective Single-Center	56	No specified	**CAK:** 3747.1 mGy	33.9
Svarc et al. (2022) [24]	Retrospective Multicenter	352	No specified	**DAP:** Variable (60–379 Gy·cm²)	38.0
Moschouris et al. (2022) [22]	Retrospective Single-Center	59	No specified	**DAP:** 164.2 Gy·cm²	NA
Kriechenbauer et al. (2020) [26]	Retrospective Single-Center	250	No specified	**DAP:** 247.1 Gy·cm² **ESD:** 2400 mGy	42.0
Schott et al. (2019) [20]	Retrospective Single-Center	100	250 µm Hydrogel Microspheres	**DAP:** 134.4 Gy·cm²	30.9
Andrade et al. (2017) [17]	Prospective Single-Center	25	PVA & Hydrogel Microspheres	**DAP:** 450.7 Gy·cm² **PSD:** 2420 mGy	30.9
Garzon et al. (2016) [18]	Prospective Single-Center	5	Particles	**DAP:** 523.9 Gy·cm² **PSD:** 2674 mGy	29.1

DAP = Dose Area Product; CAK = Cumulative Air Kerma; ESD = Entrance Skin Dose; FT = Fluoroscopy Time; PSD = Peak Skin Dose; N/A = Not Available. All values are based on the first 50 patients in the Kriechenbauer et al. study, reflecting the initial learning curve.

3.1.1. Benchmarking Radiation Exposure

To establish a reliable benchmark for PAE-related radiation exposure, large multicenter studies are invaluable. The most comprehensive data to date comes from a retrospective study by Ayyagari et al. (2024), which analyzed 1,476 patients across 10 high-volume international centers. This study reported a median procedure ED of 17.8 mSv for procedures performed with fixed interventional fluoroscopy units and 12.3 mSv for those using mobile units. For context, this is roughly equivalent to the dose from 2 to 3 abdominal CT scans. Importantly, despite the significant radiation dose, no radiation-related adverse events, such as skin injury, were reported within the 90-day follow-up period across the entire cohort [19].

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3.1.2. Typical Dose Ranges Across Literature

While large studies provide a median, single-center reports illustrate the broad spectrum of doses encountered in clinical practice. Fluoroscopy Time (FT), a commonly reported but variable metric, often ranges from 20 to 50 minutes [15,21].

DAP, a more robust metric of total radiation burden, shows significant variability. For example, prospective single-center studies have reported mean total DAP values of 450.7 Gy·cm² [17] and 134.4 Gy·cm² [20], while another study reported a mean of 164.2 Gy·cm² [22]. This highlights that a "typical" DAP can vary by a factor of three or more between institutions. Similarly, reported values for CAK often fall in the range of 500 to 2,500 mGy [17,23]. The potential for high skin doses was highlighted in an early prospective study by Garzon et al. (2016), which used direct measurement with radiochromic film to show a mean PSD of 2674 mGy, with all five patients in their cohort exceeding the 2 Gy threshold for transient erythema [18]. Likewise, Andrade et al. (2017) prospectively measured a mean PSD of 2,420.3 mGy. Crucially, despite this mean dose being above the 2 Gy threshold for skin injury, clinical follow-up at 3 months revealed no visible skin lesions in any of the 25 patients, providing important clinical context to these high skin dose values [17].

3.1.3. Variability in Doses: The Impact of Institutional Protocols and Equipment

The wide range of reported doses is not random; it is heavily influenced by local protocols and the specific technology employed. A retrospective study comparing three Scandinavian centers by Svarc et al. (2022) found considerable variation in DAP between the centers, even after accounting for patient factors. This underscores the impact of institutional technique [24]. Similarly, the high mean air kerma of 3747.1 mGy reported by Ngov et al. (2023) was generated from procedures performed on a single, high-end biplane angiography system, where CBCT was utilized in nearly all cases (92.9%), providing important context for their results [25].

This effect is starkly illustrated in a study by Sajan et al. (2024), which compared PAE procedures performed by a single interventionalist on two different angiography systems within the same institution. One system (AS2) resulted in a mean total kerma-area product of 72.7 Gy·cm², while the other (AS1) produced a mean of 259.3 Gy·cm²—a greater than threefold difference. The study concluded that the angiography system itself has a significant impact on the ability to leverage CBCT and on overall patient radiation exposure [23].

3.1.4. The Contribution of Pre-Procedural Planning CTA

The total radiation burden on a patient undergoing PAE is not limited to the interventional procedure alone. Pre-procedural planning with CTA is a common practice to delineate the complex pelvic arterial anatomy. Moschouris et al. (2022) specifically evaluated this contribution and found that the ED from the planning CTA represented, on average, 21.2% of the ED from the PAE procedure itself. The authors conclude that the radiation from planning CTA is not negligible and must be considered as part of the overall radiation exposure for the patient's course of treatment [22].

3.2. Key Factors Influencing Radiation Exposure

The significant variability in radiation doses reported for PAE is the result of a complex interplay between patient characteristics, operator experience, and specific procedural choices.

3.2.1. Patient-Related Factors

- **Body Mass Index (BMI):** The most consistently reported patient factor influencing radiation dose is BMI. Larger patients require higher X-ray penetration to maintain image quality, resulting in increased radiation output from the angiography system. This direct relationship has been robustly demonstrated across multiple studies. Ayyagari et al. (2024) found a positive correlation between BMI and both CAK and ED [19]. This relationship holds true even when procedural times are shorter; for instance, Ngov et al. (2023) observed that while procedure times

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paradoxically decreased in patients with higher BMI, the air kerma still increased significantly, a finding likely attributable to the automatic or manual increase of X-ray tube output (kVp) to maintain image quality in larger patients [25]. Svarc et al. (2022) also found that each unit increase in BMI was a significant predictor of increased DAP [24].

- **Anatomic Complexity:** The highly variable nature of the prostatic arterial supply is a primary driver of procedural complexity and, consequently, radiation dose. Patients with unusual arterial origins, steep vessel angulation, or significant atherosclerosis often require longer FTs and more DSA acquisitions [9].
- **Radiopaque Implants:** The presence of metallic hardware, such as total hip arthroplasty prostheses, can degrade image quality. The multicenter analysis by Ayyagari et al. (2024) reported a significantly higher median CAK in patients with radiopaque implants compared to those without [19].

3.2.2. Operator and Center-Related Factors

- **The Learning Curve and Experience:** PAE is a technically demanding procedure with a well-documented learning curve that directly impacts radiation exposure. Multiple studies have shown that as operators and institutions gain experience, procedural efficiency improves, and radiation doses decrease. A 4-year single-center study by Kriechenbauer et al. (2020) demonstrated that DAP, ED, and entrance skin dose were all significantly higher in the first 50 cases compared to the subsequent 50 [26]. Similarly, Svarc et al. (2022) found in their multicenter study that for each 10 additional patients treated, there was a statistically significant decrease in DAP [24]. However, it is noteworthy that this effect may plateau among already experienced operators. A study by Schott et al. (2019), involving three interventionists with over 10 years of experience each, found no significant correlation between the number of procedures performed and a further decrease in DAP, suggesting the major dose reductions occur during the initial learning curve [20]. Furthermore, advanced technologies can offer dose savings even for experts. Barral et al. (2024) demonstrated that the implementation of virtual injection software provided significant radiation and time savings for operators who already had 8–10 years of PAE experience [21].

3.2.3. Procedure-Related Factors

- **Choice of Embolic Agent:** The type of embolic material used can influence procedural dynamics. A comparative study by Sanghvi et al. (2024) found that the use of nBCA resulted in a significantly lower median FT compared to microspheres (19.8 minutes vs. 30 minutes). However, this reduction did not translate to a statistically significant difference in air kerma or DAP [15].
- **Unilateral vs. Bilateral Embolization:** The impact of performing unilateral versus bilateral PAE is complex. Logically, a unilateral procedure might be expected to use less radiation. Indeed, Svarc et al. (2022) found that an intended unilateral embolization was a significant predictor of decreased DAP [24]. In contrast, Ngov et al. (2023) reported the intriguing finding that a completed bilateral PAE was not associated with a significantly higher air kerma compared to a unilateral procedure, despite bilateral cases requiring a significantly greater number of imaging acquisitions [25]. This suggests that the procedural difficulty of the first targeted artery may be the primary driver of the total dose in many cases.

3.3. Best Practices for Dose Optimization

Adhering to the ALARA principle during PAE requires a multifaceted approach. Optimization is not achieved by a single action but through the diligent application of best practices before, during, and after the procedure. This section outlines an evidence-based framework for minimizing radiation

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exposure while maintaining procedural and clinical efficacy, the key points of which are summarized in Table 2.

Table 2. Summary of Best Practices for Radiation Dose Optimization in PAE.

Category	Best Practice / Technique	Rationale and Key Evidence
Pre-Procedural	Pre-procedural CTA/MRA Planning	Provides an anatomical "roadmap" to reduce the need for extensive diagnostic angiography, thereby decreasing procedural time and radiation. Supported by [9,22,24].
Intra-Procedural (Technology)	Utilize Modern Angiography Systems	Newer systems have advanced hardware and software dose-saving features that can significantly reduce radiation output. A >3-fold dose difference was observed between two systems [23].
	Judicious Use of Cone-Beam CT (CBCT)	CBCT is a powerful tool for confirming anatomy and avoiding non-target embolization. It should be used to *replace* multiple DSA runs, not as an addition, to optimize its dose-saving potential [7,9].
	Employ Virtual Injection Software	Creates a 3D roadmap overlay on live fluoroscopy, significantly reducing the number of DSA runs, FT, DAP, and air kerma [21].
Intra-Procedural (Technique)	Fundamental ALARA Principles	Tight collimation, minimizing electronic magnification, using "Last Image Hold," and optimizing patient-detector distance are universally effective methods to reduce dose and scatter.
	Low-Dose Acquisition Protocols	Using specifically designed low-dose settings for DSA can directly reduce radiation output without compromising necessary image quality. A 30% reduction in DAP was demonstrated [22].
	Prioritize AP Projections	Reduces the x-ray path length through the patient compared to steep oblique views, lowering both patient and operator dose. A 26.7% DAP reduction was shown by using AP-only views for at least one side [22].

3.3.1. Pre-Procedural Best Practices

Effective radiation safety begins before the patient enters the angiography suite. Performing a pre-procedural CTA or MRA to map the patient's unique pelvic arterial anatomy is a validated strategy to improve procedural efficiency and reduce the need for extensive diagnostic angiography [9,22,24].

3.3.2. Best Intra-Procedural Practices (Technology)

- **Modern Angiography Systems:** The choice of equipment can have a profound impact on radiation dose, with newer systems potentially offering more than a threefold dose reduction [23].
- **Judicious Use of Cone-Beam CT (CBCT):** CBCT is a powerful tool for confirming anatomy and preventing non-target embolization [7]. A critical best practice is to use CBCT instead of, not as an addition to, multiple DSA acquisitions [9]. For less experienced operators, CBCT may increase the total dose, underscoring the need for a strategic application [27].
- **Advanced Guidance Software:** The use of virtual injection software (VIS) represents a significant advance in dose optimization. This technology uses data from a single CBCT acquisition to create a 3D vascular roadmap that can be overlaid on live fluoroscopy. A comparative study by Barral et al. (2024) provided robust evidence for its efficacy, demonstrating that the use of VIS cut the mean number of DSA acquisitions in half (from 16.8 to 8.6 runs) and significantly reduced DAP, air kerma, and FT. Furthermore, the study's multivariate analysis confirmed that VIS was an independent predictor of radiation reduction, and its implementation also reduced the mean total procedural time by 21 minutes [21]. For example, Schott et al. (2019) described a successful low-dose protocol that relied on an initial

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CBCT acquisition to create a 3D roadmap for catheter guidance, which allowed for the minimization of subsequent DSA runs [20].

3.3.3. Best Intra-Procedural Practices (Technique)

- **Fundamental ALARA Techniques:** Always use tight collimation, minimize electronic magnification, use "Last Image Hold," and keep the image receptor as close to the patient as possible.
- **Optimize Fluoroscopy and Acquisitions:** Utilize the lowest possible fluoroscopy frame rate. A study by Moschouris et al. (2022) found that applying a specific low-dose protocol (LDP) for DSA resulted in a 30% reduction in DAP. Using the "roadmap" feature instead of repeated DSA runs is another effective strategy [22].
- **Geometric Considerations:** Prioritize anteroposterior (AP) projections whenever possible, as steep oblique views significantly increase patient and operator dose. Moschouris et al. (2022) demonstrated a 26.7% DAP reduction by performing the embolization of at least one pelvic side using only AP views [22].

3.4. Occupational Exposure and Staff Safety

Staff exposure during PAE is almost entirely due to scatter radiation originating from the patient.

3.4.1. Doses to the Primary Operator

The interventional radiologist is typically positioned closest to the radiation source and therefore receives the highest occupational dose. A prospective study by Andrade et al. (2017) measured an average ED of 17 μSv per procedure for the primary operator. The study provided detailed dosimetry via thermoluminescent dosimeters, reporting a mean equivalent dose per procedure of 378 μSv to the left eye and 781 μSv to the left wrist, noting that the operator did not use leaded eyeglasses. This finding underscores the significant, direct exposure to the lens of the eye when specific protective gear is not used [17]. Reinforcing this, Garzon et al. (2016) reported high mean doses per procedure to the operator's left eye (478 μSv), left wrist (720 μSv), and left foot (2099 μSv), linking the high values to the frequent use of left anterior oblique (LAO) projections [18].

3.4.2. Radiation Exposure to Ancillary Staff

Radiation safety protocols must be extended to all personnel. Anesthetists, in particular, may be at risk. A study by Garzon and Khoury (2019) found that without proper protection, an anesthetist could exceed the annual eye lens dose limit of 20 mSv by assisting in just one PAE procedure per week [28].

3.4.3. Essential Protective Measures

Minimizing occupational exposure relies on a combination of personal protective equipment (PPE) and structural shielding. All personnel must wear lead aprons and thyroid collars. Leaded eyewear is essential. However, the most effective tools are structural shields, such as ceiling-suspended lead screens and table-side lead curtains. A study by Garzon et al. (2016) directly linked high staff doses to the improper use of the suspended lead screen and the lead curtain during procedures [18].

4. Discussion

The preceding sections have established that while PAE is a safe and effective therapy, it involves a complex relationship with ionizing radiation. The evidence demonstrates that the radiation dose is not a fixed quantity, but a highly variable outcome influenced by patient, operator,

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and technological factors. This discussion aims to synthesize these findings, critically evaluate the current state of the literature, and propose future directions for research and practice.

Based on the evidence, PAE should be classified as a procedure with a substantial but manageable radiation dose. The median ED of approximately 17.8 mSv reported in a large multicenter study is significant, comparable to the dose from roughly two to three standard abdominopelvic CT scans or several years of natural background radiation [19]. Early prospective dosimetry studies placed PAE in the same dose category as other complex procedures like neurointerventional embolization and transjugular intrahepatic portosystemic shunt (TIPS) creation, with mean PSD frequently exceeding the 2 Gy threshold for transient erythema [17,18].

However, the question is not simply whether the dose is high, but whether it is optimized. The remarkable evolution of the procedure is demonstrated by a threefold reduction in mean PSD since its initial publications [21]. The wide variability in reported DAP across the literature, with some centers achieving doses three times lower than others using advanced technology [23]—proves that significant opportunities for optimization exist. The data strongly suggest that the adoption of specific protocols, particularly those that leverage CBCT with advanced guidance software to replace rather than supplement numerous DSA runs, is a key driver of these lower doses [20,21]. Therefore, while PAE has the potential for high radiation exposure, adherence to modern best practices can place it well within an acceptable safety margin.

While our understanding of PAE-related radiation has grown, the current body of evidence has notable limitations that must be acknowledged. Most published studies are retrospective and single-center in design, which introduces potential for selection bias and makes it difficult to generalize findings. This is compounded by a lack of standardized reporting for radiation metrics, making direct comparisons between studies challenging and hindering a full understanding of long-term stochastic risks. The need for a more rigorous, evidence-based approach is highlighted by the publication of a protocol for a systematic review by Liu et al. (2022), who noted that the radiation risks had not been studied systematically so far [29]. Furthermore, a specific point of controversy in the literature is the impact of CBCT on radiation dose. Its effect is highly dependent on operator experience and institutional protocol; for some, it may increase the total dose, while for others, it is a key tool for dose reduction [20,27]. This paradox highlights that it is the protocol and not the technology alone that dictates the final dose.

To address these limitations and continue to improve safety, the field should move in several key directions. A consensus should be established for the mandatory reporting of key radiation metrics in all future PAE publications, which would facilitate more meaningful meta-analyses and enable the creation of national or international Diagnostic Reference Levels (DRLs). These DRLs would allow individual operators and institutions to benchmark their performance against a recognized standard, driving quality improvement. Future research should also include prospective, ideally randomized, trials that are specifically designed to evaluate the impact of different technologies and techniques on both radiation dose and clinical outcomes. Ultimately, technological and methodological improvements must be paired with a strong radiation protection culture, as noted by Garzon et al. (2016) [18]. This includes not just wearing PPE, but the diligent use of structural shielding, a conscious effort to minimize dose-intensive projections, and a team-based approach to safety that ensures technological advances translate into real-world dose reduction for both patients and the entire procedural team.

5. Conclusions

PAE is a transformative, minimally invasive therapy for BPH, but its procedural complexity necessitates a deliberate and informed approach to radiation safety. The evidence synthesized in this review confirms that PAE is associated with a substantial but highly variable radiation dose, influenced by a confluence of patient, operator, and technological factors. The central conclusion of this review is that the radiation burden associated with PAE is eminently manageable. Through the consistent and multi-faceted application of best practice—spanning detailed pre-procedural

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planning, the adoption of advanced low-dose imaging technologies, meticulous intra-procedural technique, and a steadfast commitment to occupational safety—clinicians can significantly reduce exposure to both patients and staff. The goal of radiation optimization is not to curtail the use of this valuable procedure but to ensure its continued and responsible growth as a safe, effective, and patient-centered therapy.

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