Advancing radiation safety, quality assurance, and scientific integrity in medical imaging: Highlights from the physics sessions of IRC 2025

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► IRC 2025 physics session highlights

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ABSTRACT

The Physics Sessions of the 40th Iranian Congress of Radiology (IRC 2025) focused on improving patient safety, diagnostic accuracy, and evidence-based practice across ionizing and non-ionizing imaging modalities. The lectures emphasized that high-quality imaging requires effective radiation protection, rigorous quality assurance (QA), and well-trained professionals. A major theme of the congress was the development of a strong radiation safety culture based on justification, optimization (ALARA), and dose limitation. Speakers highlighted the importance of leadership, structured education, standardized safety protocols, and transparent communication in reducing unnecessary radiation exposure to patients and healthcare workers. Another key topic was quality control in diagnostic imaging. Properly implemented QA programs improve image quality while minimizing radiation dose. Monitoring parameters such as spatial and contrast resolution, image noise, artifacts, and contrast-to-noise ratio (CNR) is essential for maintaining diagnostic reliability and reducing repeat examinations. The congress also reviewed evolving evidence regarding patient lead shielding. Recent findings indicate that routine shielding may provide limited benefit in modern imaging systems and can occasionally interfere with automatic exposure control (AEC) or image quality. Current radiation protection strategies increasingly emphasize optimized imaging parameters, precise collimation, and avoidance of repeat imaging. Sessions on neonatal and obstetric ultrasound safety stressed the importance of monitoring Thermal Index (TI) and Mechanical Index (MI), minimizing scan duration, and improving operator awareness. Discussions on the Linear No-Threshold (LNT) model concluded that despite evidence of non-linear biological responses at low doses, the LNT model remains a practical and conservative framework for radiation protection policy.

INTRODUCTION

This year's Radiology Congress brought together leading experts in medical physics and radiology to address one of the most critical dimensions of modern healthcare: achieving diagnostic excellence while safeguarding patients and healthcare professionals. Across ionizing and non-ionizing modalities, the sessions emphasized evidence-based practice, technological optimization, biological understanding, and professional responsibility.

Rapid technological advances are transforming radiation safety and quality management in medical imaging. Emerging approaches increasingly combine artificial intelligence (AI), automation, and personalized medicine to improve diagnostic performance while minimizing radiation exposure. AI-assisted imaging systems now play an important role in dose optimization. Machine learning algorithms can automatically adjust exposure parameters according to patient size, anatomical region, and clinical indication, thereby reducing unnecessary radiation while preserving image quality. In computed tomography (CT), deep learning–based reconstruction techniques have demonstrated substantial potential for maintaining diagnostic accuracy at lower radiation doses.

Personalized imaging protocols represent another important direction in modern radiology. Rather than relying on fixed exposure settings, individualized protocols consider patient-specific factors such as age, body habitus, clinical condition, and prior imaging history. This approach is particularly important for radiosensitive populations, including pediatric and pregnant patients.

Automated Diagnostic Reference Level (DRL) systems are also expected to strengthen radiation safety programs. Real-time dose monitoring software can continuously compare institutional practice with regional or national DRLs, helping identify unusually high exposures and supporting quality improvement initiatives. Integration of dose-tracking systems with hospital information systems may further enhance regulatory compliance and clinical oversight.

At the same time, hybrid imaging modalities such as PET/CT and SPECT/CT introduce new challenges in radiation protection due to the combined use of ionizing radiation from both radiopharmaceuticals and CT imaging. Optimizing these complex procedures requires close collaboration among radiologists, nuclear medicine physicians, technologists, and medical physicists. Future progress in radiation safety will depend not only on technological innovation, but also on continuous education, multidisciplinary cooperation, and evidence-based clinical practice.

Stochastic versus deterministic effects: Pathophysiology, limits, and complications

Hossein Mozdarani, provided a comprehensive discussion of the two fundamentally distinct biological consequences of ionizing radiation exposure: deterministic (tissue reaction) effects and stochastic effects. The pathophysiology of deterministic effects is characterized by the depletion or functional impairment of critical cell populations, resulting in tissue and organ dysfunction once a threshold dose has been exceeded [(1)]. Below this threshold, cellular repair and tissue regeneration mechanisms are generally sufficient to maintain normal function. However, once the threshold is surpassed, both the incidence and severity of injury increase with increasing dose. Classical examples of deterministic effects include radiation dermatitis, cataract formation, and hematopoietic syndrome. To prevent such outcomes, the International Commission on Radiological Protection (ICRP) has established dose limits based on known tissue tolerance thresholds. For occupationally exposed individuals, the threshold dose for radiation-induced lens opacities is approximately 0.5 Gy, whereas transient skin erythema typically occurs at doses around 3 Gy [(2)]. These adverse effects are predictable and dose-dependent, with complications such as fibrosis, sterility, and organ failure often manifesting weeks to months after exposure.

In contrast, stochastic effects - including radiation-induced cancer and heritable genetic mutations - are primarily associated with low-dose, low-linear energy transfer (LET) radiation exposure. Their biological basis lies in non-lethal DNA damage, particularly double-strand breaks that are inaccurately repaired through error-prone mechanisms such as non-homologous end joining. These repair errors may result in point mutations, chromosomal aberrations, genomic instability, or oncogene activation, thereby increasing the risk of carcinogenesis [(3)]. Unlike deterministic effects, stochastic effects are assumed to have no threshold dose; even the smallest radiation exposure may theoretically confer a finite, albeit very small, probability of adverse outcomes. This concept forms the basis of the linear no-threshold (LNT) model adopted by the National Council on Radiation Protection and Measurements (NCRP), which assumes that cancer risk increases linearly with dose and that no safe lower limit exists [(4)].

The clinical manifestations of stochastic effects are probabilistic rather than predictable and are typically characterized by long latency periods. In practice, regulatory dose limits for occupational and public exposure are set far below the thresholds associated with deterministic injury. For example, the annual occupational effective dose limit of 50 mSv is designed to ensure that tissue-reaction thresholds are never approached. In the context of stochastic risk, radiation protection relies on the ALARA (As Low As Reasonably Achievable) principle, which seeks to minimize unnecessary exposure and thereby reduce the probability of radiation-induced malignancy. Nevertheless, considerable debate remains regarding the validity of the LNT model at very low doses (<10 mSv), where adaptive responses, enhanced DNA repair, immune modulation, and radiation hormesis have been proposed as potential modifiers of risk [(5, 6)].

Importantly, no threshold has been established for radiation-induced heritable genetic effects. However, despite extensive epidemiological investigations, conclusive evidence of heritable disease in humans resulting from parental radiation exposure remains lacking [(7)]. Consequently, while deterministic effects can be effectively prevented through adherence to established dose limits, stochastic effects continue to necessitate ongoing vigilance in fields such as medical imaging, nuclear energy, and space exploration.

Collectively, emerging radiobiological evidence suggests that cellular phenomena including differential radiosensitivity, radioadaptive responses, genomic instability, and radiation-induced bystander effects challenge the simplistic assumptions of the LNT model. Although LNT remains the prevailing conservative framework for radiation protection policy, more accurate risk assessment at environmental and occupational exposure levels (1-100 mGy) may ultimately require the incorporation of these complex biological responses into revised mechanistic models of radiation risk [6, 7].

Non-Linear biological effects and the LNT model

Seyed Mohammad Javad Mortazavi, presented a balanced discussion on the advantages and limitations of the Linear No-Threshold (LNT) model. One of the most intellectually engaging sessions examined the ongoing debate regarding low-dose radiation risk assessment. Although non-linear biological responses - including adaptive effects, hormesis-like responses, and J-shaped dose–response relationships - have been documented at low doses and dose rates, their existence does not invalidate the LNT model as a pragmatic radiation protection framework. A central ethical foundation of the LNT model is the precautionary principle. Scientists who strongly support LNT argue that, when significant uncertainties persist, this principle provides the most responsible and scientifically grounded approach - ethically, empirically, and in practical decision-making [8].

The LNT model continues to receive strong support from major international bodies such as the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for regulatory and protection purposes. These organizations emphasize its utility as a conservative, standardized tool for risk estimation in the absence of definitive epidemiological data at very low doses. At the same time, critics argue that linear extrapolation from high-dose data may overestimate risks at diagnostic levels, particularly given emerging evidence of biological repair mechanisms and adaptive responses. Radiation adaptive response (AR) refers to a biological effect in which prior exposure to low levels of radiation increases an organism's resistance to the harmful impacts of a later, higher dose [9, 10]. This tension highlights the need for ongoing research while maintaining a cautious policy approach that prioritizes patient and staff safety without undermining practical implementation of radiation protection principles.

While research has identified several biological processes that occur at low radiation doses, such as initial DNA damage and repair, shifts in gene expression, adaptive responses, and bystander effects. Yet findings at the cellular and molecular levels cannot be directly translated into estimates of risk for human populations [11]. Biological systems are complex and context-dependent; however, radiation protection policy must remain conservative, operationally feasible, and applicable across diverse populations. The LNT model provides a precautionary and reproducible basis for risk estimation when direct epidemiological evidence is limited. Recognition of biological non-linearity advances scientific understanding but does not eliminate the need for a protective and standardized policy approach.

Strengthening radiation safety culture in clinical practice

Hadi Keivan, emphasized that radiation safety culture extends beyond regulatory compliance; it represents a shared commitment to justification, optimization (ALARA), and dose limitation in everyday clinical practice. A sustainable safety culture requires structured education, accountable leadership, transparent communication, and continuous oversight. International organizations such as the WHO and IAEA stress that strengthening professional responsibility and structured decision-making significantly reduces occupational and patient exposure while improving quality of care. The consistent implementation of Diagnostic Reference Levels (DRLs), routine dosimetric monitoring, non-punitive incident reporting systems, and appropriate use of certified protective equipment are essential pillars of safe radiological practice. Ultimately, radiation safety culture reflects institutional maturity and professional ethics in healthcare delivery.

Equipment quality control and diagnostic accuracy

Vahid Changizi, highlighted that high-quality imaging at the lowest achievable dose depends on rigorous equipment quality control (QC). According to AAPM guidelines, medical physicists play a central role in designing, implementing, and supervising structured quality assurance programs. Diagnostic performance relies on measurable image quality parameters, including spatial resolution, contrast resolution, contrast-to-noise ratio (CNR), image noise, and artifact assessment. Objective phantom-based testing, combined with expert visual evaluation, ensures optimized exposure parameters and minimizes repeat examinations. Effective QC programs therefore directly support both diagnostic reliability and radiation protection objectives.

Lead shielding in medical imaging: An evidence-based reassessment

Omid Azadbakht and Hamed Zamani discussed the evolving perspective on patient lead shielding in light of technological advances and updated professional recommendations. Contemporary evidence indicates that patient-generated scatter radiation - rather than the primary beam - is often the dominant contributor to dose in many imaging procedures. In certain situations, shielding may introduce artifacts, interfere with automatic exposure control (AEC), or paradoxically increase radiation dose. Modern radiation protection strategies emphasize precise collimation, optimized exposure parameters, and reduction of repeat examinations instead of routine reliance on physical shielding. While occupational shielding for staff remains essential, decisions regarding patient shielding should be procedure-specific and guided by anatomical considerations, beam geometry, and current evidence-based recommendations.

Safety metrics in neonatal ultrasound

Roghayeh Kamran Samani, noted that although ultrasound is a non-ionizing modality, neonatal imaging demands particular vigilance due to increased susceptibility to thermal and mechanical bioeffects. The Thermal Index (TI) and Mechanical Index (MI) serve as primary safety indicators. Maintaining TI below 1.0 and MI below 0.5, particularly in cranial and cardiac imaging, combined with minimized scan duration and prudent use of Doppler modes, supports safe neonatal practice. Enhanced operator education, neonatal-specific presets, clearly visible safety indices, and collaboration with medical physicists are essential for maintaining safety in this vulnerable population [12, 13].

Obstetric ultrasound safety and bioeffects

Effat Soleimani addressed the importance of careful risk–benefit assessment in modern obstetric ultrasound, especially when Doppler techniques are used in early pregnancy [14]. Experimental data suggest that excessive thermal exposure during embryonic development may affect sensitive structures, including the central nervous system [15, 16]. Operators are responsible for interpreting on-screen output indices and applying the ALARA principle to acoustic exposure [17]. Comprehensive training must include both technical scanning skills and a solid understanding of ultrasound physics and bioeffects to ensure safe fetal imaging [18].

Concluding remarks

Collectively, the lectures conveyed a unified message: patient safety and diagnostic excellence are inseparable. Whether addressing ionizing radiation, ultrasound bioeffects, equipment performance, shielding practices, or theoretical dose–response models, each session reinforced the principles of justification, optimization, and professional accountability.

The panel highlighted that:

- Safety culture is foundational to clinical excellence.
- Quality control directly influences both diagnostic accuracy and dose reduction.
- Evidence-based reassessment of traditional practices strengthens modern care.
- Even non-ionizing modalities require disciplined adherence to safety metrics.
- Scientific debate on dose–response relationships must inform - rather than undermine - practical radiation protection.

In an era of advancing technology and growing imaging demand, radiologists and medical physicists bear the responsibility not only to produce high-quality diagnostic images but also to uphold the highest standards of safety, ethics, and scientific integrity.

The Radiology Congress 2025 reaffirmed that knowledge-driven optimization remains the cornerstone of modern medical imaging.

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