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Guidelines

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Radiation Principles, Protection, and Reporting for Interventional Pulmonology: A World Association of Bronchology and Interventional Pulmonology White Paper

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Abstract

The use and availability of diverse advanced X-ray based imaging and guidance systems in the field of interventional pulmonology are rapidly growing. This popularity links inextricably to an increase in ionizing radiation use. Knowing ionizing radiation is hazardous, knowledge and competent use of X-ray imaging and guidance systems are important. The globally implemented As Low As Reasonably Achievable (ALARA) principle demands careful attention to minimize radiation exposure while achieving the precise goals of the intervention and imaging therein. To allow careful and targeted weighing of risk against reward while using X-ray based equipment, proper background knowledge of physics as well as imaging system aspects are needed. This white paper summarizes the principles of ionizing radiation which

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are crucial to enhance awareness and interpretation of dosimetric quantities. Consecutively, a consensus on standards for reporting radiation exposure in interventional pulmonology procedures is indicated to facilitate comparisons between different systems, approaches and results. Last but not least, it provides a list of practical measures, considerations and tips to optimize procedural imaging as well as reduce radiation dose to patients and staff.

Introduction

In the past decade, the field of interventional pulmonology has been transformed by the significant increase in the use of advanced imaging modalities and technological guidance for both diagnostic and therapeutic procedures. The advent of these technologies leads the ability to perform more procedures through bronchoscopy. In diagnostics for peripheral pulmonary lesions, for example, advanced technologies such as electromagnetic tracking, virtual endoscopic guidance based on pre-procedural CT scans, novel shape sensing technologies, and multiple other technologies are being used. Whereas the majority of these technologies aim to provide navigation as a standalone modality, the vast majority of procedures sees it accompanied or integrated with real-time X-ray imaging. While only a decade ago the portfolio consisted predominantly of basic fluoroscopy guidance, recent advancements have introduced algorithms enabling not only simple two-dimensional (2D) fluoroscopy but also three-dimensional (3D) imaging modalities such as tomosynthesis and cone-beam CT (CBCT). Although access to high-end hybrid operating rooms (ORs) or interventional radiology suites equipped with fixed flat panel CBCT systems is still limited in many countries, the advent of mobile CBCT systems will likely translate into a rapid increase in the use of these devices.

As diverse image-guiding systems become more available to interventional pulmonologists, increasing the use of ionizing radiation, it is crucial to enhance awareness and education about ionizing radiation principles among both patients and hospital staff. Furthermore, there is a pressing need to establish an international reporting standard for consistent and accurate reporting on radiation dose and safety. This would enable standardized and comparable assessment of radiation metrics among studies. This paper aims to (1) refresh our knowledge on the basic principles of ionizing radiation, (2) guide researchers to address radiation dose and safety accurately and consistently in (future) studies, and (3) create awareness and provide practical tips on how to prevent unnecessary exposure to radiation for the safety of our patients, our staff and ourselves.

Physics of Ionizing Radiation in Diagnostic Imaging

Ionizing radiation refers to any form of electromagnetic or particle radiation with sufficient energy to remove tightly bound electrons from atoms. Ionizing radiation includes photons, alpha particles, beta particles, and neutrons. In the case of diagnostic X-ray imaging, the elementary ionizing particles that are of interest are photons (X-rays and gamma rays). These photons possess higher energy levels (expressed in the term electronvolt) than photons known from visible light and therefore have different properties while interacting with tissue. In diagnostic, imaging photons are generated in the X-ray tube (Fig. 1). An image is created by summating all the photons at the detector that did not interact with matter. X-ray photons that interact with matter can either be absorbed or scattered. The chance of interaction between a photon and tissue is small but can be optimized for diagnostic imaging by adjusting the number of photons emitted, photon energy, density of tissue, and pathway length. The difference in absorption per tissue is the building block of images and causes the variation in contrast of the image. As an obvious example, air is less dense than bone tissue so it is more likely that photons interact with bone tissue than with air. Upon interaction of photons with tissue, they are scattered in different directions. The scattered portion negatively contributes to image quality as the scattered radiation can also reach the detector but have an unknown trajectory that cannot be fully distinguished from the original radiation beam causing a reduction in image contrast. Therefore, a grid (Fig. 1) is installed between the patient and the detector to prevent incoming scattered radiation from reaching the detector. The radiation that scatters to the side of the X-ray tube is called "back-scattered radiation" and is much more intense than "forward-scattered radiation" (Fig. 1).

The exposure settings of the X-ray imaging system influence the image quality and radiation dose received by the patient. The tube voltage (kilovoltage peak, kVp) and tube electrical current multiplied with the exposure time (milliampere seconds, mAs), respectively, determine the energy the photons will get and the number of photons

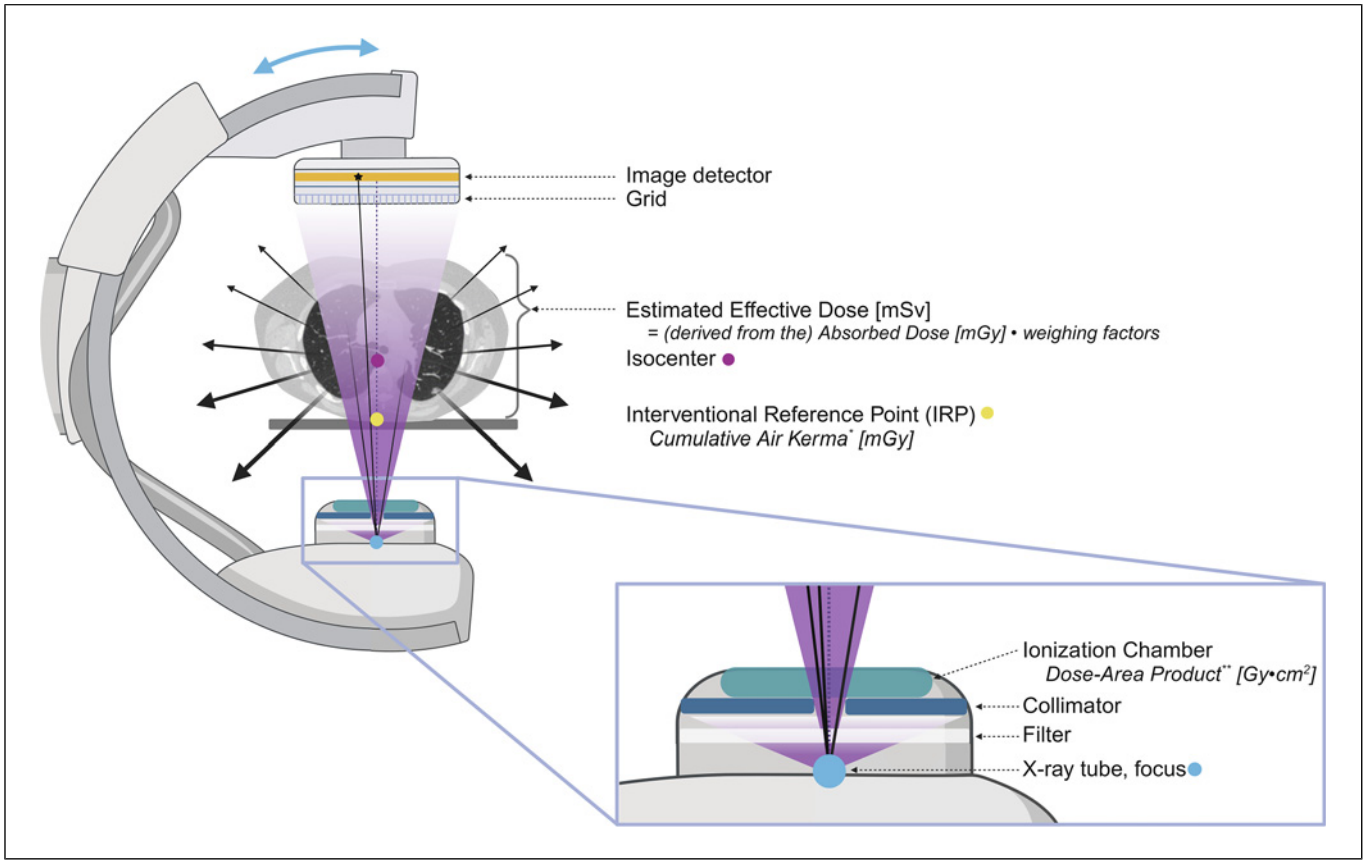

Fig. 1. Schematic cross-section of a C-arm-based X-ray imaging setup in which the different components are illustrated by color. X-ray photons are generated in the X-ray tube (blue dot) and will partially pass the filter (white colored box) and collimator diaphragm (blue colored boxes). The exiting bundle dose is measured in the ionization chamber (aqua colored box) and reported as the dose area product (DAP). The cumulative air kerma (CAK) is a measure of the procedural radiation dose and estimated at the Interventional Reference Point (IRP, yellow dot), at a standard distance from the isocenter (purple dot). The X-ray photons that are not absorbed in the patient (gradient-opaque purple colored box) or scattered (black arrows), need to pass the filtering grid (wire frame in light blue) to reach the image detector (orange colored box). The summation of signals received in the image detector leads to the image formation. Radiation scatter is the greatest radiation exposure source to staff. *The cumulative air kerma is measured in the IRP. **The dose area product is measured using an ionization chamber. This figure was created with BioRender.com.

that are generated. In order for the detector to obtain any signal the photons require adequate energy to allow penetration (i.e., sufficiently high voltage) but also interaction with the tissue (i.e., the voltage should not be too high). To allow the generation of sufficient photons for clinical image quality, the tube electric current should be sufficiently high. Newer fluoroscopy systems have specialized automatic exposure control feedback loops that can adjust the tube kVp and mA to achieve optimal imaging quality (radiation dose vs. imaging quality). As an example, when using specific lung-tailored protocols in larger adult torsos there is a need for higher energy X-ray photons to penetrate the anatomy than in that of a small child's torso.

Radiation Effects

There is a general consensus that ionizing radiation negatively affects the human body. X-ray photon and tissue interactions typically do not lead to problematic disruptions at atomic or molecular level. However, dysregulations in the chemical bonds in the DNA can have significant consequences even with a minimal amount of energy. Normally, DNA repair mechanisms will address these damages immediately, or the affected cells undergo apoptosis. However, DNA double-strand breaks or misrepairs can cause mutations in cells that can result in the induction of cancer. It is widely acknowledged that an increase in radiation exposure corresponds to an increased risk for individuals. The risk of developing

cancer due to radiation cannot be clinically distinguished from the same type of cancer arising from other causes. Hence, any cancer risk estimates at diagnostic and interventional levels must be treated with caution [1].

The interaction of tissue with radiation can lead to two different effects in the human population:

1. Deterministic effects: deterministic effects are effects in which the severity of the injury (rather than its probability of occurrence) increases once a threshold dose has been exceeded. Below the threshold, no effect will be apparent. For example, after an interventional procedure where the peak skin dose (PSD) ranges from 2 to 5 Gy, symptoms such as skin erythema may appear within 2 weeks and hair loss (epilation) can occur within two to 8 weeks. Complete recovery from these symptoms is typically expected at the lower threshold skin doses. Higher doses (>5 Gy) will have longer or even permanent consequences.
2. Stochastic effects: Stochastic effects refer to the probability of an effect occurring (rather than its severity) and increase with dose, e.g., radiation-induced cancer and hereditary effects. There is no defined threshold dose for stochastic effects.

Radiation Metrics

In interventional pulmonology literature, various metrics have been used to report on radiation use. These are not only metrics provided by the system but also metrics that require additional assumptions about the procedure and the patient (including simulation modeling) for accurate calculation. For example, to estimate the effective dose, one must know the specific organs involved and their positioning within the irradiated field. As rotating the C-arm would significantly alter the geometry, this would significantly affect the procedural effective dose measurements. The use of different units and diverse assumptions complicates the comparison of radiation doses between studies, procedures, hospitals, operators, devices, or even personal performance over time. Below is a brief overview of core metrics as commonly referenced in radiation literature.

Modern fluoroscopy systems report the CAK and the DAP as Dose Metrics:

- Cumulative Air Kerma (CAK, in Gy): The total cumulative Kinetic Energy Released in MAtter (KERMA), specifically in air (Air Kerma) is reported for fluoroscopy systems at a specific location known as the interventional reference point (IRP, Fig. 1). It is expressed in Gray (Gy), which is the SI (International System of Units) base unit of absorbed ionizing radiation. The CAK is roughly correlated with the risk of deterministic effects of radiation on biological tissue and reflects the dose received by the skin. It is important to note that the CAK is reported for the entire patient exam, which may have been distributed over the patient surface opposed to delivering it all at one surface location.
- Dose Area Product (DAP, in Gy·cm^2): The DAP is calculated by multiplying the Dose (Gy) by the area of irradiation (cm^2). This measurement reflects the absorbed dose within a specific area of tissue that has been irradiated. DAP is measured using an ionization meter placed beyond the X-ray collimators (Fig. 1). DAP is approximately correlative with the risk of stochastic effects, such as cancer, due to radiation exposure in biological tissue. Akin to CAK, fluoroscopy systems also report the total DAP for a patient examination and thus never reflect the dose in a specific organ.
- Effective Dose (ED, in Sv): The ED accounts for the fact that different tissue types exhibit varying levels of sensitivity to the stochastic risk of radiation (reflected in a weighing factor Wt). The ED is expressed in Sieverts (Sv), which is the SI-unit that represents the stochastic health risk of ionizing radiation. The ED is estimated from the DAP using conversion factors. The accuracy of this estimation depends on many factors such as the C-arm angle, collimation used, organ presence in the field of view, type of exam performed, et cetera. The conversion from DAP to effective dose is rarely generalizable across cohorts in non-standardized imaging procedures (i.e., procedures which allow the operator to adjust imaging performed). Due to the multiple variables involved in estimating the effective dose from DAP in X-ray imaging systems such as C-arms and CBCT systems, a significant error margin can be expected in the calculated effective dose [2–4]. In interventional pulmonology, it should therefore be regarded with caution and only used as a means to allow the risks to be compared with other imaging modalities like PET-CT and CT in a general sense.
- Note that fluoroscopy systems generally only report total CAK and DAP in a procedural summary report. More recent systems may also provide CAK and DAP for every radiation exposure event, including the beam geometry, in a more detailed Radiation Dose Structured Report which the clinical physicist of the hospital can provide. We recommend that conversion from the reported total CAK and DAP to PSD for deterministic risk and ED for stochastic risk is conducted by a physicist.

Table 1. Effective doses for various examinations (per scan) using ionizing radiation

	Examination	Average effective dose, mSv[a]	Reference
Background radiation level	–	2.4	[6]
X-ray	Thorax	0.1	[7]
CT diagnostic	Chest CT Low-dose CT lung cancer screening	6–8 0.4–2.4	[7, 8] [8–10]
CT interventional	CT-TTNA Coronary angiography (diagnostic) Coronary percutaneous transluminal angioplasty, stent placement, or radiofrequency ablation	1–3.5 7 15	[11] [7] [7]

The reported effective dose is expressed in millisievert (mSv) and can serve as a reference in evaluating the radiation exposure in the field of intervention pulmonology. CT, computed tomography; TTNA, transthoracic needle aspiration. [a]The actual radiation exposure depends on many things including the imaging system used, the duration of imaging, patient size, patient positioning, and sensitivity of the tissue being targeted.

- Personal Dose Equivalent (in Sv): For occupational radiation protection monitoring, the personal dose equivalent is measured by dosimeter badges. It is used as an estimation of the effective dose of the staff. Depending on the photon energy and position where the badge is worn, the badge may lead to inaccuracies of the actual effective dose received [5].

Background Dose and Diagnostic Imaging Procedures

Radiation exposure does not only occur in healthcare facilities as every human is exposed to background radiation occurring in nature every day. The average annual background radiation level worldwide is estimated to be 2.4 mSv [6]. An example of effective dose estimations that patients are exposed to in diagnostic imaging can be found below in Table 1. Note that the effective dose should not be used for individual patient doses but rather to compare doses across exam types and modalities.

Image-Guided Procedures in Interventional Pulmonology

Historically, the use of ionizing radiation in interventional pulmonology primarily involved fluoroscopy as facilitated by either mobile or fixed C-arm systems with only 2D imaging capabilities. Diagnostic applications of fluoroscopy included the assessment of interstitial lung diseases or nodules, as well as the evaluation of diaphragm motility. Therapeutic interventions often involved bronchoscopic lung volume reduction using coils or valves for severe emphysema, airway stents for central airway obstructions, and less frequently brachytherapy as a form of local radiotherapy. Although *trans*-thoracic needle aspiration has had a consistent place in interventional pulmonology, it has predominantly been performed under CT guidance by (interventional) radiologists.

Advanced X-ray image guidance has garnered significant interest in interventional pulmonology, particularly with the rise of navigation bronchoscopy procedures. The use and development of advanced X-ray imaging techniques has captured the attention of physicians and the health industry worldwide. The available clinical setups nowadays include (advanced) fluoroscopy, tomosynthesis, fixed CBCT systems in hybrid ORs and interventional radiology suites, and mobile CBCT systems capable of 3D imaging. Numerous studies have been published addressing the procedure outcomes utilizing these technologies. However, the associated radiation exposures are often absent, limited or presented in formats that are difficult to interpret, complicating the task of making accurate comparisons. For example, an extensive but non-exhaustive review of the literature on navigation bronchoscopy technologies that included radiation metrics is presented in Table 2. There is considerable variability in how procedures are performed; with physicians balancing the use of 2D fluoroscopy and 3D image acquisition based on their specific needs. Increasing the use of 2D fluoroscopy can lead to fewer 3D acquisitions and vice versa. The adoption of supplementary guidance technologies plays a role in this clinical decision as well. Aside of differences in individual physician preferences in imaging, imaging and guidance systems also have specific requirements that result in different radiation exposures. The limited subset of studies as shown in Table 2 show the

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Table 2. Radiation exposure reported in navigation bronchoscopy literature

Modality	Specification		Author	Year	Lesions, *N*	BMI, kg m^{-2}	Diagnostic or Therapeutic	Procedural time, min	Fluoroscopy time, min	Fluoroscopy DAP, Gy·cm^2	No. of 3D spins	Total 3D DAP, Gy·cm^2	Total DAP, Gy·cm^2	Total CAK FL+3D, mGy
CBCT with fluoroscopy (2D + 3D)	Fixed system	CBCT-AF, FL	Casal et al. [13]	2018	20	–	D	62.5	8.6	–	1.5	50.5	64.57	–
			Steinfort et al. [14]	2018	4	–	D	–	0.5	–	5.5	–	–	–
			Verhoeven et al. [12]	2021	26	25.3	D	–	9.9	19.0	2.47	29.9	47.5	–
					7		D	–	13.6	7.1	2.47	29.9	45.3	–
					24		D	–	13.6	7.1	2.0	27.2	29.8	–
					13		D	–	15.6	2.2	2.25	31.1	28.2	–
					30		D	–	15.6	2.2	2.93	25.8	25.4	–
			Verhoeven et al. [15]	2021	47	–	D	–	9.9	–	2.2	–	–	–
			Yu et al. [16]	2021	53	–	D	40.8	2.2	3.17	1	16.42	19.59	–
			Lin et al. [17]	2022	115	–	D	41.9	–	2.7	–	22.78	25.48	–
			DiBardino [18]	2023	57	–	D	–	–	–	2.0	–	70.4	–
			Pritchett et al. [19]	2023	58	28.3	D	–	–	–	1.75	–	56.0	–
			Lian et al. [20]	2024	23	22.6	D	–	3	2.04	2	22.66	25.90	–
				2024	2	21.6	D	–	2	6.46	3	51.99	58.45	–
				2024	2	20.7	D	–	3.5	0.71	2	34.11	35.94	–
				2024	11	22.3	D	–	3	3.95	2	27.30	29.32	–
				2024	7	24.3	D	–	9	12.47	3	61.46	73.17	–
			Watson et al. [21]	2024	10	–	T	–	0.3	–	3	–	77.78	–
		CBCT-AF, FL and ENB, VNB, or RAB	Bowling et al. [22]	2017	14	–	D	–	17.0	–	–	–	–	–
			Pritchett et al. [23]	2018	9	–	D	–	6.2		1.5		31.0	–
			Benn et al. [24]	2021	59	–	D	65	–	–	–	–	–	1.69
			Chan et al. [25]	2021	30	–	D & T	126	–	–	7.6	–	278.7	–
			Katsis et al. [26]	2021	29	–	D	78.7	8.8	–		–	–	259.6
			Verhoeven et al. [15]	2021	40	–	D	–	7.3	–	1.5	–	–	–
			Podder et al. [27]	2022	17	–	D	–	–	–	3.5	–	–	858.5
			Bondue et al. [28]	2023	25	26	D	80	–	–	3	–	–	–
			Styrvoky et al. [29]	2023	269	27.1	D	68	5.6	–	1.5	–	22.6	63.5
			Lau et al. [30]	2024	30	–	D & T	123	–	–	11.1	–	–	697.8

Table 2 (continued)

Modality	Specification		Author	Year	Lesions, *N*	BMI, kg m^{-2}	Diagnostic or Therapeutic	Procedural time, min	Fluoroscopy time, min	Fluoroscopy DAP, Gy·cm^2	No. of 3D spins	Total 3D DAP, Gy·cm^2	Total DAP, Gy·cm^2	Total CAK FL+3D, mGy
	Mobile system	CBCT, FL and RAB	Avasarala et al. [31]	2020	8	–	D	–	8.4	–	3.25	–	40.93	–
			Kalchiem-Dekel et al. [32]	2020	10	–	D	81.9	–	–	1.5	–	37.1	–
			Reisenauer et al. [33]	2022	30	27.7	D	–	8.7	–	2.5	–	50.3	–
			Abia-Trujillo et al. [34]	2023	117	26.0	D	81	8.40	–	–	–	37.20	–
			Salahuddin et al. [35]	2023	51	–	D	85	13.6	30.6	1.82	11.4	41.92	–
			Kalchiem-Dekel et al. [4]	2024	45	27.1	D	36	4.8	–	1	–	9.78	71.0
					47	26.5	D	58	6.3	–	2	–	15.15	107.6
					15	24.9	D	66	8.4	–	3	–	20.37	141.4
					11	27.5	D	75	9.4	–	≥4	–	29.35	204.1
		CBCT (O-arm), FL and ENB or RAB	Cho et al. [36]	2021	6	–	D	–	1.2	–	4.33	–	–	–
			Chambers et al. [37]	2023	79	–	D	80	–	–	2.9	–	–	–
Tomosynthesis (2D + 3D)		Tomosynthesis, FL	Bhadra [38]	2018	30	–	D	–	3.3	–	–	–	–	–
			Mathew and Roy [39]	2023	46	–	D	–	7	–	1.6	–	38	–
Fluoroscopy (2D)		FL	Steinfort et al. [40]	2010	45	–	D	–	1.6	–	N/A	N/A	–	–
		FL and/or VNB	Katsurada et al. [41]	2014	132	21.98	D	20	7.6	–	N/A	N/A	–	–
		FL and RAB	Abia-Trujillo et al. [34]	2023	75	26.3	D	51	5.23	–	N/A	N/A	27.15	–
			Kalchiem-Dekel et al. [4]	2024	48	26.7	D	25	2.2	3.07	N/A	N/A	3.07	14.7

Numbers can be a mean or median. Some reported values were converted to other quantities for ease of comparison (e.g., seconds to minutes, μGy·m^2 to Gy·cm^2). 2D, two-dimensional; 3D, three-dimensional; AF, augmented fluoroscopy; BMI, body mass index; CAK, cumulative air kerma; CBCT, cone-beam CT; DAP, dose area product; ENB, electromagnetic navigation bronchoscopy; FL, fluoroscopy; N/A, not applicable; RAB, robotic assisted bronchoscopy; VNB, virtual navigation bronchoscopy.

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radiation exposure variates considerably even in a similar approach and that there is no consistent total radiation exposure difference between fixed and mobile systems with 3D capabilities nor is there a consistent difference in single or multi-modality settings. The considerable variability as caused by individual preference as well as technological background shows multiple variables are needed to understand differences between studies and procedure performance. For example, although the fluoroscopy time and number of CBCT spins are frequently mentioned, it does not linearly correlate with radiation dose. Comparing the number of spins or fluoroscopy time between reports and then taking an "average" CBCT scan or fluoroscopy dose per amount of time leads to an inaccurate estimation of the total dose. An initial CBCT scan at the start of a navigation bronchoscopy procedure might use a wider field of view and higher image quality for airway visualization than subsequent scans that utilize only collimated 3D imaging with lower quality to confirm tool-in-lesion positioning. As highlighted in the study of Verhoeven et al. with precise radiation measures both fluoroscopy time and the number of spins can increase while still decreasing the overall radiation dose [12].

Radiation Reporting Recommendations

The International Commission on Radiological Protection (ICRP) is an independent, international organization that provides guidance and recommendations on protection against the harmful effects of ionizing radiation. These recommendations are recognized by many countries and adopted into legislation to minimize patient dose and protect employees and citizens against the dangers of uncontrolled use of ionizing radiation. In 2015, ICRP Publication 129 stated that the most important dose index that should be reported and tracked in fluoroscopy and CBCT imaging is the kerma area product, which is in diagnostic X-ray imaging interpreted to be equal in value to the DAP. They conclude that reporting DAP facilitates a direct comparison between 2D examinations such as fluoroscopy and 3D examinations such as 3D CBCT spins. The commission further stated that the effective dose is not a suitable dosimetric quantity for reporting patient doses in fluoroscopic or cone-beam imaging [42].

The radiation dose per procedure is not only determined by the extensive fluoroscopy and 3D image usage but also determined by the patient on the table. The body mass index (BMI) has a strong influence on the radiation dose produced during the procedure, resulting in a significant increase in DAP for overweight (25.0–29.9) and obese (>30) patients compared to healthy weight BMI range (18.5–24.9) [43]. Also increasing patient's BMI is associated with a significant increase in the physician's radiation dose during fluoroscopy use [44]. Therefore, it is important to mention the mean/median BMI together with your radiation reports.

Detailed data reporting on radiation exposure is crucial and should, at minimum, include several key metrics to allow meaningful comparison of procedural imaging approaches and study outcomes. For future research involving radiation exposure in interventional pulmonology, we recommend including the information outlined in Table 3.

Dose Reduction Measures – Practical Tips

Engaging in activities that involve the use of ionizing radiation, particularly in clinical settings, demands careful attention to minimize exposure while preserving the quality of diagnostic images. This approach is steadfastly guided by the ALARA principle – As Low As Reasonably Achievable – signifying a dedicated commitment to use the minimum radiation exposure necessary to achieve the precise goals of imaging [45]. While image quality and radiation exposure share a close relationship, it might be inferred that decreasing radiation exposure could potentially compromise image quality, impacting decision-making during procedures. Nonetheless, numerous measures exist to manage radiation exposure without significantly impacting image quality. In general, a reduction of patient dose directly translates to a reduction in dose for the staff.

In the following section, practical tips for interventional pulmonology procedures are listed.

Exposure Time and Number of 3D Imaging Spins

- Critically examine fluoroscopy use, do you need to see your instruments continuously or is intermittent fluoroscopy use also sufficient? Instruct to disengage the fluoroscopy pedal when imaging is no longer relevant.
- Fluoroscopic imaging at multiple imaging angles can help validate the 3D position of instruments but consider using only intermittent instead of continuous imaging while performing the rotation.
- Fluoroscopic imaging in pulsed mode obtains images in short X-ray pulse emissions compared to continuous fluoroscopy. It can significantly reduce radiation exposure while keeping sufficient image fluency [46]. Review your fluoroscopy frame rate; how low can you go without compromising image quality?
- Most 3D imaging systems have a subset of protocols available ranging in radiation dose and image quality; do you need the highest quality at every time point in the procedure or for every patient, or is a lower dose with reduced image quality also sufficient?

Table 3. Recommended dose report metrics for fluoroscopy (2D) and CBCT/tomosynthesis image acquisition (3D) in interventional pulmonology studies

Metric	Reporting unit	Relevant for modality
General information		
BMI	kg/m^2	FL + CBCT + tomosynthesis
Fluoroscopy		
Time	min:s	FL + CBCT + tomosynthesis[1]
DAP	Gy·cm^2	FL + CBCT + tomosynthesis[1]
CAK	mGy	FL + CBCT + tomosynthesis[1]
CBCT/tomosynthesis		
Number of scans	#	CBCT + tomosynthesis[1]
Average scan DAP	Gy·cm^2	CBCT + tomosynthesis[1]
Total scan DAP	Gy·cm^2	CBCT + tomosynthesis[1]
Total scan CAK	mGy	CBCT + tomosynthesis[1]
Procedure		
Procedural total time (scope in – scope out)	min:s	FL + CBCT + tomosynthesis
DAP	Gy·cm^2	FL + CBCT + tomosynthesis
CAK	mGy	FL + CBCT + tomosynthesis

It is recommended to make a distinction in reporting between fluoroscopy and CBCT/tomosynthesis imaging. However, not all systems will have a 2D and 3D distinction for DAP and CAK, only a total cumulative report per procedure. It is recommended to use the mean or median along with standard deviation or 95% confidence interval based on the distribution of data (non-normal vs. normal). BMI, body mass index; CAK, cumulative air kerma; CBCT, cone-beam CT; CT, computed tomography; DAP, dose area product; FL, fluoroscopy. [1]If available: tomosynthesis fluoroscopy dose for fluoroscopy or 3D imaging separately.

- Some hybrid imaging systems allow the acquisition of 3D information through tomosynthesis of fluoroscopy at a limited set of angles rather than performing a full 3D CBCT scan; evaluate the comparative radiation dose of both imaging sequences and assess the imaging quality needed with the least radiation dose.

Distance

The radiation emanating from a point source follows the inverse square law, wherein the dose (or dose rate) reduces proportionally to the square of the distance from the source (irradiation from a point source in a spherical fashion). To illustrate, doubling the distance from the radiation "source" (i.e., tube and/or patient) results in a reduction of the radiation dose by approximately a factor of four.

Distance is a very applicable term in radiation protection and is two-fold.

- Patient distancing: as direct X-ray beams traverse patients to reach the detector, physicians are encouraged to adhere to optimal radiographic geometry practices to improve image quality while reducing radiation dose.
  - This entails positioning the patient as close to the image detector as feasible, to minimize the air gap. The detector in most fixed C-arm and CBCT systems can be mechanically lowered, or the table height increased. A high table position reduces the PSD of the patient and increases the field of view without requiring magnification. These adjustments may not always be possible when mobile CBCT is being utilized and "isocentering" is required to ensure visualization of the target in CBCT images. The height of the table is then mostly adjusted according to how anterior or posterior the target is located. At all times, keep the ergonomic working position of the interventional pulmonologist in mind for evaluating the right position.
  - Posteroanterior projection angles demand the minimal dose (or dose rate) necessary for effective imaging, as this is the smallest distance for the X-ray source to transverse the (least amount/dense) tissue. However, when transitioning to the left anterior oblique or right anterior oblique system orientations and further into lateral orientation, the dose may escalate significantly [47].
- Staff distancing: as scattered radiation emanates from the patient, it is omnidirectional but more potent in the backscattered direction (Fig. 1). It is the greatest radiation exposure source for staff.
  - Every staff member should avoid direct exposure to the primary X-ray beam.

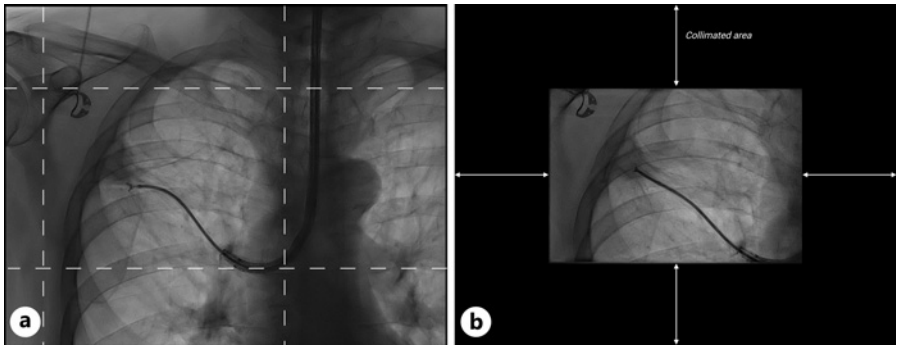

Fig. 2. Example of an uncollimated image (**a**, left) and collimated image in cranio-caudal and mediolateral direction (**b**, right).

- Positioning the X-ray tube beneath the patient support is most efficient in terms of radiation protection for the staff. The primary source of staff exposure arises from scattered X-rays emanating back from the patient (back-scattered radiation, Fig. 1). Consequently, the patient serves as a natural shield for staff positioned near the image detector. This protective effect is particularly pronounced as the majority of backscattered radiation tends to be directed towards below the pelvis level, targeting tissue that are less susceptible to X-ray exposure compared to those in the upper part of the staff's body. The angulation of the C-arm or CBCT to the left or right anterior oblique can significantly increase the scattered dose [47–49].
- It is advised to maximize the distance of staff to the X-ray source and limit the presence of staff near the patient. Position yourself in a low-scatter area. For example, it is a common mistake that the operator stands on the side of the X-ray tube during lateral fluoroscopy, which is the area of the most intense back-scattered radiation [48]. In tomosynthesis image acquisitions with prolonged manual spin of the fluoroscopy arm between certain left and right anterior oblique orientations can increase the scatter for staff if they are not distancing.
- Reconsider your physical location relative to the X-ray source when you dedicated 3D imaging, move away as far as reasonably possible or find proper shielding. As most physician's find proper shielding during 3D imaging, the main source of occupational radiation dose originates from the 2D fluoroscopy.

Collimation

An X-ray collimator is a crucial device positioned in close proximity to the X-ray tube to control and confine the area of the X-ray beam horizontally, vertically or circularly (Fig. 1). Collimation primarily serves to limit the radiation exposure only to the specific area of interest and to a lesser extent improves image quality due to a reduction in the number of scattered X-ray photons. Reducing the area reduces the DAP.

- While using fluoroscopy imaging during interventions, the operator mainly focuses on a certain point while the whole field of view is irradiated. Collimation is a useful technique for reducing the radiation exposure of the areas of no interest (Fig. 2).
- In 3D CBCT spins, collimation can also be applied in cranio-caudal orientations, which results in a significant dose saving [14].

Magnification

There are multiple types of magnifying modes associated with fluoroscopic equipment. Modern systems with flat panel detectors allow for analog magnification by increasing the spatial resolution to obtain a greater level of image detail. An additional magnification feature is also available in some systems and is referred to as digital zooming. Using this mode, the resultant image can be magnified while the inherent resolution properties of the image remain unchanged.

- Analog magnification increases the exposure rate, ensuring that the signal-to-noise ratio of the image is approximately constant regardless of the X-ray pathway length, and density of the anatomical region in the field of view. Therefore, the use of analog magnification should be minimized unless it is specifically necessary for diagnosis.

Irrelevant Objects

Irrelevant objects, especially metal objects with a high attenuation coefficient, will trigger the automatic exposure control to increase the dose rate of the X-ray system. These objects in the field of view, such as parts of the navigation systems and blood pressure band connectors,

etc., should be removed by either repositioning the object, moving the field of view of the imaging system or collimation of the imaging system.

Protective Equipment

Protective equipment is available in many forms and includes both shielding and radiation monitoring devices. Radiation exposure is mainly caused by the scattered radiation from the patient. It should be rare for staff to be exposed to the primary X-ray beam.

- Shielding in the form of lead equivalent aprons and thyroid collars is best used for occupational work with image-guided radiation. Lead protective glasses are optional and mainly recommended for interventions with high fluoroscopy workloads where the operator is continually in close proximity to the patient [50].
- Additional shielding in the form of glass screens and table skirts minimizes exposure.
- Depending on local requirements, occupational radiation monitoring devices may be worn at the torso or thyroid level, either beneath or outside lead protective garments. Regular monitoring of these dosimetry devices is essential to track the annual radiation exposure of the operator. This task is typically carried out by the Radiation Safety Officer or Medical Physicist. Precautionary measures must be applied to respect national radiation levels.

Room Ambience

The number of shades of gray the human eye can distinguish is greatly affected by the lighting conditions.

- During fluoroscopic examinations, the room lighting should be minimal to enhance the visualization of the gray-scale images on the monitor. Excessive light will decrease the ability of the eye to resolve detail on the monitor which could cause the physician to modify the exposure parameters to increase the brightness of the resultant image. Once again, an increase in the exposure parameters will directly impact on patient's dose.
- Large display monitors can be used to reduce image magnification and prevent the interventional pulmonologist from leaning in high-risk irradiated fields.

Pregnancy

Extra considerations arise when a patient or staff member is pregnant. On top of the practical measures listed above, alternative treatments, additional shielding, or monitoring may be worth considering.

- Pregnant patients: In every patient, the justification for using ionizing radiation should outweigh the risks that radiation exposure may cause. The fetus is more susceptible to radiation effects; it is important to have sufficient reason for using radiation near the fetus and at least additional radiation reduction and optimization measures.
- Staff Pregnancy: Staff working with ionizing radiation should inform hospital authorities to ensure that the fetus is afforded the appropriate level of protection. The local Radiation Safety Officer should be able to assist with more frequent radiation monitoring of the exposure via the use of specialized electronic dosimeters [51].

Implementation, Training, and Monitoring

The above-mentioned practical dose reduction measures can be easily implemented into everyday clinical workflows, however, to further optimize the use of radiation additional measures should also be considered. Training is an important aspect of this clinical implementation of dose reduction measures in the imaging suite, as many interventional pulmonologists have not received a formal radiation safety training during their careers. Any training implemented should include both the operator of the imaging equipment and staff routinely required to be in attendance during these imaging procedures or interventions. Any training package offered should be delivered by educators with both clinical experience and radiation protection/medical physics expertise. The interventional pulmonologists should be made aware of and recognize the situations in which dose reduction measures can be applied and act accordingly. Additionally, further optimization measures can be achieved for complex procedures requiring prolonged fluoroscopic imaging using medium to high output imaging equipment with the presence of radiography support (radiographer, medical imaging technologist, etc.) for these exams. The involvement of radiography support during fluoroscopic applications is a key element in minimizing patient exposure. Not only to keep prioritization and awareness as physicians are often mentally burdened with procedure performance but also as an adept and experienced teams collaborates best. The radiography support can assist the interventional pulmonologists to recognize the situations in which dose reduction measures can be applied, and act accordingly.

The contribution of clinical physicists and other technologists can help the team gain insight into the radiation dose per procedure and strive for lower radiation levels to further implement ALARA principles to minimize risks. The clinical physicist should be involved in the initial setup, periodic quality control and staff education. Incorporating radiation protection into the

briefing or debriefing can help ensure that every team member is aware. Dosimeters can provide insights into the radiation doses to which people in the OR are exposed. Real-time dosimeters, which provide dose rates in real-time, are available on the market and are an effective tool for achieving these outcomes. In addition to the operational aspects of optimizing radiation exposure, facilities should also review or benchmark their patient exposures against facilities performing similar procedures or against published literature for that type of examination. By uniformly reporting radiation doses in the literature, a multi-institutional analysis can help individuals improve radiation reduction measures. Additionally, some countries have implemented diagnostic reference levels for specific procedure types. The objective of a diagnostic reference level is to assist in the avoidance of excessive radiation dose to the patient that does not contribute additional clinical information to the medical imaging task. Dose monitoring software that alert when a threshold is exceeded are recommended. Cases where the expected threshold is exceeded can be reviewed to clarify and justify why the dose was excessive and serve as an opportunity to improve practice.

Future Perspectives

Given the recent advances in image-guided diagnostic procedures in interventional pulmonology, it is inevitable that X-ray imaging will be increasingly used in the interventional pulmonology field over the coming years. This is especially apparent in the increasing demand and interest in peripheral pulmonary nodule procedures where advanced 3D imaging in combination with high-tech navigation systems is developing into the new gold standard. With the increasing use of chest CT scanning and where lung cancer screening programs are being implemented broadly, more (incidental) nodules will be detected requiring tissue diagnosis [52]. Also, new developments for both diagnostics and local therapy will increase and expand the demand for X-ray guided procedures.

To accommodate this need, advanced mobile systems and hybrid imaging systems have become commercially available over recent years. Although these systems yet have lower image quality and longer acquisition time compared to currently available fixed systems, these systems are a solution for sites without 3D image confirmation systems or limited capacity for intervention radiology rooms and may save costs [31, 33]. Furthermore, the fixed CBCT system developments have not reached their technological limits, as there is room for improvement in more advanced fluoroscopy to guide the bronchoscopist to the lesion and give insight into margins for therapy [19]. Accurate tool-in-lesion confirmation requires reliable imaging systems with 3D acquisition capabilities. Software tools for tool-in-lesion reconstruction lack sufficient accuracy at a millimeter level. In local therapeutics such as microwave ablation, accurate 3D imaging and advanced fluoroscopy are essential for the reconfirmation of nodule margins to critical structures, catheter positioning confirmation and post-ablation zone evaluation [30]. Although all these developments will increase the number of 3D acquisitions in our procedures, it is a challenge to limit radiation exposure for both patients and staff.

Conclusion

The use of advanced X-ray image guidance is rapidly increasing. Interventional pulmonologists are encouraged to minimize radiation exposure for both patients and staff, by understanding the physics of radiation and maximizing the use of radiation safety measures according to the ALARA principles. In daily care, the correct interpretation of your own site's radiation exposure is important in order to apply correct radiation measures and it should be seen as an effort of the total interventional team. All future clinical research using X-ray image guidance in the field of interventional pulmonology should systematically and uniformly report radiation exposure and safety measures to allow interpretation and comparison of different procedures, clinical setups and devices. We also advise future researchers, reviewers, and editors to address radiation safety. To report doses, our advice is that DAP and CAK should be used relative to the patient's BMI. In conclusion, as the reliance on advanced X-ray imaging continues to grow in interventional pulmonology, it is imperative for the entire interventional team to rigorously apply radiation safety measures in line with ALARA principles, continually monitor and interpret site-specific radiation data and ensure that future research adheres to consistent reporting standards for radiation exposure to enhance safety, comparability, and clinical outcomes.

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Statement of Ethics

Statement of Ethics is not applicable as this research is based on literature, physics, and published articles.

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Data Availability Statement

All data are available in the references, as it is based on literature, physics, and published articles.

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