

RADIATION SAFETY AND PATIENT PROTECTION IN HYBRID OPERATING ROOMS: AN INTERPROFESSIONAL SYSTEMATIC REVIEW OF THE ROLES OF RADIOLOGIC TECHNOLOGISTS, ANESTHESIA TECHNICIANS, AND MEDICAL PHYSICISTS
SYSTEMATIC REVIEW

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Abstract

Background: Hybrid operating rooms combine a sterile surgical theatre with fixed, high-output angiographic and cone-beam computed tomography (CBCT) imaging. They improve procedural precision but expose patients to substantial radiation and place a multiprofessional team, including staff who are not radiation specialists, close to scattered radiation. Radiologic technologists, anesthesia technicians and medical physicists each hold part of the responsibility for protection, yet their combined contribution has not been synthesised.

Objective: To systematically review the evidence on occupational and patient radiation safety in hybrid operating rooms and fluoroscopy-intensive procedural settings, with a focus on the roles of radiologic technologists, anesthesia personnel and medical physicists, and to compare Saudi Arabian evidence with the international literature.

Methods: The review followed PRISMA 2020. PubMed/MEDLINE was searched from January 2010 to 23 October 2026 with 17 search strings, supplemented by a targeted search for Saudi studies. Primary studies and systematic reviews reporting staff dose, patient dose, dose-reduction interventions, or radiation-protection knowledge and practice among hybrid-OR or peri-procedural teams were eligible. Data were extracted into a structured table, quality was appraised with design-specific criteria, and findings were synthesised narratively across four domains.

Results: Of 360 screened records, 36 studies were included (29 international, 7 Saudi). Occupational doses in hybrid operating rooms were generally below the 20 mSv annual limit; a Saudi national registry of 7,530 operating-room workers reported a mean annual effective

dose of 0.59 mSv. Exposure was nonetheless uneven: digital subtraction angiography increased operator dose up to 33-fold, anaesthesiologists in neuro-interventional work received facial doses 3.2 times those of the radiologist, and anaesthesia technologists in a Saudi cohort received higher doses than consultants (0.80 vs 0.63 mSv). Shielding and positioning measures reduced dose by 71–90%, equipment and protocol optimisation by 22–76%, and education or simulation by 16–79%. Saudi surveys showed marked gaps: only 3.9% of orthopaedic surgeons had formal radiation-protection training, 19.6% wore a dosimeter, and 76% of non-radiology staff had low awareness.

Conclusions: Radiation safety in hybrid operating rooms depends on coordinated action across professions: medical physicists set and audit protocols, radiologic technologists translate them into exposure choices at the table, and anesthesia staff, who are often closest to the scatter field and least trained, need dedicated shielding, monitoring and education. Saudi hospitals record low average doses but weak training and monitoring culture, which supports a structured, team-based radiation-safety programme.

Keywords: hybrid operating room; radiation protection; occupational exposure; patient dose; anesthesia technicians; radiologic technologists; medical physicists; interprofessional collaboration; Saudi Arabia

1. Introduction

The hybrid operating room (hybrid OR) brings a fixed C-arm angiography system, frequently with cone-beam computed tomography (CBCT), navigation and image fusion, into a theatre that meets surgical asepsis standards. Since its adoption in cardiovascular surgery, it has spread to neurosurgery, spine and trauma surgery, thoracic surgery and interventional oncology. Systematic reviews of its clinical use report higher procedural success and fewer revision operations, but they also identify radiation exposure as one of the main unresolved disadvantages (Gharios et al., 2023; Jin et al., 2021).

Radiation in the hybrid OR differs from that in a conventional theatre in three ways. First, fixed angiographic systems deliver more radiation per unit time than mobile C-arms, and digital subtraction angiography (DSA) and rotational CBCT acquisitions contribute a disproportionate share of patient and staff dose (Andrés et al., 2017; de Ruiter et al., 2016). Second, procedures such as complex endovascular aortic repair are long, so cumulative skin dose to the patient can approach thresholds for tissue reactions (Kirkwood et al., 2013). Third, the room is staffed by a large interprofessional team—surgeons, interventional radiologists, scrub and circulating nurses, anaesthesia staff, radiologic technologists and, in the background, medical physicists—many of whom have little formal training in radiation protection (Bartal et al., 2014).

Concern has sharpened since the International Commission on Radiological Protection reduced the recommended occupational equivalent-dose limit for the lens of the eye from 150 to 20 mSv per year, averaged over five years (ICRP, 2012). Studies of interventional cardiology personnel found posterior lens opacities consistent with radiation exposure in a substantial proportion of nurses and technicians as well as physicians (Ciraj-Bjelac et al., 2010; Vano et al., 2010). Professional guidance now recommends dose management programmes that combine equipment optimisation, shielding, monitoring and education, with explicit roles for physicians, radiographers and medical physicists (Bartal et al., 2014; Modarai et al., 2023; Tsapaki, 2020).

Within this team, three professions are central yet under-represented in the literature. Radiologic technologists operate the imaging chain and control many dose-determining choices at the table. Medical physicists commission equipment, design low-dose protocols, audit patient and staff dose, and investigate high-dose events (Tsapaki, 2020). Anaesthesia personnel, including anesthesia technicians and technologists, work at the head of the table, often on the tube side and close to the patient, where scatter is high and where they must repeatedly approach the field to manage the airway, drugs and monitoring (Dagal, 2011; Hussey et al., 2019). Their exposure is rarely the focus of hybrid-OR studies, which tend to measure the primary operator.

Saudi Arabia is expanding hybrid-OR and interventional capacity within its health-sector transformation, and radiation safety in hospitals is regulated nationally and assessed through accreditation. Local evidence on occupational dose and staff knowledge exists but has not been brought together with the international hybrid-OR literature. This gap matters for hospitals that are designing staffing, training and monitoring arrangements for new hybrid suites.

This systematic review therefore aimed to (1) synthesise evidence on occupational and patient radiation exposure in hybrid ORs and closely related fluoroscopy-intensive procedural settings; (2) identify interventions that reduce dose, and which professions lead them; (3) characterise the exposure and protection of anaesthesia personnel; and (4) compare the Saudi evidence with international findings to inform an interprofessional radiation-safety model.

2. Methods

2.1 Protocol and reporting

The review was conducted and reported in accordance with the PRISMA 2020 statement (Page et al., 2021). The protocol defined the question, eligibility criteria, search strategy, data items and synthesis approach in advance.

2.2 Eligibility criteria

Eligibility was framed with a population–exposure–comparator–outcome (PECO) structure, summarised in Table 1. Studies were eligible if they reported quantitative staff or patient dose, the effect of a dose-reduction measure, or radiation-protection knowledge, attitudes and practice among staff working in hybrid ORs, fluoroscopy-guided operating theatres or interventional suites where anaesthesia or multiprofessional teams are present. Primary quantitative, qualitative and phantom/simulation studies were eligible, as were systematic reviews that answered a question within scope. Narrative reviews, commentaries, guidelines and consensus statements were excluded from the synthesis but used to frame the discussion. Studies of diagnostic CT, dental imaging, nuclear medicine or radiotherapy were excluded, as were retracted articles and single case reports.

Table 1. Eligibility criteria (PECO framework)

Element	Inclusion	Exclusion
Population	Staff working in hybrid ORs, fluoroscopy-guided theatres or interventional suites with multiprofessional or anaesthesia presence (surgeons, interventionalists, nurses, anaesthesia personnel, radiologic technologists, medical physicists); patients undergoing hybrid-OR procedures	Diagnostic radiology, CT, dental, nuclear medicine or radiotherapy settings; animal studies
Exposure / intervention	Fluoroscopy, DSA or CBCT in the procedural setting; dose-reduction technology, protocol change, shielding, positioning, dosimetry practice, education or training	Non-ionising imaging only
Comparator	Alternative system, protocol, — shielding, position or professional group; before–after; none for descriptive studies	
Outcomes	Occupational dose (effective, personal dose equivalent, eye lens, extremity); patient dose (KAP/DAP, air kerma, peak skin dose, effective dose); radiation-protection knowledge, attitudes and practice; team processes	No radiation outcome
Design	Primary quantitative, qualitative, phantom/simulation studies; systematic reviews	Narrative reviews, commentaries, guidelines (background only); case reports; retracted articles
Other	English language; January 2010 – 23 October 2026	Abstract-only conference records

Abbreviations: CBCT, cone-beam computed tomography; DAP, dose–area product; DSA, digital subtraction angiography; KAP, kerma–area product; OR, operating room.

2.3 Information sources and search strategy

PubMed/MEDLINE was searched for articles published from January 2010 to 23 October 2026. Seventeen search strings combined terms for the setting ("hybrid operating room", operating room, theatre, C-arm, fluoroscopy, interventional), the professional groups (anesthesiologist, anaesthetist, anesthesia personnel, radiographer, technologist, medical physicist, nurse, staff), the outcomes (radiation dose, occupational exposure, eye lens, cataract, radiation protection, radiation safety, knowledge, training) and, in dedicated strings, Saudi Arabia and Gulf Cooperation Council countries. Title-field restrictions were used to increase

precision for the anaesthesia and Saudi strings. Because indexing of Saudi studies is inconsistent, a targeted web search was used to identify additional Saudi studies, which were retained only if they were indexed in PubMed Central. Reference lists of included studies and of the European Society for Vascular Surgery radiation-safety guideline (Modarai et al., 2023) were checked for further studies. Only English-language articles were included.

2.4 Study selection

Records were de-duplicated by PubMed identifier. Titles and abstracts were screened against the eligibility criteria, and potentially eligible reports were assessed in full against the PECO criteria, with the reason for each exclusion recorded.

2.5 Data extraction

A structured extraction form captured author and year, country, setting tag (Saudi Arabia, other Gulf/Middle East and North Africa, or international), design, population and setting, professional groups addressed, dose metrics (effective dose, personal dose equivalent, eye-lens dose, kerma–area product [KAP] or dose–area product [DAP], air kerma, peak skin dose), interventions, knowledge and practice indicators, and main findings. Percentage dose reductions were taken as reported or calculated from reported pre- and post-intervention medians or means.

2.6 Quality appraisal

Methodological quality was appraised with design-specific criteria adapted from the Joanna Briggs Institute checklists for analytical cross-sectional studies, cohort and quasi-experimental studies and qualitative research. For dosimetry and phantom studies, appraisal considered dosimeter calibration and placement, reproducibility of geometry and reporting of uncertainty. Each study was rated as low, moderate or high risk of bias. Ratings informed the weight given to findings in the narrative synthesis; no study was excluded on quality grounds.

2.7 Synthesis

Because designs, dose quantities and outcome definitions were heterogeneous, a meta-analysis was not appropriate. Findings were synthesised narratively in four domains: (A) occupational exposure in the hybrid OR; (B) exposure and protection of anaesthesia personnel; (C) patient dose and system optimisation; and (D) education, knowledge and team practice. Reported dose reductions were tabulated and displayed graphically to compare the magnitude of effect across types of intervention. Saudi evidence was synthesised separately and compared with international findings. Finally, findings were mapped to the responsibilities of radiologic technologists, anaesthesia personnel and medical physicists to build an interprofessional framework.

3. Results

3.1 Study selection

The searches identified 380 PubMed records and 6 records from other sources. After removing 26 duplicates, 360 records were screened and 298 were excluded on title and abstract. Sixty-two reports were assessed for eligibility; 26 were excluded, most often because they were narrative reviews, commentaries or guidelines ($n = 13$) or did not report a radiation outcome ($n = 6$). One scoping review was excluded because it had been retracted. Thirty-six studies were included (Figure 1).

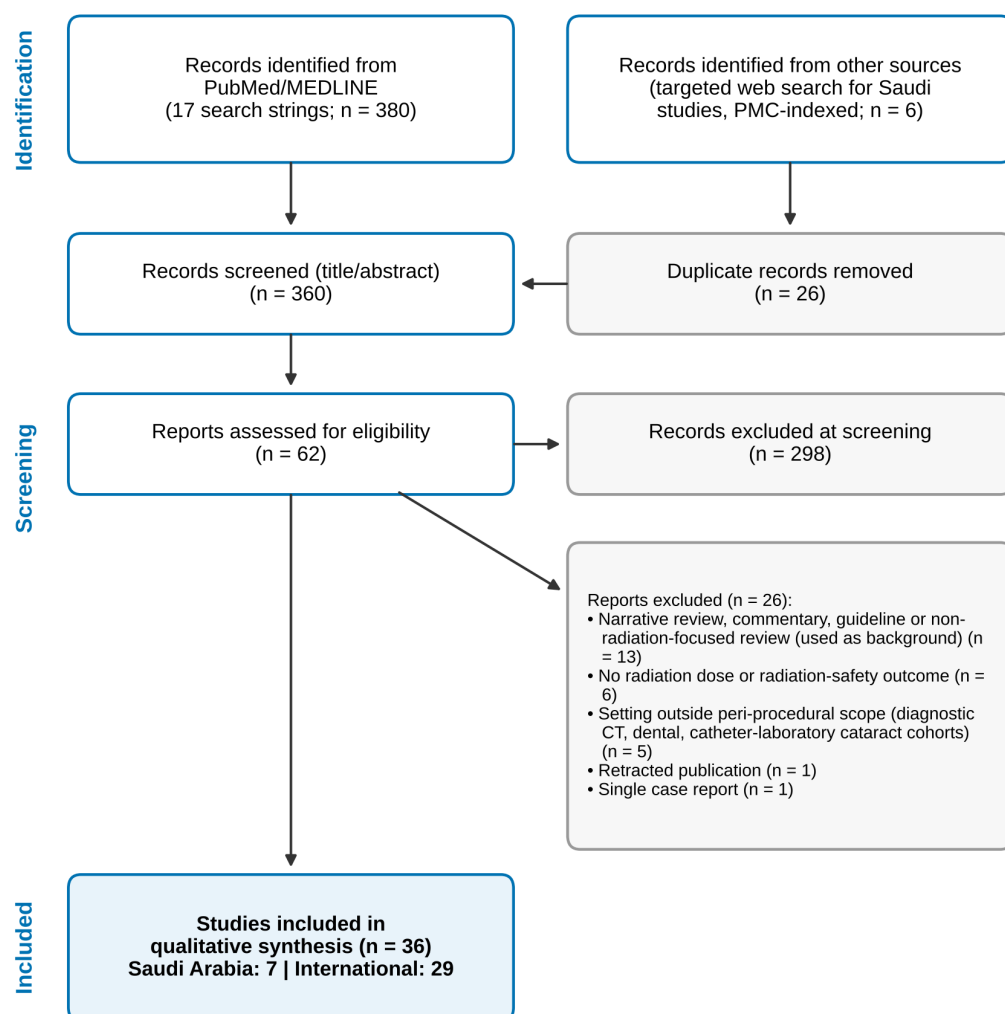


Figure 1. PRISMA 2020 flow diagram of study identification, screening and inclusion. Records were identified from 17 PubMed/MEDLINE search strings (January 2010 to 23 October 2026) and a targeted search for Saudi studies indexed in PubMed Central.

3.2 Characteristics of included studies

The 36 studies were published between 2011 and 2024 and came from 15 countries, plus one multinational study led from Belgium. Seven were conducted in Saudi Arabia; no eligible study from another Gulf or Middle East and North Africa country was identified. Thirteen studies addressed occupational exposure in the hybrid OR (Domain A, including one Saudi cardiac-catheterisation study), seven addressed anaesthesia personnel (Domain B), nine addressed patient dose and system optimisation (Domain C), and seven addressed education, knowledge or team practice (Domain D). Designs included prospective dosimetry studies, phantom and simulation experiments, before–after evaluations, retrospective dose audits and registries, cross-sectional surveys, one qualitative study and one systematic review. Three studies were rated as low, 29 as moderate and four as high risk of bias. Surgeons and other primary operators were the most frequently studied group; anaesthesia personnel were addressed in 11 studies (the main focus of seven), radiologic technologists in eight and medical physicists, as study

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participants or as drivers of the intervention, in seven (Figure 2). Table 2 summarises each study.

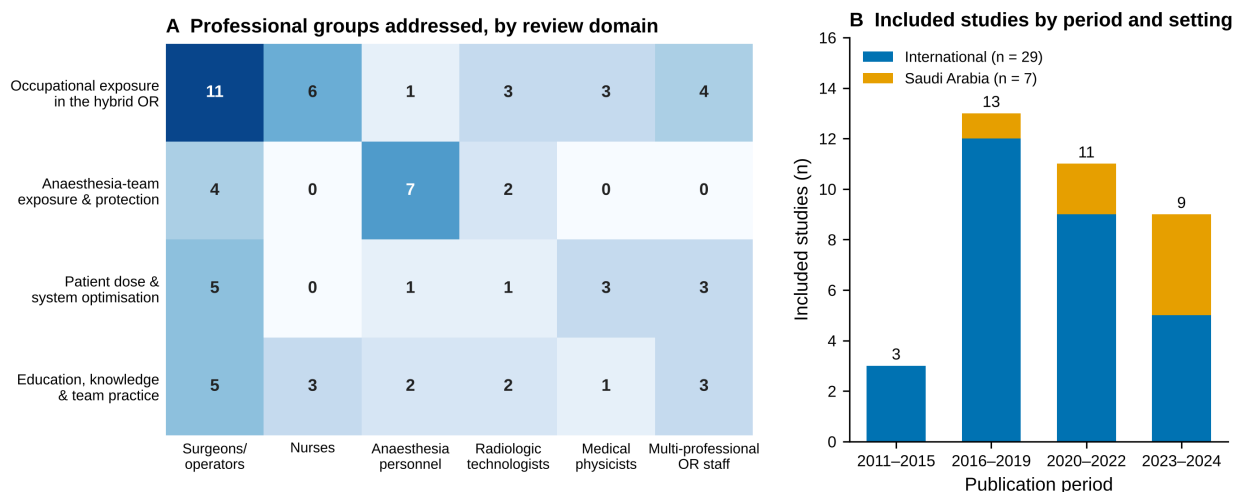


Figure 2. Evidence map of the 36 included studies. (A) Number of studies addressing each professional group within each review domain; a study can address more than one group. (B) Included studies by publication period and setting. Professional groups were coded from each study's population and authorship description in Table 2.

Table 2. Characteristics and main findings of the 36 included studies, by review domain

Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
Domain A – Occupational exposure in the hybrid OR						
Andrés et al., 2017	Spain (International)	Prospective observational (1-year audit)	260 vascular interventions, hybrid (robotic C-arm)	Surgeons, nurses, radiographers; medical physics	Mean KAP 67 Gy·cm ² , peak skin dose 0.23 Gy; acquisition <5% of beam-on time but >60% of patient effective dose; all staff doses below legal limits.	Moderate
Schuetze et al., 2019	Germany (International)	Prospective observational	109 pelvic/spine cases, hybrid OR	Surgeon, assisting nurse	Navigation lowered surgeon dose; standing between C-arm during screw placement te raised dose six-fold; lumbar dose comparable to conventional OR.	Moderate
Schuetze et al., 2018	Germany (International)	Experimental (cadaver) dosimetry	Intra-operative 3D scans, hybrid OR	Surgeon, assistant, scrub nurse	Highest scatter on assistant side during pelvic 3D scans (39.5 µSv at 1 m); dose-reduction protocol cut scatter ≈66%; protection wall/leaving room near-eliminated exposure.	Moderate
Cewe et al., 2022	Sweden (International)	Phantom dosimetry	3D image-guided spine set-ups, hybrid OR	All OR staff positions; medical physicists (co-authors)	Ceiling-mounted CBCT reduced occupational dose 22% vs mobile O-arm; free-standing shields cut scatter >90%, allowing apron-free work during CBCT.	Low
Serna Santos et al., 2020	Finland (International)	Phantom dosimetry (active electronic dosimeters)	Hybrid OR imaging modes	Operator and team positions	Roadmap tripled and DSA increased operator dose 33-fold vs low-dose fluoroscopy; narrowing field size halved dose; table shield reduced DSA dose; six behavioural rules derived.	Low

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Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
Chiang et al., 2024	Taiwan (International)	Phantom clinical EVAR)	+ EVAR, (26 OR	hybrid Principal/assistant operator, sterile nurse	Conventional chest-badge orientation under-estimated occupational dose, most at distant positions (assistant, nurse); estimates correlated with measured dose ($R^2 \approx 0.8$).	Moderate
de Ruiter et al., 2018	Netherlands (International)	Prospective observational	65 endovascular patients, OR	aortic hybrid sterile & non-sterile nurse, anaesthesiologist, radiation technician	Median effective dose per procedure 0.036–0.345 mSv (highest in F/BrEVAR); support-staff dose 3.5–8.2% of C-arm reference badge; DSA and target-vessel steps drove dose.	Moderate
Attigah et al., 2016	Germany (International)	Prospective multicentre	171 endovascular procedures, hybrid ORs	Vascular surgeons (eye, finger)	Eye and finger doses correlated with DAP ($r \approx 0.55$); $\approx 1,404$ fluoroscopy minutes predicted to reach the 20 mSv/y eye-lens limit.	Moderate
Jungi et al., 2022	Germany (International)	Before–after (dose-reduction programme)	181 endovascular procedures, hybrid OR	First operator	Unprotected eye dose fell 75% (EVAR), 79% (TEVAR), 55% (F/BEVAR) after programme; lead glasses reduced eye dose 3.4-fold.	Moderate
Quan & Lee, 2019	South Korea (International)	Prospective comparative	81 endovascular procedures (mobile C-arm vs hybrid room)	Endovascular surgeon	DAP per second higher in hybrid room (4.5 vs 3.1 $\mu\text{Gy}\cdot\text{m}^2/\text{s}$); peak dose shifted to lower apron in hybrid room vs neck/shoulder with mobile C-arm.	Moderate

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Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
Krebs et al., 2022	France (International)	Measurement + Monte Carlo simulation	Simulated clinician, hybrid OR	Clinician; physics/engineering team	Clinician dose highly sensitive to shield position; optimised shield placement reduced exposure 79–89% vs no external shield.	Low
Almalki et al., 2021	Saudi Arabia (Saudi)	Retrospective national dosimetry registry (TLD)	7,530 personnel, hospitals, 2015–2019	OR 52 personnel (multi-professional)	Operating-room Mean annual effective dose 0.59 mSv; Modera >88% <1 mSv; maximum 15 mSv; no te worker exceeded 20 mSv.	
Sulieman et al., 2023	Saudi Arabia (Saudi)	Prospective OSL dosimetry	32 cath-lab patients; 10 staff	Cardiologists, nurses, X-ray technologists	Personal dose equivalent: cardiologists 1.11, nurses 0.84, technologists 0.68 mSv; te annual estimates below 20 mSv; patient doses below tissue-reaction thresholds.	Modera
Domain B – Anaesthesia personnel						
Anastasian et al., 2011	USA (International)	Prospective observational	31 neuro-interventional procedures	Anaesthesiologist vs radiologist	Anaesthesiologist facial dose 6.5 μSv/procedure, 3.2-fold the radiologist's; te dose rose with number of anaesthetic interventions.	Modera
Mayr et al., 2019	Germany (International)	Observational pilot	32 transfemoral TAVI procedures	Anaesthesiologist	Head dose outside a 0.35 mm Pb cap reached 0.55 mSv vs 0.08 mSv inside (≈85% reduction).	High

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Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
Miyazaki et al., 2021	Japan (International)	Phantom dosimetry (device evaluation)	Structural-heart interventions in hybrid OR	Anaesthesiologist, TEE operator; radiologic technologists (developers)	Head-side/cradle shield cut dose 82.6–86.4% (anaesthesiologist, 100 cm height) and 72.9–91.0% (TEE operator).	Moderate
Shbeer, 2024	Saudi Arabia (Saudi)	Retrospective 5-year TLD analysis	175 anaesthesia staff in interventional cardiology	Anaesthesia technologists (72%) and consultants	Mean annual effective dose 0.76 mSv; Modera technologists higher than consultants (0.80 vs 0.63 mSv, p = .008); all far below 20 mSv.	Moderate
Rhea et al., 2016	USA (multinational studies) (International)	Systematic review	Orthopaedic OR dosimetry studies	Anaesthesia providers	At ≥ 1.5 m from the source, anaesthetist dose was nil or at dosimeter detection limits; routine apron use at that distance questioned.	Moderate
Ali et al., 2020	Pakistan (International)	Cross-sectional survey	54 anaesthesiology trainees	Anaesthesia trainees	59.3% exposed 1–5 times/week; only 20.4% used both apron and thyroid shield despite 68.5% believing precautions were adequate.	Moderate
Khamtuikrua & Suksompong, 2020	Thailand (International)	Cross-sectional survey	214 anaesthesia personnel and surgical subspecialists	Anaesthesia personnel, surgeons	86.4% always wore apron, 78.5% thyroid shield; mean knowledge 6.4/15, with gaps on eyewear and dose limits.	Moderate

Domain C – Patient dose and system optimisation

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Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
van den Haak et al., 2015	Netherlands (International)	Prospective before–after	138 aorto-iliac endovascular patients	Surgeons; medical physics; vendor	Image-processing upgrade cut patient air kerma 56% (EVAR) and 76% (occlusive disease); staff dose fell 16% and 69% without longer fluoroscopy.	Moderate
de Ruiter et al., 2016	Netherlands (International)	Retrospective comparative	85 EVAR (mobile vs fixed C-arms)	Vascular team	Fixed hybrid C-arm roughly tripled fluoroscopy KAP vs mobile C-arm; noise-reduction technology cut KAP per DSA frame 61%; BMI predicted dose on fixed systems.	Moderate
Haga et al., 2020	Japan (International)	Retrospective dose audit	EVAR/TEVAR in hybrid OR system	Radiological technologists (authors)	Mean DAP 324 (TEVAR) and 371 Gy·cm ² (EVAR); air kerma 0.92–1.11 Gy; no deterministic skin effects; routine dose evaluation recommended.	Moderate
Arnautovic et al., 2024	Germany (International)	Retrospective comparative	93 (T)EVAR, standard vs hybrid OR	Vascular team	Hybrid OR had higher DAP and longer fluoroscopy but lower contrast volume than mobile C-arm theatre.	Moderate
Wermelink et al., 2019	Netherlands (International)	Retrospective cohort	77 EVAR after hybrid OR commissioning	Surgeons after structured hybrid-OR training	With pre-commissioning training, no dose learning curve was seen; DAP comparable to experienced centres.	Moderate
Ruffino et al., 2018	Italy (International)	Before–after	100 EVAR (normal vs 'Eco' protocol)	Physics-led protocol change + staff training	Added filtration and halved pulse rate cut DAP 53–57% and air kerma 45–57%; staff dose fell 25.6% without loss of usable image quality.	Moderate

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Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
Kohmaru et al., 2024	Japan (International)	Retrospective + phantom/simulation	67 thoracic-surgery patients, intra-operative CBCT	Surgeons, anaesthesia (equipment positioning)	Mean skin dose 3.69 mGy/dosimeter; 5th–8th intercostal spaces most exposed because arm, anaesthesia machine and table restricted CBCT path; ≤3 scans advised.	Moderate
Chia et al., 2024	Singapore (International)	Retrospective case series	30 patients, lung-nodule localisation	Interventional radiology, thoracic surgery	Median effective dose 10.4 mSv (pre-operative IR localisation) vs 3.2 mSv when localisation was done intra-operatively in the hybrid OR.	High
Kirkwood et al., 2013	USA (International)	Before–after (education)	300 fluoroscopically guided procedures, hybrid room	Vascular surgeons; dose-investigation team (medical physics)	Institutional review of >6 Gy cases and surgeon education raised table height ~10 cm and cut estimated peak skin dose 16%.	Moderate
Domain D – Education, knowledge and team practice						
Soenens et al., 2024	Belgium & 3 other countries (International)	Multicentre prospective cohort (e-learning)	150 hybrid-OR team members, 8 centres	Surgeons, nurses, anaesthetists (43%), radiographers	Massive open online course raised radiation-safety knowledge from 48% to 71% (+22.8%); smaller gain where a radiographer was already embedded.	Moderate
Popovic et al., 2022	France (International)	Before–after (simulation training)	10 cardiology residents	Trainee operators	Mentored simulation lowered patient DAP (≈39%) and operator eye-lens dose (39→11 μSv); most gains persisted at 12 weeks.	High

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Study	Country (setting tag)	Design	Population setting	/ Professional groups	Main findings	Risk of bias
Lindberg et al., 2019	Sweden (International)	Longitudinal qualitative	Hybrid OR team	Surgeons, radiologists, nurses, radiographers, anaesthesia	Safe radiation use emerged through negotiated coordination and situated learning across professions; no single profession held authority over practice.	Moderate
Alshabi et al., 2022	Saudi Arabia (Saudi)	Cross-sectional survey	57 orthopaedic surgeons, Madinah	Orthopaedic surgeons	66.7% untrained in C-arm use; 78.9% used aprons but 17.5% apron + thyroid shield; 43.9% practised radiation safety in theatre.	Moderate
Abanomy, 2024	Saudi Arabia (Saudi)	Cross-sectional survey	102 orthopaedic surgeons, national	Orthopaedic surgeons	3.9% had formal radiation-protection training; 7.8% knew ALARA; 67.6% wore aprons; 80.4% wore no dosimeter.	Moderate
Wally et al., 2024	Saudi Arabia (Saudi)	Cross-sectional survey	203 non-radiology staff, 3 Tabuk hospitals	Physicians, nurses, allied staff	76% had low radiation-safety awareness; course attendance and imaging frequency associated with higher knowledge.	Moderate
Salama et al., 2016	Saudi Arabia (Saudi)	Cross-sectional survey + area measurement	4 health-care facilities, Eastern Province	Medical imaging staff	Aprons and thyroid shields widely available but lead glasses/shields in ~50% of facilities; dosimeter use 57.7%–68.9%.	High

Domains: A, occupational exposure in the hybrid OR; B, anaesthesia personnel; C, patient dose and system optimisation; D, education, knowledge and team practice. Abbreviations: CBCT, cone-beam computed tomography; DAP, dose–area product; DSA, digital subtraction angiography; EVAR/TEVAR, (thoracic) endovascular aortic repair; F/B(r)EVAR, fenestrated/branched EVAR; KAP, kerma–area product; OR, operating room; OSL, optically stimulated luminescence; TAVI, transcatheter aortic valve implantation; TEE, transoesophageal echocardiography; TLD, thermoluminescent dosimetry. Risk of bias appraised with design-specific criteria (see Methods).

3.3 Domain A: occupational exposure in the hybrid OR

Across settings, measured occupational doses were low in absolute terms. A one-year audit of 260 vascular procedures in a Spanish hybrid OR found all staff doses below legal limits (Andrés et al., 2017), and support staff in Dutch endovascular procedures received a median effective dose of 0.036–0.345 mSv per procedure, highest during fenestrated or branched repair (de Ruiter et al., 2018). The largest data set came from Saudi Arabia: a national thermoluminescent-dosimetry registry of 7,530 operating-room workers in 52 hospitals reported a mean annual effective dose of 0.59 mSv over 2015–2019, with more than 88% of workers below 1 mSv and none above 20 mSv (Almalki et al., 2021).

Average values, however, concealed large variation by imaging mode, position and task. In a phantom study with active dosimeters, roadmapping tripled and DSA increased operator dose 33-fold compared with low-dose fluoroscopy, whereas narrowing the field of view halved it (Serna Santos et al., 2020). In the Spanish audit, acquisition modes accounted for less than 5% of beam-on time but more than 60% of patient effective dose (Andrés et al., 2017). During intraoperative 3D scans of the pelvis, scatter was highest on the side of the surgical assistant rather than the main surgeon (Schuetze et al., 2018), and standing between the C-arm during spinal screw placement increased the surgeon's dose six-fold (Schuetze et al., 2019). A Korean comparison found a higher dose rate in the hybrid room than with a mobile C-arm and a shift of the surgeon's highest dose from the neck and shoulder to the lower body (Quan & Lee, 2019). Eye-lens exposure was the dose of greatest concern. In two German hybrid ORs, eye and finger doses correlated with DAP, and roughly 1,400 minutes of fluoroscopy were predicted to reach the 20 mSv annual eye-lens limit (Attigah et al., 2016). Monitoring practice can itself mislead: a Taiwanese study showed that the conventional chest badge facing the table under-estimated dose, especially for distant team members such as the assistant and the sterile nurse (Chiang et al., 2024). These findings indicate that staff at the periphery of the table, who are often not the subject of dosimetry studies, may be the ones whose exposure is least well measured.

3.4 Domain B: anaesthesia personnel

Seven studies addressed anaesthesia staff. In 31 neuro-interventional procedures, the anaesthesiologist's facial dose averaged 6.5 μ Sv per procedure, 3.2 times that of the radiologist, because the usual C-arm configuration directs scatter toward the head of the table; dose increased with the number of pharmacological interventions performed (Anastasian et al., 2011). During transcatheter aortic valve implantation, dosimeters on the outside of an anaesthesiologist's 0.35 mm lead-equivalent cap recorded up to 0.55 mSv, against 0.08 mSv inside (Mayr et al., 2019). A shielding device mounted at the head side and cradle of the table, developed by a hospital radiology technology division, reduced dose at the anaesthesiologist's position by 82.6–86.4% at 100 cm height and at the transoesophageal echocardiography operator's position by up to 91.0% (Miyazaki et al., 2021). In the Dutch endovascular study, the anaesthesiologist was among the support staff whose doses were a small fraction of the reference badge on the C-arm (de Ruiter et al., 2018).

The only study that separated anaesthesia technologists from physicians was Saudi. Over five years, 175 anaesthesia staff in interventional cardiology had a mean annual effective dose of 0.76 mSv; technologists, who made up 72% of the cohort, received significantly higher doses than consultants (0.80 vs 0.63 mSv; $p = .008$) (Shbeer, 2024). This difference is consistent with technologists' closer and more frequent presence at the patient's head. By contrast, a systematic

review of orthopaedic theatres found that anaesthesia providers standing at least 1.5 m from a mobile C-arm received negligible doses, often at the detection limit of dosimeters (Rhea et al., 2016). Distance therefore determines whether anaesthesia staff are meaningfully exposed, and in hybrid ORs, where anaesthesia staff often work within that distance, the protective effect of distance cannot be assumed.

Protection behaviour among anaesthesia staff was incomplete. Among 54 anaesthesiology trainees in Pakistan, 68.5% believed their precautions were adequate, yet only 20.4% used both an apron and a thyroid shield (Ali et al., 2020). In a Thai academic centre, 86.4% of anaesthesia personnel and surgical subspecialists always wore an apron and 78.5% a thyroid shield, but the mean knowledge score was 6.4 of 15, with particular gaps on eye protection and dose limits (Khamtuikruea & Suksompong, 2020).

3.5 Domain C: patient dose and system optimisation

Patient doses in hybrid-OR endovascular repair were substantial but generally below deterministic thresholds. Japanese aortic procedures recorded mean DAP values of 324 (thoracic) and 371 Gy·cm² (abdominal) and air kerma of 0.92–1.11 Gy without skin injury (Haga et al., 2020). Compared with mobile C-arms in a standard theatre, fixed hybrid systems were associated with higher DAP and longer fluoroscopy times but lower contrast volume (Arnautovic et al., 2024; de Ruiter et al., 2016). In thoracic surgery, intraoperative CBCT produced the highest skin doses in the 5th to 8th intercostal spaces, because the patient's arm, the anaesthesia machine and the table restricted the rotation of the C-arm; the authors advised a maximum of three scans (Kohmaru et al., 2024). Performing lung-nodule localisation within the hybrid OR, rather than as a separate pre-operative procedure, was associated with lower effective dose (median 3.2 vs 10.4 mSv) (Chia et al., 2024).

Equipment and protocol optimisation, which is typically led by medical physicists and implemented by radiologic technologists, produced the most consistent dose reductions (Figure 3). An upgrade to advanced image processing reduced patient air kerma by 56% in aneurysm repair and 76% in occlusive disease, and staff dose by 16% and 69%, without increasing fluoroscopy time (van den Haak et al., 2015). A similar technology reduced KAP per DSA frame by 61% (de Ruiter et al., 2016). An Italian "Eco" protocol that added copper filtration and halved the fluoroscopy pulse rate, combined with staff training, reduced patient DAP by 53–57% and staff dose by 25.6% (Ruffino et al., 2018). Low-dose 3D-scan settings reduced scatter by about two-thirds (Schuetze et al., 2018), and a ceiling-mounted CBCT system produced 22% less occupational dose than a mobile CBCT unit (Cewe et al., 2022).

Radiation Safety And Patient Protection In Hybrid Operating Rooms: An Interprofessional Systematic Review Of The Roles Of Radiologic Technologists, Anesthesia Technicians, And Medical Physicists

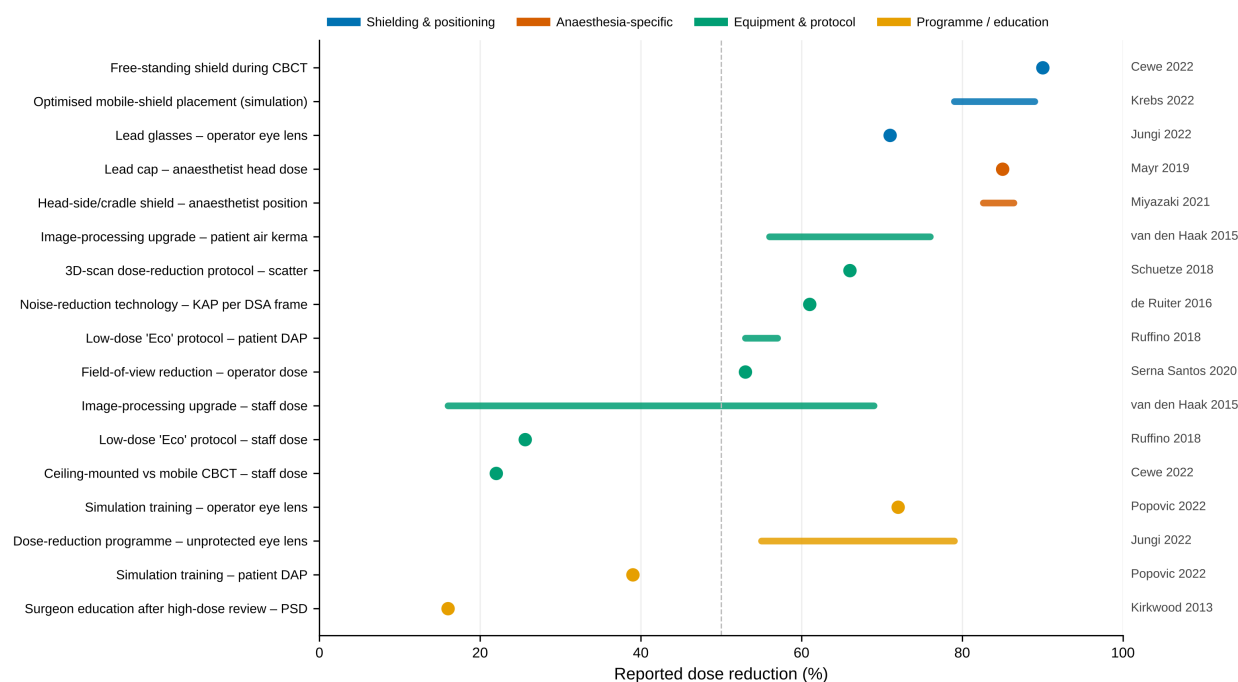


Figure 3. Dose reductions reported for interventions in the included studies, grouped by type of intervention. Dots show single reported values; bars show the range reported across procedure types or measurement positions within a study. Values derive from different dose metrics (effective dose, eye-lens dose, KAP/DAP, air kerma, scatter dose) and settings and are not directly comparable effect sizes. Dashed line marks 50%. CBCT, cone-beam computed tomography; DAP, dose–area product; DSA, digital subtraction angiography; KAP, kerma–area product.

Shielding and positioning produced the largest reductions in staff dose. Free-standing shields reduced scatter by more than 90% during CBCT, allowing staff to work without heavy aprons during acquisitions (Cewe et al., 2022), and optimised placement of mobile shields reduced clinician exposure by 79–89% in simulation, with small displacements of the shield producing large changes in dose (Krebs et al., 2022). Lead glasses reduced eye-lens dose 3.4-fold (Jungi et al., 2022). Structured dose investigation also helped: an institutional policy of reviewing every case exceeding 6 Gy reference air kerma led to targeted surgeon education, a 10 cm average rise in table height and an estimated 16% reduction in peak skin dose (Kirkwood et al., 2013).

3.6 Domain D: education, knowledge and team practice

Education improved both knowledge and dose. A multicentre massive open online course for hybrid-OR teams, in which anaesthetists made up 43% of participants, raised radiation-safety knowledge from 48% to 71%; the gain was smaller in centres where a radiographer was already embedded in the team (Soenens et al., 2024). Mentored simulation training for cardiology trainees reduced patient DAP by about 39% and operator eye-lens dose from 39 to 11 μ Sv, with most benefits persisting at 12 weeks (Popovic et al., 2022). A structured dose-reduction programme in a German hybrid OR was followed by 55–79% lower unprotected eye-lens dose to the first operator (Jungi et al., 2022). When a Dutch team completed hybrid-OR training before commissioning, no radiation learning curve was observed and doses matched those of experienced centres (Wermelink et al., 2019).

A longitudinal qualitative study of a Swedish hybrid OR showed that safe use of radiation was not owned by any single profession. It emerged through negotiation among surgeons, radiologists, nurses, radiographers and anaesthesia staff, recognition of each other's expertise and situated learning in daily work (Lindberg et al., 2019). This finding helps explain why the presence of a radiographer altered the benefit of e-learning in the multicentre course (Soenens et al., 2024).

3.7 Saudi Arabian evidence

The seven Saudi studies present a consistent picture of low measured doses alongside weak training and monitoring practice (Figure 4). Measured doses were low: 0.59 mSv per year for operating-room personnel nationally (Almalki et al., 2021); 0.80 and 0.63 mSv per year for anaesthesia technologists and consultants (Shbeer, 2024); and, in a cardiac catheterisation laboratory at Prince Sattam bin Abdulaziz University, personal dose equivalents of 1.11 mSv for cardiologists, 0.84 mSv for nurses and 0.68 mSv for X-ray technologists (Sulieman et al., 2023).

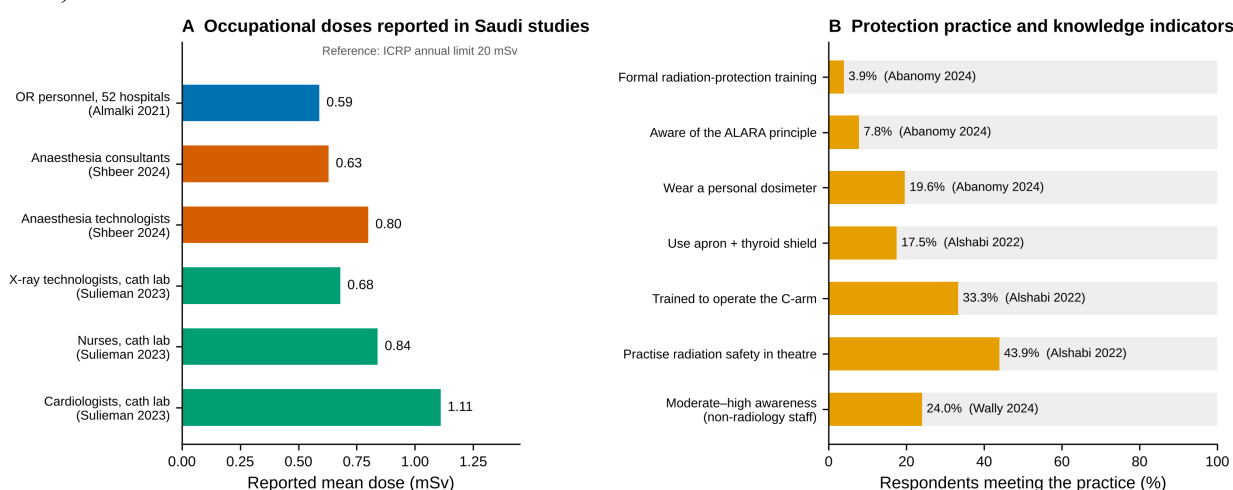


Figure 4. Saudi Arabian evidence. (A) Mean occupational doses reported in Saudi studies (annual effective dose for Almalki et al., 2021 and Shbeer, 2024; personal dose equivalent over the monitoring period for Sulieman et al., 2023). (B) Proportion of respondents meeting selected radiation-protection practice and knowledge indicators in Saudi surveys (Abanomy, 2024, n = 102; Alshabi et al., 2022, n = 57; Wally et al., 2024, n = 203).

Knowledge and practice indicators were poor. Among 102 orthopaedic surgeons, only 3.9% had formal radiation-protection training, 7.8% understood the ALARA (as low as reasonably achievable) principle, and 80.4% did not wear a dosimeter (Abanomy, 2024). In Al-Madinah, two-thirds of orthopaedic surgeons had not been trained to use the C-arm, only 17.5% used both an apron and a thyroid shield, and 43.9% reported practising radiation safety in theatre (Alshabi et al., 2022). Among 203 non-radiology staff in Tabuk, 76% had low radiation-safety awareness; attending a radiation-protection course was associated with better knowledge (Wally et al., 2024). An earlier survey in the Eastern Province found aprons and thyroid shields widely available but lead glasses and mobile shields in only about half of facilities, with incomplete dosimeter use (Salama et al., 2016). No Saudi study measured eye-lens dose, evaluated a dose-reduction intervention, or described the role of medical physicists in hybrid ORs.

3.8 Interprofessional synthesis

Mapping the findings to professional roles produced the framework in Table 3. Medical physicists appeared mainly as architects of the system: they commission equipment, design low-dose protocols, set and audit dose thresholds, investigate high-dose events and design shielding layouts. Radiologic technologists translate these protocols into exposure choices during each case, including pulse rate, collimation, field size, acquisition mode and C-arm geometry, and several included studies were led by them. Anaesthesia personnel are frequently the team members closest to the scatter field and the least trained; the evidence supports giving them dedicated head-side shielding, eye and head protection, correctly placed dosimeters and inclusion in team training.

Table 3. Interprofessional radiation-safety framework for the hybrid OR, derived from the included evidence

Profession	Core responsibilities supported by evidence	Key supporting studies
Medical physicist	Acceptance testing and commissioning; design of low-dose fluoroscopy, DSA and CBCT protocols (filtration, pulse rate, frame rate); patient-dose audit against reference levels; investigation of high-dose cases; staff dosimetry review including eye lens; shielding design and positioning studies; staff education	Kirkwood et al., 2013; van den Haak et al., 2015; Ruffino et al., 2018; Cewe et al., 2022; Krebs et al., 2022; Tsapaki, 2020
Radiologic technologist	Applying optimised protocols case by case; collimation, field size, table height and C-arm geometry; choosing low-dose modes and limiting DSA/CBCT runs; pre-acquisition warnings so staff step back; recording dose indicators; on-the-floor coaching of the team	Serna Santos et al., 2020; Haga et al., 2020; Miyazaki et al., 2021; Soenens et al., 2024; Sulieman et al., 2023
Anaesthesia personnel (anesthesia technicians and anaesthesiologists)	Use of head-side shields, lead glasses or caps and thyroid shields; maximising distance and stepping back during acquisitions; positioning the anaesthesia machine and lines so they do not obstruct CBCT rotation; correct dosimeter wearing; participation in team training	Anastasian et al., 2011; Mayr et al., 2019; Miyazaki et al., 2021; Shbeer, 2024; Kohmaru et al., 2024; Ali et al., 2020
Whole team (with surgical lead)	Shared protocol and briefing; pre-commissioning simulation or e-learning; negotiated roles and situated learning; monitoring of dosimeter compliance and protective-equipment use	Lindberg et al., 2019; Wermelink et al., 2019; Soenens et al., 2024; Popovic et al., 2022; Abanomy, 2024

Abbreviations: CBCT, cone-beam computed tomography; DSA, digital subtraction angiography; OR, operating room.

4. Discussion

This review brought together 36 studies on radiation safety in hybrid ORs and related procedural settings and examined them through the lens of three professions that are often peripheral in the hybrid-OR literature. Four main findings emerge. First, average occupational doses are low, both internationally and in Saudi Arabia, but the averages hide steep gradients by imaging mode, position and role. Second, anaesthesia personnel, particularly technologists, can receive doses comparable to or higher than those of the physicians they work alongside, yet they are seldom studied. Third, the largest and most reliable reductions come from engineering controls and protocol optimisation, which are led by medical physicists and executed by radiologic technologists, while education contributes smaller but durable gains. Fourth, Saudi hospitals report low measured doses but weak training, dosimetry and protective-equipment culture.

4.1 Average doses are not the right safety target

Low annual whole-body doses, such as the 0.59 mSv reported for Saudi operating-room personnel (Almalki et al., 2021), are reassuring with respect to stochastic risk. They do not, however, address the eye lens, which is now the limiting organ for interventional staff (ICRP, 2012). Studies of interventional personnel have documented radiation-associated lens opacities in nurses and technicians, not only in physicians (Ciraj-Bjelac et al., 2010; Vano et al., 2010). In Finland, nurses and radiographers were estimated to be well below the eye-lens limit, but only when appropriate glasses were worn and doses were properly measured (Pekkarinen et al., 2022). The hybrid-OR studies included here show that badge orientation can under-estimate dose to peripheral staff (Chiang et al., 2024) and that DSA and CBCT acquisitions dominate exposure (Andrés et al., 2017; Serna Santos et al., 2020). Whole-body averages from chest badges are therefore an incomplete safety indicator. Radiation-safety programmes should add eye-lens dosimetry for high-exposure roles, record which team members are present during acquisitions, and treat individual outliers as signals for review rather than relying on mean values.

4.2 Anaesthesia personnel: close to the field, far from the training

The anaesthesia findings are consistent across settings. The head-of-table position puts anaesthesia staff on the path of scatter from oblique and lateral projections (Anastasian et al., 2011), and every intervention at the airway or infusion line brings them closer to the field. The Saudi finding that technologists received higher doses than consultants (Shbeer, 2024) suggests that much of this exposure falls on the anaesthesia technician, who is the team member most continuously present at the patient's head. Commentaries addressed to anaesthesiologists recommend aprons, thyroid collars, lead glasses, mobile shields, distance and dual dosimetry (Dagal, 2011; Hussey et al., 2019), and similar concerns have been raised for interventional echocardiographers, who share the head-of-table position (Garcia-Sayan et al., 2024). The device and cap studies show that targeted head-side shielding can reduce dose by more than 80% (Mayr et al., 2019; Miyazaki et al., 2021). The conclusion of the orthopaedic review that aprons may be unnecessary at 1.5 m (Rhea et al., 2016) should not be extrapolated to hybrid ORs, where anaesthesia staff routinely work closer to the patient and where high-output acquisitions are frequent. Yet the knowledge surveys show that anaesthesia staff over-estimate their own protection (Ali et al., 2020; Khamtuikruea & Suksompong, 2020). Anaesthesia technicians should therefore be explicitly included in radiation-protection training, dosimetry

and fitting of protective eyewear, and the hybrid-OR layout should provide a ceiling-suspended or mobile shield at the head of the table.

4.3 The physicist–technologist partnership as the engine of optimisation

The interventions with the largest and most consistent effects—filtration and pulse-rate changes, image-processing upgrades, low-dose CBCT protocols and shield placement—share a common feature: they change the system rather than relying on individual vigilance (Cewe et al., 2022; Krebs et al., 2022; Ruffino et al., 2018; van den Haak et al., 2015). Achieving these gains requires a medical physicist to specify and validate protocols and a radiologic technologist to apply them case by case, choosing the lowest-dose mode compatible with the clinical task and prompting the team before acquisitions. This division of labour matches the optimisation process recommended by the International Atomic Energy Agency, which places a radiologist, medical physicist and radiation technologist in a joint optimisation team (Tsapaki, 2020), and the dose management programmes recommended for interventional practice (Bartal et al., 2014; Modarai et al., 2023). The high-dose investigation model described by Kirkwood et al. (2013) shows that a structured audit loop, a task for which physicists are trained, can change surgeons' behaviour and patient dose. The smaller knowledge gain from e-learning in centres with an embedded radiographer (Soenens et al., 2024) suggests that the technologist already acts as an informal educator, a role that could be formalised.

4.4 Saudi Arabia in the global context

Saudi measured doses are comparable to or lower than those reported internationally, and in this respect the national picture is reassuring (Almalki et al., 2021; Shbeer, 2024; Sulieman et al., 2023). The contrast lies in culture and systems. Fewer than one in twenty Saudi orthopaedic surgeons reported formal training, and four in five did not wear a dosimeter (Abanomy, 2024), whereas international hybrid-OR teams that trained before commissioning avoided a dose learning curve (Wermelink et al., 2019). Low recorded doses in a setting where dosimeters are often not worn may under-state true exposure, so they cannot be taken as evidence that current practice is adequate. In addition, the Saudi evidence contains no eye-lens measurements, no evaluation of a dose-reduction intervention and no description of how medical physicists support hybrid ORs. Given the national expansion of complex surgical and interventional services, Saudi hospitals have the opportunity to build hybrid-OR radiation-safety programmes from the start: physicist-led commissioning and protocol design, technologist-led dose management at the table, routine eye-lens dosimetry for high-exposure roles, mandatory pre-commissioning team training that includes anesthesia technicians and nurses, and dose indicators reported through hospital quality and accreditation structures.

4.5 Implications for practice

- Form a hybrid-OR radiation-safety team with named responsibilities for the medical physicist, the lead radiologic technologist, the anaesthesia team and the surgical lead.
- Commission low-dose default protocols (pulse rate, filtration, acquisition frame rate, CBCT settings) and review them annually against local diagnostic reference levels.
- Make the radiologic technologist responsible for a pre-acquisition announcement so that non-essential staff step back or behind shields during DSA and CBCT.
- Provide a ceiling-suspended or mobile shield at the head of the table, lead glasses and head protection for anaesthesia staff, and position the anaesthesia machine so that it does not restrict CBCT rotation.

- Introduce dual (over- and under-apron) and eye-lens dosimetry for operators, anaesthesia technicians and other high-exposure roles, and audit dosimeter compliance.
- Establish a physicist-led review of procedures exceeding agreed patient-dose thresholds, with feedback to the team and patient follow-up for possible skin effects.
- Require interprofessional radiation-safety training, including simulation or e-learning, before staff work in a new hybrid OR, and repeat it periodically.

4.6 Strengths and limitations

This review is, to our knowledge, among the first to examine hybrid-OR radiation safety explicitly through the roles of radiologic technologists, anaesthesia personnel and medical physicists, and to combine Saudi and international evidence. It included phantom, clinical, educational and qualitative studies, which allowed both the magnitude of exposure and the organisational conditions of safe practice to be examined. Several limitations apply. Only PubMed/MEDLINE was searched systematically, and only English-language articles were included, so studies indexed solely in Scopus, Web of Science, CINAHL or regional databases, and grey literature such as national dose-registry reports, may have been missed. The heterogeneity of dose quantities, dosimeter types and procedures precluded meta-analysis, and the percentage reductions in Figure 3 come from different metrics and settings and should be read as indicative rather than comparable effect sizes. Most studies were single-centre with moderate risk of bias, and several relied on phantoms. Few studies isolated anesthesia technicians or described medical physicists' practice directly, so parts of the interprofessional framework are inferred from the roles that drove the interventions. The Saudi evidence came mainly from surveys and from settings adjacent to the hybrid OR, and no eligible study from other Gulf countries was found.

5. Conclusion

Hybrid operating rooms can be operated with low average occupational doses, but exposure is concentrated in particular imaging modes, positions and roles, and the eye lens remains insufficiently monitored. The most effective protection is systemic, combining physicist-designed low-dose protocols, technologist-led dose management at the table, well-placed shielding and team training. Anaesthesia personnel, particularly anesthesia technicians, are close to the scatter field yet are rarely studied or trained, and should be explicitly included in protection programmes. In Saudi Arabia, reassuring dose records coexist with marked gaps in training, dosimeter use and local intervention research. A structured interprofessional radiation-safety programme, together with Saudi studies of eye-lens dose and of dose-reduction interventions in hybrid ORs, would strengthen both staff protection and patient safety.

Declarations

Ethical approval. Not applicable. This study is a systematic review of published literature and did not involve human participants or identifiable data.

Consent for publication. Not applicable.

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Conflicts of interest. The authors declare no conflicts of interest.

Data availability. All data analysed are drawn from published studies cited in this article. The extraction table is provided in Table 2; further data are available from the corresponding author on reasonable request.

Author contributions. Conceptualisation: F.M.A., H.M.A.A.; methodology: F.M.A., H.M.A.A.; literature search and screening: F.M.A., F.B.A., B.O.A., M.A.S.A.; data extraction and quality appraisal: B.O.A., M.A.S.A., F.B.A.; writing—original draft: F.M.A.; writing—review and editing: all authors. All authors approved the final manuscript.

Use of artificial intelligence. An AI assistant (Claude, Anthropic) was used to support literature retrieval, data extraction, figure generation and drafting. The authors verified all sources and data against the original publications and take full responsibility for the content.

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