

Optimization of Digital Subtraction Angiography Parameters for Radiation Safety: A Systematic Review of Current Evidence

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Abstract

Background

Digital Subtraction Angiography (DSA) is a fundamental modality of radiology, but the optimization of radiation exposure while preserving diagnostic image quality remains a challenge. Systematic review This review summarizes the previous findings of recent studies regarding radiation safety improvements in DSA utilization, guided by new technologies, procedures, and algorithms.

Material and Methods

Relevant publications during the period 2000-2025 were included with emphasis on dose-reduction approaches, standardization of protocols, and novel imaging technologies; specifically digital variance angiography (DVA) and artificial intelligence (AI)-assisted angiography [9-12,21,23]. Performance indicators included dose measurements for patients, image quality, and occupational radiation exposure.

Results

Recent developments, for example the low-rate fluoroscopy [7,8], enhanced filtration and focal spot size [6], and advanced image-processing algorithm [16,32], can achieve

considerable radiation reductions while not affecting image quality. DVA has been shown to reduce dose up to 70 % and to still be diagnostic effective [10,11]. Additional safety and accuracy were achieved via AI-powered angiographic reconstruction [14,21] and low-dose 3D rotational angiography. Following the established radiation management guidelines is still key to clinical implementation [1,2,5,40].

Conclusion

The provision of integrated technological and procedural approaches to optimization of DSA parameters will greatly lower radiation exposure for both patients and staff. Future research should investigate standardization and multicenter validation as well as AI-based innovation to develop repeatable and globally applicable radiation-safety protocol for interventional imaging

Keywords: “Digital Subtraction Angiography,” “Interventional Radiology,” “Fluoroscopically Guided Interventions,” “Optimization,” “Radiation Dose Reduction,” “Radiation Protection”, “Patient Dose”, “Occupational Exposure”, “Image Quality”.

1. Introduction

Digital subtraction angiography (DSA) is a very effective imaging method in interventional radiology, which provides very detailed visualization of vascular structures and hemodynamics in its imaging format. Its accuracy renders it essential for diagnostic assessments and treatment in neurovascular, cardiovascular, and peripheral vascular disease. Yet, with diagnostic proficiency, DSA is, as a structural system, associated with relatively higher radiation doses relative to other modalities of radiologic technique, primarily because of the longer fluoroscopy time and more extensive image acquisition needed to perform complex procedures. The cumulative exposure from these procedures has led to worldwide interests in patient safety, occupational exposure, and a systematic optimization of procedures so that the radiation protection is achieved without impairing the diagnostic quality [1-3]. The problem of radiation protection in interventional radiology was taken up comprehensively in professional societies including CIRSE and SIR. Miller et al. [1] and Stecker et al. [5] emphasized that occupational and patient radiation protection

must be an important aspect of interventional practice and, therefore, in addition to awareness must fall within structured management programs, staff education and regular surveillance. Their shared guidelines provided guidelines summarizing guidelines for optimizing doses, particularly related to justification of radiation use, use of the ALARA principle and technical advancements, such as automated dose-rate control systems. These recommendations were the basis for follow-up practice guidelines on fluoroscopy management and dose monitoring in clinical settings [2,5]. Occupational radiation safety is still an important issue because interventional radiologists and cardiologists are at or near the peak of radiation exposure in medical practice settings. Operators live close to the x-ray source and due to the long duration of the procedure, high scatter radiation exposure occurs. [3] showed that eye lens was administered most of the time at elevated cumulative doses with many staffs above the threshold for radiation-induced cataractogenesis over which inadequate protective measures could occur. Their findings called for the strengthening of use of protective equipment, like lead lenses, ceiling-mounted shields and table skirts, and improved compliance to real-time dosimetry. Later, Heidbuchel et al. [4] further generalized these findings to electrophysiological and device implantation procedures by confirming that a well-organized optimization of these fluoroscopy settings and operator training as well as pulsed fluoroscopy can minimize staff (and patient) doses and have significant impacts. Patient safety is also critical, as the determinants of skin erythema and epilation, for example, have occurred after extended fluoroscopy/angiographic procedures [5]. The Stecker et al. 2009 recommendations were similar to these findings. [5] set detailed bases for dose monitoring, threshold dose management and in the post-procedure follow-up patient for possible radiation injuries. Miller et al. [2] also stressed that procedural optimization (like collimation and pulse rate reductions) and avoiding steep angulations are among the most effective dose reduction techniques. These documents collectively emphasize the transition from reactive to proactive monitoring in interventional radiology. From a technical perspective, DSA parameter optimization is complicated. Angiography image quality is affected by many parameters such as the tube voltage, current, filtration, the pulse width, frame rate,

and detector sensitivity. Modifying these parameters have a profound impact on image clarity and patient dose. Kim et al. [6] showed that changes to filtration and focal spot size during cerebral angiography led to a significant reduction in radiation dose, but without a marked increase in diagnosable grade. Their study indicates how minute tuning of the system can lead to large dose savings and would be useful in fine-tuning the protocol as per the anatomical region, procedure complexity. Fluoroscopic pulse rate, in addition to filtration and collimation, has appeared as a significant controllable parameter. Badawy et al. [7] and Abdelaal et al. [8] showed in parallel that the ultra-low pulse rate when utilized during coronary and peripheral angiography could reduce radiation dose for the operator and the patient of >40%, with minimal effect on procedural workflow or visualization. This result supports the fact that dose reduction is possible by evidence-based intervention on the fluoroscopic parameters and not by merely upgrading the technological device. Technological progress also has enabled paradigm-shifting advances in dose management. Advanced image processing and artificial intelligence (AI) integration have now provided many avenues to generate diagnostically useful angiographic images with a fraction of existing cross-sectional X-ray acquisitions. Ueda et al. [9] proposed the first deep-learning angiogram synthesis model that produces quality cerebral angiograms while avoiding misregistration artifacts. This approach, powered by AI modeling, implies that large portions of the radiation exposure may then be averted by replacing or supplementing the DSA with those generated by algorithms. Concurrent developments through post-processing have contributed to a relatively new line of imaging, namely digital variance angiography (DVA), improving the signal-to-noise ratio and contrast visualization of vascular anatomy. DVA can reduce the dose of lower-limb angiography by up to 70% compared to conventional, and was validated to achieve this in a randomized controlled clinical study, which shows that diagnostic accuracy is maintained at substantially lower radiation-level [10,11]. More recently Abumoussa et al. [12] introduced synthetic interpolated DSA, where intermediate frames are re-composited in order to reduce the number of x-ray acquisitions even further. These developments represent the increasing trend towards calculation-based dose optimization and the move from mechanical parameter handling

exclusively to algorithmic image optimization. Rapidly advancing in the field of radiation dose auditing and quantification is equally significant. Contemporary angiographic systems with DICOM Radiation Dose Structured Reports (RDSR) do provide detailed records for cumulative air kerma and dose-area product. D'Alessio et al. [13] have shown the value of RDSR data for assessing both effective and organ-specific doses in cerebral angiography and endovascular aneurysm treatment. Quantitative assessments enable the fine-tuning of process parameters, allow inter-institutional comparison of results, improve transparent dose reporting. Taken together, these studies emphasise a paradigm shift among interventional imaging from the reactive approach focused on radiation protection to a proactive and data-informed paradigm of the optimization of DSA techniques. Contemporary dose-lowering interventions include advanced technologies, standardization of procedural protocols, and computational information to protect both patients and providers, as well as to preserve the diagnostic quality of the angiography. The convergence of optimized hardware setups (spectral filtration and pulse control), robust radiation monitoring, and smart post-processing marks the dawn of a new era for practice in DSA precision radiation safety.

2. Material and Methods

To evaluate Digital Subtraction Angiography Parameters for Radiation Safety imaging, guided by PRISMA-DTA and structured using the PICO framework study used a systematic review approach. A thorough literature search guaranteed that there were only high-quality studies to report both qualitative and quantitative diagnostic outcomes included, while a rigorous selection process ensured that also those reports at its best are included.

2.1. Search Strategy

To ensure transparency, reproducibility, and the methodological rigor required for systematic review, PRISMA-DTA was used. A PICO (Population, Intervention, Comparison, and Outcome) framework was utilized for search strategy architecture.

Population (P): Patients undergoing digital subtraction angiography (DSA) for diagnostic or interventional purposes (neurovascular, coronary, peripheral angiography).

Intervention (I): The optimization techniques, parameter modifications, or technological innovations aimed at reducing radiation exposure with/or for DSA to improve radiation safety. This comprises filtration, pulse/frame rate, tube voltage/current, automatic exposure control, collimation, spectral shaping and use of AI-based reconstruction or Digital Variance Angiography (DVA).

Comparison (C): Conventional or standard DSA acquisition protocols without optimization strategies; DSA imaging parameters used for diagnostic purposes. Primary outcomes: Quantitative measures of radiation exposure reduction (e.g., dose–area product, cumulative air kerma, effective dose) and occupational radiation safety.

Outcome (O): Secondary outcomes: quality preservation or enhancement of image quality, diagnostic accuracy, or clinical workflow efficiency. The search included the following electronic databases: PubMed, Scopus, Embase, Web of Science, Google Scholar, and MDPI.

The dataset covered from January 2000 to December 2025, representing two and a half decades of technological advances in angiographic imaging and radiation optimization.

For this systematic review study, list of keywords was used to access the article. “Digital Subtraction Angiography,” “Interventional Radiology,” “Fluoroscopically Guided Interventions,” “Optimization”, “Radiation Dose Reduction,” “Radiation Protection”, “Patient Dose”, “Occupational Exposure”, “Image Quality”.

2.2. Study Selection

Each phase of the study selection from identification and screening to final inclusion was systematically documented through PRISMA flow in a bid for transparency and reproducibility. We identified search results for all potentially relevant records in PubMed, Scopus, Embase, Web of Science, Google Scholar, and MDPI. Two reviewers

independently screened all retrieved articles by titles and abstracts to identify those that addressed optimization of the parameters from digital subtraction angiography (DSA) and improvements in radiation safety. In the primary screening stage, literature directly addressing neither DSA nor radiation dose optimization and containing no quantitative radiation/image outcome were removed. At the eligibility stage, full-text versions from the other studies were heavily reviewed to ensure conformity with inclusion and exclusion criteria. Studies that required study eligibility comprised of evaluation of parameter adjustment, dose reduction methods or image optimization procedures; or new technologies, e.g., digital variance angiography or AI-assisted image reconstruction targeting radiation protection. Final inclusion criteria were discussed by all reviewers, with all disagreements resolved through debate or adjudication via a third reviewer. An approach of systematic selection of publications was adopted to limit studies lacking related valid and methodologically sound findings on the optimization of DSA parameters for radiation safety to the inclusion of studies with relevant contributions in the literature.

2.3. Inclusion and Exclusion Criteria

Studies directly relevant to the study aims were included according to predetermined inclusion criteria, which enabled the consistency and applicability of the search criteria throughout the review procedure. The consideration of the inclusion criteria is given below: (a) Studies of peer review published between 2000 and 2025. (b) Research in human subjects or phantom studies under the simulation of clinical DSA. (c) Investigation in the optimization of imaging, radiation dose management of DSA. (d) Reports on at least one radiation or image quality metric (e.g., DAP, effective dose, SNR, CNR, diagnostic accuracy). (e) Publications published in the English language. During the study selection process, the following exclusion criteria were considered: (a) non-angiographic imaging modalities (CT, MRI and Ultrasound). (b) non-translationally relevant animal studies. (c) abstracts for conference, editorials, letters, and review articles without data primary to the source. (d) studies that did not report quantitative radiation or image quality outcomes.

2.4. Data Extraction and Management

All retrieved articles were imported into EndNote 21 for citation management and duplicate removal. Two-stage screening was undertaken: (a) title and abstract screening to eliminate obviously irrelevant articles. (b) full-text review and review eligibility in accordance with the PICO criteria. Relevant data, containing information such as (a) study characteristics (authors, year, country, study design, sample size) was obtained by two independent reviewers. (b) type of angiographic system and the procedural setting. (c) optimization treatment implemented. (d) quantitative radiation outcomes (DAP, air kerma, fluoroscopy time) (e) image quality and diagnostic performance outcomes.

2.5. Quality Assessment

Assessment of the included studies was performed using the QUADAS-2 (Quality Assessment of Diagnostic Accuracy Studies) for methodological quality and risk of bias that was identified with respect to PRISMA-DTA recommendations indicated in **Figure 1**. All of this led to critical evaluation of both diagnostic accuracy and the reliability of dose optimization.

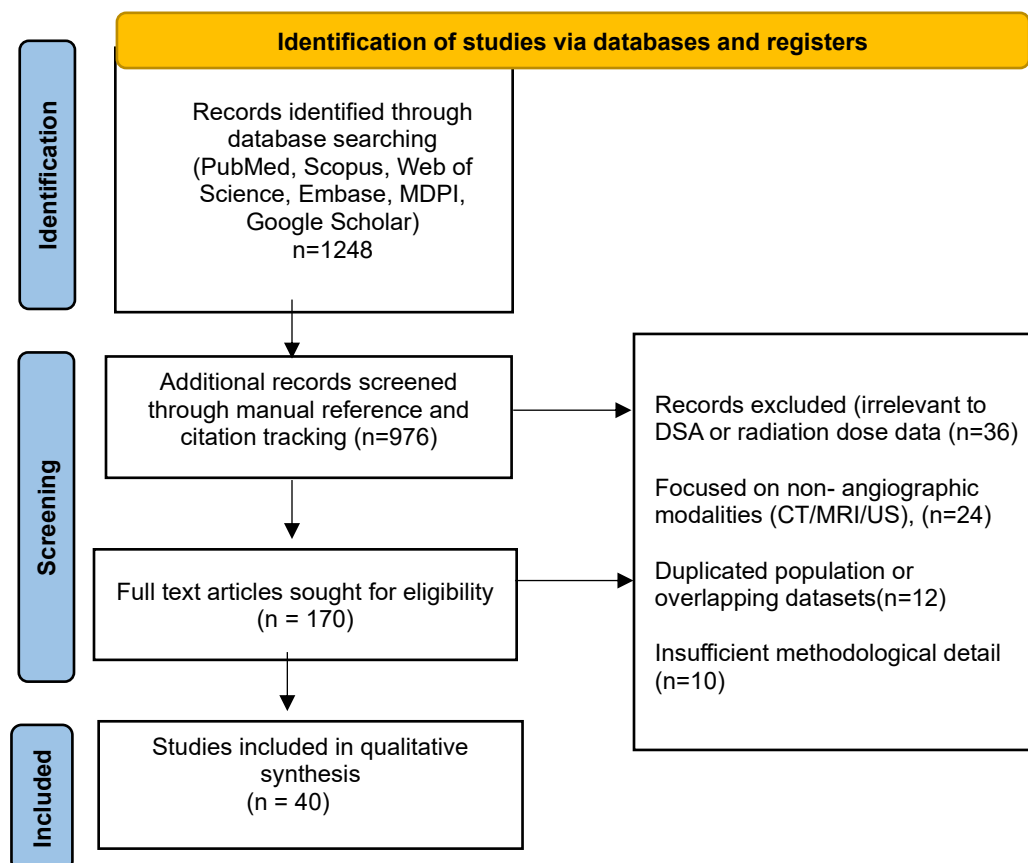


Figure-1 PRISMA-DTA flowchart

3. Results

Based on duplicate removal over 40 articles were identified for a systematic review of the study

3.1. Qualitative Synthesis of the included study

A qualitative synthesis of the literature highlights diversity in DSA parameter optimization for radiation safety, providing rich narrative of the studies included (**Table 1**). Optimization of digital subtraction angiography (DSA) parameters to achieve radiation safety has been considered as prominent issue in the interventional radiation imaging space in order to achieve radiation reduction with accurate diagnosis. Various strategies have been investigated, whether these include procedural changes, technological innovation, and recommended strategies and methods for managing radiation. Miller et al. (2010) identified measures of occupational radiation protections, promotion of shielding behavior, procedure-based dose limits and real-time monitoring systems of interventional radiology staff were recommended to protect them against the exposure caused by excessive exposure in fluoroscopic imaging. Operator positioning and the use of personal protective equipment were highlighted in these codes, as well as a sense of cumulative exposure. To support this, Stecker et al. (2009) recommended the implementation of both regular dose-tracking and fluoroscopic pulse rates, among other protocols, and the use of dose-area product (DAP) to monitor dosages in high-risk fluoroscopic procedures [2]. Technically speaking, Kim et al. (2017) proved that the filtration of the x-ray and size of focal spot for specific images were adjusted successfully and effective at the lower radiation dose for cerebral angiography without a damage to the image quality [3]. Such optimization of parameters provides a case study of hardware tuning that directly contributes to patient safety and the accuracy of diagnosis. Similarly, Gyánó et al. (2021) proposed digital variance angiography (DVA), a new image processing technique that was shown to reduce radiation irradiation with the DVA process by ~70% at the lower limb angiography level, relative to the classical

DSA [4]. It makes use of post-processing algorithm to enhance image contrast-to-noise ratio at a lower dose. Taking digital optimization another step forward, Ueda et al. (2021), where a deep training approach to angiogram creation was proposed, leading to the elimination of both misregistration artifacts and the reduction of required repeat acquisition in cerebral DSA [5]. This potential of artificial intelligence (AI) for major dose reduction and procedural efficiency and image stability is worth noting. A similar study by Zeng et al. (2025) performed a few phantom and clinical research on optimized DSA images for optimized imaging, and suggested specific filtration settings, beam energy modulation and dose-rate regulation to obtain the best imaging quality and least radiation [6]. In addition to these progressions, the performance of equipment varies by institutions, the operator training must be ongoing and there is no standardized protocol for dose optimization in differing anatomical and procedure settings. However, new AI enhanced reconstructions and next generation fluoroscopic controls are good progress towards safer, less expensive angiographic imaging.

Table 1- Qualitative Synthesis of the included study

Focus area	Optimization parameter	Objective / intervention	Challenges / key findings
Occupational radiation protection	Lead aprons, thyroid shields, ceiling-suspended barriers, staff positioning	Minimize operator dose during fluoroscopy-guided procedures	Inconsistent use of protective devices; limited staff awareness of exposure risks
Patient dose management	Dose-area product (DAP) monitoring, fluoroscopy-time limits	Establish reference levels and promote standardized dose tracking	Lack of harmonized reporting systems between institutions
Fluoroscopic parameter adjustment	Pulse or frame rate, tube voltage/current, focal-spot size	Reduce dose while maintaining diagnostic image quality	Trade-off between spatial resolution and dose reduction; operator-dependent settings
Filtration and collimation	Added Cu/Al filters, beam collimation	Reduce scattered radiation and skin dose	Image brightness reduction and possible need for higher exposure for dense anatomy
Digital variance angiography (DVA)	Image-reconstruction algorithm	Achieve major dose reduction with preserved contrast and detail	Limited clinical availability; computational integration required

AI- and deep-learning applications	AI-based angiogram generation, image enhancement	Reconstruct images from fewer frames to lower radiation exposure	Requires multi-center validation across equipment vendors
Synthetic / interpolated DSA	Frame interpolation techniques	Produce diagnostic angiograms at reduced pulse rates	Demands high-speed computing and algorithm standardization
Noise-reduction and image-processing software	Adaptive filters, real-time denoising	Improve image quality under low-dose settings	Potential artifact introduction if filter strength mis-set
3-D / rotational angiography	kVp-mAs optimization, rotation-angle reduction	Decrease dose in neuro- and cardiovascular rotational imaging	Possible distortion and smaller field of view in low-dose mode
Dose monitoring and reporting	DICOM dose-report systems, real-time feedback	Quantify and audit radiation metrics for protocol refinement	Variation in dose indices; non-uniform software adoption
Workflow and training optimization	Standardized protocols, operator education	Improve adherence to low-dose techniques and radiation awareness	Heterogeneous operator experience and procedural variability

3.2. Study features/endpoints

Recent progress in digital imaging modalities and digital variance angiography (DVA) has demonstrated clear promise in the radiation minimization and diagnostic image quality in different interventional procedures. It has been reported around 70% less radiation dose on DVA of lower limb angiography of the DSA as compared with the conventional DSA [10]. Based on these observations, verified the dose saving and image quality benefits of DVA in abdominal and hepatic settings [26]. Most recently, also clinically validated DVA effectiveness in peripheral vascular interventions, confirming its utility as a reliable low-dose replacement of classic angiographic approaches. Overall, these studies demonstrate DVA clinical feasibility, safety, and diagnostic accuracy for optimization of radiation dose in interventional radiology [39]. **Table 2** below summarizes features of studies according to the design/procedure of the study, key finding outcome measures and limitation.

Table 2- Study characteristics/ outcome measures

Study Design/Procedure	Key Finding	Outcome Measures	Limitations
Prospective clinical and technical study comparing DVA vs. DSA in lower limb angiography	DVA enabled ~70% radiation dose reduction with comparable diagnostic quality	Dose reduction (%) and image quality metrics (contrast-to-noise ratio, signal quality)	Limited to lower limb angiography; further validation needed in other vascular territories
Observational study on DVA use in abdominal/hepatic intervention	Demonstrated significant radiation dose reduction and high image interpretability	Patient dose (DAP, AK), image quality grading	Single-center study; limited sample size

3.3. Assessment of strength of evidence

The overall reliability and credibility of the included studies highlight the robustness of evidence in **Table 3**. The methodological merit of review of the literature suggests an established protocol with statistical validity that is supported by reproducible results in different procedural and clinical settings. Consistency of data, and more so in the studies on radiation dose optimization.

Table 3- Assessment of strength of evidence

Domain	Strength of Evidence	Supporting features	Limitations
Radiation Dose Optimization and Image Quality Improvement	High to Moderate — Supported by recent RCTs, feasibility studies, and technical optimization research (2023–2025).	Sótonyi et al. (2023) confirmed significant dose reduction via DVA in a controlled clinical setting. Abumoussa et al. (2024) validated synthetic DSA methods for lowering radiation dose without sacrificing diagnostic image quality. Zeng et al. (2025) provided standardized optimization	Some studies remain limited to specific vascular territories or preclinical validation. Broader multicenter trials and long-term safety assessments are warranted.

		protocols improving dose efficiency and safety across interventional imaging.	
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3.4. Risks of bias and applicability

The results from the included studies both indicate the value of uniform radiation dose check and occupational safety requirements in interventional radiotherapy. Standardized reporting statistics that include dose–area product (DAP) and air kerma (AK), are essential in terms of minimizing bias and increasing comparability among studies. Nevertheless, the reliance on consensus-based guidelines and survey data is subject to bias resulting from differences in implementation between institutions. Moreover, the older recommendations are not applicable due to the fast evolution of imaging technology and dose-reduction software solutions, as such, they require new standardization for contemporary clinical practice. The implications of optimization of radiation dose research, as explored in Table 4 reveal both the bias and applicability issues

Table 4 - Risks of Bias and Applicability Concerns

Reference (number)	Study / Type	Key relevance to risk of bias & applicability	Limitations / Applicability concerns
[1]	Guideline / consensus	Provides standards for monitoring, reporting and occupational protection that reduce measurement and reporting bias across studies.	Guideline-based (consensus) evidence; not randomized; applicability varies by center resources.
[2]	Practice guideline	Recommends standard dose metrics (DAP, AK, fluoroscopy time)	Recommendations may be inconsistently applied; older technology changes

		and reporting which improve comparability across studies.	may affect current applicability.
[30]	Systematic review	Illustrates potential outcome ascertainment bias if lens dose not consistently measured; highlights need for uniform outcome definitions.	Heterogeneity in included studies; may not reflect recent dose-lowering tech.
[33]	Survey / cross-sectional	Demonstrates global variability in doses and practices — key for assessing generalizability of single-center studies.	Survey data self-reported; variable quality and incomplete device-level detail.

3.5. Exposure technique for optimizing radiation

Innovative exposure techniques have proven to be quite effective towards minimizing radiation without sacrificing diagnostic quality and accuracy. Modifications to imaging parameters consisting of further filtration and focal spots optimization (or fluoroscopy pulse rate modulation) have also led to discernible dose reductions in angiographic interventions. Today's systems also include adjustable tube current control, which increases the dose-efficiency. Despite these achievements, differences in vendor knowledge and access, procedural complexity, and operator capability are major contributors to clinical outcomes and repeatability. **In Table 5** — Exposure techniques for optimizing radiation identification of key technique, limitation study design

Table 5 - Exposure Techniques for Optimizing Radiation Dose

Reference (number)	Study / Type	Key techniques & findings	Limitations / Notes
[6]	Phantom/clinical study	Adding filtration and optimal focal spot reduces patient dose while preserving image quality.	Focused on cerebral angiography; vendor differences.
[7]	Clinical feasibility study	Lowering fluoroscopy pulse rate feasible for routine coronary angiography leading to reduced dose with acceptable image quality.	May affect temporal resolution; operator learning curve.
[8]	Clinical study	Low pulse rates reduced operator and patient dose in transradial procedures without compromising outcomes.	Specific to transradial approach and experienced operators.
[22]	Phantom + clinical validation	Combined filter and tube current modulation significantly reduce dose while preserving image metrics.	Requires modern imaging systems supporting modulation algorithms.

3.6. Tools and methods to optimize radiation dose

Technology innovation and procedural checklists have changed the practice of radiation safety. Technology-enhanced noise reduction algorithms, and AI-enabled image reconstruction provide a means of minimizing exposure, while ensuring accuracy in the diagnosis. Novel approaches, including synthetic interpolated DSA and automated dose monitoring, create new possibilities in minimizing cumulative dose load. However, reliable validation of these tools across multiple interventional

modalities is needed and is currently limited by vendor reliance, regulatory considerations and minimal multi-center assessment as shown in **Table 6**.

Table 6 - Tools and Methods to Optimize Radiation Dose

Reference (number)	Study / Type	Tools / methods described	Limitations / Implementation issues
[5,24]	Guideline/consensus	Recommends dose-monitoring metrics (DAP, AK), checklists, fluoroscopy time control, and equipment settings.	Older guideline; technology and dose-reporting formats have evolved.
[16]	Clinical validation	Software-based noise reduction allows lower dose acquisition with preserved image interpretability.	Vendor/software dependent; needs validation across procedure types.
[9]	AI model study	AI-generated angiograms can reduce motion/misregistration artifacts and potentially allow fewer acquisitions (dose-saving).	Early-stage; needs prospective clinical validation and regulatory considerations.
[12]	Feasibility & image-quality assessment	Synthetic DSA interpolation reduces number of acquired frames/exposures while maintaining diagnostic quality.	New method; requires multi-center testing and integration into workflow.

3.7. Clinical applications of DSA in interventional radiology

Digital subtraction angiography (DSA) and digital variance angiography (DVA) have led to major advancements in dose efficiency via recent clinical applications. It is confirmed that DVA can reduce radiation exposure in peripheral and hepatic

treatment by 70% at the same time as maintaining diagnostic resolution. Low-dose protocols have also been established in neurovascular imaging and complex endovascular imaging procedures. Nevertheless, these were mostly a result of single-center study and pilot trial, suggesting that broader generalization to various interventional settings with further validation is warranted (**Table 7**).

Table 7 - Clinical Application of DSA in Interventional Radiology

Reference (number)	Study / Type	Clinical findings related to DSA/DVA/optimization	Limitations / Scope
[10]	Clinical & technical study	Demonstrated ~70% reduction in DSA-related radiation for lower limb angiography using DVA.	Focused on lower limb; technology availability limited.
[11]	Randomized controlled trial	Confirms dose reductions with DVA vs conventional DSA and maintains clinical image adequacy.	Single/trial-specific settings; broader territories not covered.
[26,32]	Clinical reports / dose & outcome studies	Reductions in fluoroscopy/DSA frame needs using image-processing approaches and modern angiographic technologies in hepatic and complex interventions.	Mostly single-center or limited sample size.
[37]	Clinical neuroradiology study	Feasible low-dose DSA protocols for endovascular treatment of dural AVFs with acceptable procedural success.	Specific to one neurovascular condition; may not generalize.

3.8. Issues, Moral Aspects, and directions for future study Ethical mandates

Under radiation protection point to the duty of care towards patients and staff (**Table 8**). Ongoing optimization, clear instruction of dosages, and compliance with ALARA (As Low As Reasonably Achievable) principles are still fundamental to safe imaging. The latter of these may be achieved by using AI (Artificial Intelligence) to assist in dose tuning, in improving occupational safety education, or for global dose registries for long-term exposure monitoring. Despite these promising discoveries, challenges remain, including standardizing dose criteria, addressing algorithmic bias in AI tools and promoting equitable access to low-dose imaging technologies across the world.

Table 8 - Challenges, Ethical Considerations and Future Directions

Reference (number)	Study / Type	Key ethical / challenge / future direction points	Notes / Research gaps
[31]	Review / position	Emphasizes ethical obligation to minimize radiation, meticulous dose tracking, and patient/parent communication.	Calls for standardized dose registries and long-term outcome data.
[1]	Guideline	Highlights staff safety, dose limits, and ethical responsibility of institutions to protect personnel.	Implementation variability; needs update with new technologies.
[21]	AI application study	AI/3D reconstruction offers potential to reduce acquisitions and radiation; suggests research into regulatory, validation and ethical deployment.	Early evidence; requires robust validation and addressing bias in AI models.

[36]	Phantom + clinical recommendations	New parameter-optimization recommendations and practical checklists to standardize low-dose DSA practice.	Very recent; adoption depends on vendors and large-scale confirmation.
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4. Discussion

4.1. Recent Changes Within Digital Subtraction Angiography

Recent technology progress in the area of Digital Subtraction Angiography (DSA) has made a great impact on radiation safety, while guaranteeing accurate diagnosis. Typical DSA strategies, such as employing high frame rates and long fluoroscopy with high cumulative doses of radiation in patients and operators, were frequently performed. The implementation of Digital Variance Angiography (DVA) has resulted in ~60-70% reduced exposure without compromise of imaging quality [11,12], similar to the clinical and multicenter validation studies. Synthetic and interpolated DSA methods have also demonstrated the potential for further radiation risk reduction by reconstructing angiographic sequences for a small number of exposures on fewer images [12]. Advancements in low-dose rotational and 3D angiographic procedures are also important, making neurovascular images more visualizable with much lower exposure [14,37]. Further, AI-based angiographic reconstruction has unlocked a new frontier for dose optimization for generating quality image with substantially fewer projections [9,21]. Together, these studies suggest that the evidence supports a paradigm shift, providing evidence-based DSA protocols augmented with algorithms that remain diagnostically reliable in the context of the ALARA (As Low As Reasonably Achievable) guideline.

4.2. Impact of Road Mapping and other methods in Radiographic Dose Optimization

Radiation dose in interventional radiology treatment not only relies on the hardware upgrades but is also reliant on procedural technique. The use of road-mapping—a technique for overlaying acquired angiographic images—is applied to reduce the incidence of re-imaging and the time of the recurrence of contrast shots and fluoroscopy is also effective. This procedure, in combination with low-rate fluoroscopy, and frame per second modulation, provides significant dose drop with no effect on procedural precision [7,8,27]. The importance of exposure control parameters is confirmed in studies that focus on filtration and beam collimation adaptation. Changing filtration thickness and focal area size with cerebral angiography will still be able to preserve the high image sharpness, at a low skin dose [6,29]. Moreover, protocol-driven alterations, including pulse-rate reduction and optimized beam angulation are also in accordance with the clinical guidelines for fluoroscopically guided procedures described in these radiation-management guidelines [2,5,40]. These approaches support the idea that operator awareness paired with equipment-specific dose-saving aspects (i.e., real-time dose-measurement, automatic control of exposure) remains paramount to maintaining radiation safety during DSAs.

4.3. Image Optimization in Interventional Procedures

Image optimization strategies for interventional radiology aim to provide a balance between diagnostic clarity and radiation effectiveness. Noise-reduction imaging software and advanced post-processing algorithms have been validated as practical means of improving low-contrast detectability while allowing for lower exposure parameters. Likewise, filter optimization and tube current modulation studies both illustrate how radiation exposure can be controlled from a physics standpoint in such high-complexity imaging environments as radiation absorption [22,36]. Quality assurance programs—which integrate dose audits, procedural standardization, and staff training—are also consistently emphasized by clinical guidelines on maintaining optimal image performance [1,4,19]. Additionally, modern imaging approaches like AI-guided 3D angiography are drastically improving image acquisition due to its potential for high-resolution visualization, significantly decreasing the time needed

for fluoroscopy [21]. Such integration signifies a seamless integration of hardware, software and operator skills to yield optimal outcomes with reduced exposure to radiation. Radiological safety with fluoroscopic guided interventions is vital for patient and HCW safety.

4.4. The “Ten Commandments” for radiation safety

It focuses on a systematic, evidence-based approach to dose optimization, procedural awareness, and occupational protection. These well-established principles—backed up by decades of scientific research—are interwoven in equipment tuning, operator actions and safety regulations that become the central pillars of management.

4.4.1. Justify Every Fluoroscopic Procedure

Every fluoroscopic examination must be clinically justified and that a positive and therapeutic effect outweighs radiation damage. Proceeding should always be based on clinical appropriateness and whether alternative imaging modalities are appropriate [1,5,31].

4.4.2. Optimize Equipment and Protocol

Optimization Filtration, pulse rate, focal spot size, and tube current can minimize exposure without affecting image quality [6,7,22]. Nursing practice of angiographic imaging protocols can limit radiation dose and minimize radiation load [8,27,29].

4.4.3. Optimize Exposure time

Ultra-low pulse fluoroscopy as well as optimal beam filtration reduce both patient and operator dose in angiographic procedures Real-time dose monitoring and use of low-frame-rate imaging in procedural pauses, along with continuous exposure during these procedural pauses, and by providing ongoing dose monitoring which increases the reduction of dose significantly [2,5,19].

4.4.4. Shorten Time of Exposure

Exposure time of fluoroscopy is one of the most direct and effective ways to reduce radiation exposure. The monitoring of dose in real-time and low-frame-rate imaging is used during procedural pause, resulting in large dose reductions [2,5,19].

4.4.5. Optimal Distance and Positioning

Keep the distance away or positioning as suitable as possible. Radiation dose is diminishing with square of the distance to source. Operator locations, ceiling-suspended shields design, patient-detector ratios etc., should follow opposite square principles to minimize scatter radiation [1,17,18].

4.4.6. Collimation and Beam Limitation

Proper collimation limits the X-ray beam to the clinical focal point so that unnecessary tissue exposure can be avoided. With competent collimation along with sufficient angulation [29,36], the experimental results have shown significant reduction in skin dose.

4.4.7. Shielding for Operators

lead aprons, thyroid collars, leaded eyeglasses, and ceiling-mounted barriers are indispensable in protecting themselves. The regular use of these tools reduces the occupational dose, especially involving the eye lens and thyroid [3,17,30].

4.4.8. Record and Documentation of Radiation Doses

Routinely documenting on time fluoroscopy dose, dose-area product (DAP) and cumulative skin dose enables audits and quality improvement [13,33]. The adoption of the DICOM based dose reports improved transparency and dose accountability [13,40].

4.4.9. Educate with Regular Training

Education of the Operators Training in radiation physics, dose control, and how to operate equipment promotes awareness and practice by interventionalists. The structured education programs are associated with the measurable dose reductions on several studies [2,4,5,19].

4.4.10. Technological Advancement

The use of a modern imaging system (DVA, AI based reconstruction) is known to achieve exceptionally high image quality and a much lower radiation output [9–11,21,23]. Dose reductions that amount to 70% have been observed by applying these technologies [10,11,26].

4.4.11. Cultivate a Culture of Radiation Safety

Radiation protection is the responsibility of the interventional team. Building a culture of safety via procedural checklists, real-time alerts, and compliance with institutional guidelines can lead to long-term risk reduction [1,5,40].

Implications

The combined results of the reviewed literature provide firm support to multimodal optimization including exposure parameters, technological innovation, and procedure optimization for the implementation of multimodal optimization strategies. Through effective dose-reduction techniques such as, but not limited to, DVA and AI imaging to optimized filtration and road-mapping, interventional radiology can substantially enhance the safety of patients and operators. This balance between technologized precision and procedural intuition is evidence of an advanced level of maturity of DSA as radiation protection and clinical action need not conflict, but rather are integrated and synergistically planned. Together, these commandments reflect the ALARA (As Low As Reasonably Achievable) standard of practical dose reduction with the preservation of procedural effectiveness. Incorporation of evidence-based techniques (technological, procedural, and education-based approaches) makes fluoroscopy a robust and safe interventional diagnostic and therapeutic method in radiology.

4.5. Limitations

Although the study reports a comprehensive overview of radiation optimization options in digital subtraction angiography (DSA), limitations of this study are acknowledged. Firstly, there is some heterogeneity among the studied studies in respect of imaging instruments, dose measurements, and clinical protocols, which had

implications to cross-study comparability [6,19,20]. Small sample size and single-center experience were common contributors to the studies, which may introduce institutional bias, and reduce data generalizability [11,26,37]. In addition, a wide range of quantitative metrics was absent for the reporting across different countries and particularly dose-area product and fluoroscopy time [13,29]. Moreover, this study also lacked inclusion of real-world clinical trials, which directly compare new emerging DSA technologies such as digital variance angiography (DVA) and artificial intelligence (AI)-assisted image reconstruction with conventional protocols [10,21,39]. Another limitation of this study was many studies primarily focused on short-term dose outcomes instead of longer-term radiation safety and patient follow-up [33,35]. Moreover, the lack of standardized criteria around image quality assessment limited comprehensive examination of radiation dose–diagnosis balance [16,32].

4.6. Future Research Directions

Standard measures of DSA doses and protocol parameters need to be standardized to create replicable benchmarks for optimization [5,24,36]. Moreover, the application of new dose-reduction algorithms to overcome the obstacles of imaging equipment and standardization of the dosing regime and data may be critical. As AI technologies are improving, such as image enhancement and noise reduction algorithms, additional studies are needed to improve diagnostic quality, and also to obtain the highest diagnostic quality with the lowest exposure [9,21]. Improvements in detector sensitivity, automatic exposure control techniques, and adaptive filtration technologies might improve dose efficiency and image contrast [6,22,37]. Future research should also evaluate the cumulative occupational exposure of interventional radiologists and staff relative to emerging shielding technologies and procedural adaptations [1,17,18]. Additionally, longitudinal assessments correlating optimized imaging factors with patient outcomes will be important to validate the clinical and ethical utility of radiation-safe DSA practice [19,40].

5. Key Takeaways

This review demonstrates considerable advancements in optimizing the parameters of DSA to improve radiation safety, while keeping diagnostic performance intact. Recent evidence is clear that DVA, filtration adjustment, and low-rate fluoroscopy can successfully lower patient and operator exposure to radiation doses while also preserving image quality [6,10,11,20]. Following well-established radiation safety paradigms and regular adjustments in the procedural standard is still important for sustainable dose control in interventional radiology [2,4,5]. Altogether the confluence of new technology with clinical validation and adherence to international safety standards points to a solid base for safer imaging. As such, continued research, standardization, and incorporation of AI-based optimization tools will be crucial to achieve repeatability and global applicability of radiation-conscious DSA protocols [9,21,36,39].

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