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An Integrated Visual–Interactive Framework for Teaching Ionizing Radiation and its Human Health Effects in the Context of Nuclear Power Plants

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ABSTRACT: Ionizing radiation is an essential topic in nuclear physics education because its understanding requires students to connect fundamental physical principles with radiation exposure, biological effects, and human health risks. These relationships become particularly important in the context of nuclear power plants, where misconceptions about radiation may hinder an adequate understanding of both radiation safety and its potential health consequences. This study presents an integrated instructional approach designed to support students' conceptual understanding of ionizing radiation by combining scientifically structured content with visual and interactive learning strategies. The approach integrates Venn diagrams, Mind Maps, and the Flower Grids method to organize and compare the physical characteristics, ionization and energy-deposition behaviour, penetration characteristics, exposure relevance, and protection considerations of alpha (α) particles, beta (β) particles, gamma (γ) photons, neutrons, and internal conversion electrons. Natural background radiation is treated separately as a source and exposure context that may involve multiple forms of ionizing radiation and both external and internal exposure pathways. The instructional sequence further connects radiation forms and exposure contexts with dosimetric quantities, biological responses, tissue reactions, potential heritable effects, and stochastic effects. Unlike conventional presentations in which these concepts are often introduced as separate factual elements, the proposed approach organizes them into interconnected conceptual structures and encourages learners to compare, classify, reconstruct, explain, and interpret scientific information. Particular emphasis is placed on linking the physical properties of ionizing radiation with exposure conditions, dosimetric interpretation, biological significance, and radiation-protection principles. The proposed methodology provides a structured framework for teaching complex radiation-related concepts and may support a more coherent understanding of radiation physics, human health effects, and radiation safety within nuclear power plant education.

1. INTRODUCTION

The increasing application of nuclear technologies in energy production, medicine, industry, and scientific research has made an accurate understanding of ionizing radiation increasingly important. This issue is particularly relevant in the context of nuclear power plants (NPPs), where public and student perceptions of radiation are often shaped by its association with nuclear accidents and adverse health consequences. From a scientific perspective, however, the presence of a radioactive source does not by itself determine the magnitude of health risk. The biological significance of radiation exposure depends on several interacting factors, including radiation type and energy, absorbed dose, duration and pathway of exposure, spatial distribution of energy deposition, and the radiosensitivity of exposed tissues. Consequently, meaningful radiation education requires learners to move beyond a general perception of radiation as simply "dangerous" and develop an understanding of the physical and biological mechanisms through which ionizing radiation interacts with matter and living systems (1–3).

Ionizing radiation transfers sufficient energy to matter to produce ionization and excitation at atomic and molecular levels. These initial physical interactions may be followed by physicochemical processes, including the generation of reactive species, and subsequently by biological changes involving cellular structures and macromolecules. Depending on the type and magnitude of exposure, such interactions may result in cellular damage, tissue reactions, or an increased probability of longer-term health consequences. For this reason, radiation protection cannot be understood adequately without connecting the physical properties of radiation with dosimetric concepts and biological responses. The original instructional framework underlying the present study similarly considers radiation type, penetration and ionization characteristics, dose-related concepts, dose-related concepts, biological responses, tissue reactions, potential heritable effects, and stochastic effects as interconnected components rather than isolated topics as interconnected components rather than isolated topics.

A major instructional difficulty is that the term *ionizing radiation* encompasses forms of radiation with markedly different physical characteristics. Alpha (α) and beta (β) particles, gamma (γ) radiation, and neutrons differ in their physical nature, charge, mass, mechanisms of interaction with matter, penetration depth, ionization characteristics, and shielding requirements. These differences also affect the conditions under which each type of radiation represents a health concern. Alpha particles, for example, have relatively low external penetration but can become particularly important when alpha-emitting radionuclides enter the body. Gamma radiation is substantially more penetrating and is therefore relevant to external exposure and shielding. Neutrons, being electrically neutral, interact with matter through nuclear processes and require different approaches to both dosimetric interpretation and radiation protection. Internal conversion electrons and naturally occurring background radiation further extend the conceptual scope that students are expected to understand.

The complexity of these relationships creates substantial opportunities for misconceptions. Recent research involving preservice teachers has shown that difficulties may persist even among individuals with formal science backgrounds. Prokop and Nawrodt (4), for example, identified inadequate differentiation between radioactive matter and ionizing radiation, as well as between radioactive decay and nuclear fission. Their findings demonstrate that difficulties in learning radioactivity are not limited to memorizing terminology; they can reflect deeper problems in how learners organize relationships among matter, radiation, energy, and nuclear processes. Similar concerns are evident in health-related education. A 2024 study involving 786 healthcare students reported considerable deficiencies in knowledge of ionizing radiation and radiation protection, with only a small proportion of participants demonstrating a high level of knowledge (5).

These findings have an important implication for the teaching of radiation physics. Presenting radiation types through separate definitions, descriptive paragraphs, or extensive tables may provide factual information without necessarily enabling students to construct relationships among the concepts. A learner may correctly recall that α-radiation has low penetration or that γ-radiation has high penetration while remaining unable to explain how these characteristics relate to ionization, exposure pathways, shielding, and potential biological effects. Conceptual understanding therefore requires more than the reproduction of individual facts; it involves organizing knowledge into meaningful structures that allow learners to compare phenomena, recognize relationships, and apply physical principles to new situations.

This requirement becomes particularly important when radiation physics is connected with human health. Students must relate the physical characteristics of radiation to the amount and distribution of energy deposited in biological material and subsequently distinguish among different categories of biological effects. They also need to understand why external and internal exposures cannot always be interpreted in the same manner and why radiation protection measures differ according to radiation type and exposure conditions. Within the instructional material on which the present study is based, these relationships extend from the characteristics of α-, β-, γ-, and neutron radiation to dosimetric quantities and subsequently to these relationships extend from the characteristics of α-, β-, γ-, and neutron radiation to dosimetric quantities and subsequently to biological responses, tissue reactions, potential heritable effects, and stochastic effects. An effective instructional strategy should therefore help learners establish connections across these levels rather than treating nuclear physics, dosimetry, and radiation biology as independent blocks of information.

One approach to addressing such conceptual fragmentation is the use of visual knowledge representations. Graphic organizers spatially arrange concepts and their relationships and can therefore support learners in identifying similarities, differences, hierarchies, and causal or associative links. Evidence supporting this approach has strengthened in recent years. A meta-analysis by Anastasiou et al. (6), incorporating 55 studies and 5,364 students, found that concept mapping was positively associated with science achievement across biology, chemistry, physics, and earth science, with particularly substantial effects reported for physics and earth science. These results indicate that visually structured conceptual representations can be especially useful in science domains where learners must integrate multiple interdependent concepts.

More recent evidence also suggests that the educational value of graphic organizers extends beyond factual recall. Lei et al. (7), in a meta-analysis covering 66 empirical studies and 4,824 participants, reported a positive association between graphic-organizer use and higher-order thinking, with particularly strong effects for mind maps. This distinction is important for radiation education because the instructional objective is not simply to remember the characteristics of individual radiation types. Learners must compare those characteristics, interpret their physical significance, relate them to biological exposure, and use this understanding when reasoning about radiation protection.

Mind mapping provides a particularly useful mechanism for representing such interconnected knowledge. Instead of presenting concepts in a linear sequence, a Mind Map organizes information around a central idea and displays relationships among associated concepts through branching structures. A systematic review of mind mapping in educational contexts has emphasized its potential contribution to learning and retention (8). More specifically, a recent systematic review of mind maps in STEM education identified 50 empirical studies published between 2019 and 2024 and reported outcomes related to academic performance, conceptual understanding, critical thinking, motivation, and cognitive load (9). These findings provide a broader empirical basis for using visually structured knowledge representations when teaching conceptually dense scientific material.

Nevertheless, the effectiveness of visual tools depends on how they are incorporated into instruction. Providing students with a completed diagram may facilitate the presentation of information, but it does not automatically require them to reconstruct or explain the relationships represented within it. Interactive use of graphic organizers can place greater cognitive responsibility on learners by requiring them to classify information, compare alternatives, retrieve concepts, establish connections, and reconstruct conceptual structures. Studies in other areas of science education have similarly demonstrated the instructional potential of graphic-organizer-based approaches. For example, graphic organizers have been investigated in astronomy education as visual-verbal scaffolds supporting performance, retention, and learning experience (10), while studies in chemistry have reported benefits of concept and mind mapping for organizing and understanding complex scientific content (11).

The instructional framework examined in the present study builds on this principle by assigning different cognitive functions to three complementary visual approaches: **Venn diagrams, Mind Maps, and Flower Grids**. A Venn diagram is used primarily for comparison, enabling learners to distinguish and relate the properties of α-, β-, and γ-radiation within a common visual structure. Mind Maps provide a broader representation in which individual radiation types and their associated physical characteristics can be organized around the central concept of ionizing radiation. Flower Grids offer a different structure: a selected radiation type occupies the conceptual center, while its defining characteristics are distributed around it. Importantly, the Flower Grid can be transformed from a static illustration into a reconstruction activity by separating its components and asking students to identify and restore the appropriate conceptual relationships. These methods and their proposed applications constitute the core of the original instructional methodology.

Although concept maps, mind maps, Venn diagrams, and other graphic organizers have been investigated across different areas of science education, the literature provides considerably less attention to an integrated visual framework specifically designed to connect the **physical characteristics of ionizing radiation with exposure conditions, dosimetric interpretation, biological effects, and human-health implications in an NPP-related educational context**. Existing research also indicates that misconceptions concerning radioactivity and radiation can persist despite prior scientific education (4), reinforcing the need for instructional designs that explicitly connect concepts rather than merely presenting additional information. The relevant pedagogical problem is therefore not simply whether visual tools should be used, but how complementary visual and interactive representations can be organized into a coherent learning sequence for a conceptually demanding radiation topic.

Against this background, the present study develops a structured instructional approach for teaching ionizing radiation and its potential effects on human health in the context of nuclear power plants. The approach integrates Venn diagrams for comparative reasoning, Mind Maps for conceptual organization, and Flower Grids for structured classification and reconstruction. These tools are linked to the physical characteristics of radiation, exposure pathways, dosimetric concepts, biological effects, and fundamental radiation-protection principles. The purpose is to provide learners with a progression from identifying individual radiation characteristics to interpreting relationships among **radiation type, interaction with matter, exposure, dose, biological response, and health significance**.

The principal methodological contribution of the study therefore lies not in introducing an individual graphic organizer as a new educational technique, but in **integrating complementary visual and interactive strategies into a unified conceptual framework for radiation education**. Such integration is intended to reduce fragmented learning and provide a scientifically coherent structure through which students can interpret the relationships between nuclear-physics concepts and their human-health implications. This framework also provides a basis for subsequent empirical evaluation of students' conceptual understanding and the effectiveness of interactive visual instruction in radiation-related education.

2. MATERIALS AND METHODS

2.1. Study Design

The study was designed as a methodological investigation aimed at developing an integrated instructional framework for teaching ionizing radiation and its potential effects on human health in the context of nuclear power plants. The methodological design was based on the premise that conceptual learning of radiation-related content requires more than the sequential presentation of definitions and physical properties. Instead, students need to establish explicit relationships between the physical nature of radiation, its interaction with matter, exposure conditions, dosimetric interpretation, biological response, and radiation-protection principles.

Accordingly, the instructional framework was constructed as a sequence of interconnected learning operations rather than as a collection of independent teaching techniques. The design incorporated three principal forms of visual organization—Venn diagrams, Mind Maps, and Flower Grids—each assigned a different instructional function. The Venn diagram was used for comparative differentiation, the Mind Map for conceptual integration, and the Flower Grids method for classification and active reconstruction of radiation-related knowledge.

The methodological structure was developed around the following conceptual pathway:

radiation source → radiation type → physical characteristics → interaction with matter → ionization and penetration → exposure pathway → dosimetric interpretation → biological effects → human-health implications → radiation protection.

This progression was selected to prevent the fragmentation that can occur when radiation physics, dosimetry, and biological effects are taught as independent topics. The structure also reflects the broader educational principle that complex scientific information becomes more meaningful when learners are required to establish relationships among concepts rather than memorize them in isolation (6, 7).

The study did not involve the generation of experimental biological material or clinical data. Its primary material consisted of scientifically established radiation characteristics and instructional representations developed to organize these characteristics for educational purposes. The source manuscript similarly presents the work as a methodology for systematically teaching radiation types, their properties, dosimetric quantities, and their effects on the human body.

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2.2. Selection and Scientific Organization of the Instructional Content

The scientific content was organized into two conceptually distinct groups: **radiation forms** and **radiation-source/exposure contexts**. The radiation forms considered in the instructional framework included alpha (α) particles, beta (β) particles, gamma (γ) photons, neutrons, and internal conversion electrons. **Natural background radiation was treated separately as a source and exposure context rather than as an independent physical type of radiation.** This distinction was introduced to prevent the conflation of radiation type with radiation source or exposure origin. Together, these components provide a sufficiently broad instructional basis for explaining particulate and electromagnetic radiation, directly and indirectly ionizing radiation, and naturally occurring as well as technologically relevant sources of radiation exposure.

To ensure consistency in the comparative analysis, the **physical radiation forms** were characterized using a common set of scientifically relevant parameters:

1. physical nature;
2. electric charge;
3. origin or production mechanism;
4. ionization and energy-deposition characteristics;
5. penetration characteristics;
6. relevance to external exposure;
7. relevance to internal exposure;
8. characteristic energy considerations;
9. principal shielding principles; and
10. representative medical, scientific, technological, or monitoring applications.

The use of common comparison criteria was methodologically important because it enabled the physical radiation forms to be examined within the same conceptual structure. Without such standardization, learners may encounter individual forms of radiation through different descriptive variables, making direct comparison and interpretation more difficult. Applying a common set of parameters therefore provides a systematic basis for identifying similarities and differences in physical behaviour, interaction with matter, exposure relevance, and radiation-protection requirements.

Natural background radiation was characterized separately because the parameters used to distinguish individual radiation forms cannot be applied to it as a single physical entity. Instead, it was organized according to its principal source categories, radiation components, and exposure pathways. These include cosmic radiation, terrestrial sources associated with naturally occurring radionuclides, radon and its progeny, and naturally occurring radionuclides present within the human body. Depending on the source, natural background exposure may involve different forms of ionizing radiation and both external and internal exposure pathways. Within the proposed framework, natural background radiation therefore serves as a practical context for demonstrating the distinction and relationship among **radiation source, radiation form, exposure pathway, dose, and biological significance**.

The initial organization of these parameters was performed in tabular form. This representation served as the **content matrix** from which subsequent visual organizers were derived. Thus, the table was not considered the final instructional product but rather the structured scientific source for developing the Venn diagram, Mind Map, and Flower Grid activities.

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Table 1. Comparative physical and radiological characteristics of the principal radiation forms included in the instructional framework

Parameter	Alpha (α) particles	Beta (β) particles	Gamma (γ) photons	Neutrons	Internal conversion electrons
Physical nature	Helium nuclei (2p + 2n)	Electrons (β^-) or positrons (β^+)	High-energy electromagnetic photons	Electrically neutral nucleons	Orbital electrons emitted following nuclear de-excitation
Electric charge	+2e	−e or +e	0	0	−e
Origin / production mechanism	Alpha decay of unstable heavy nuclei	Beta decay of unstable nuclei	Nuclear de-excitation and other photon-emission processes	Nuclear reactions, including fission and other neutron-producing processes	Transfer of nuclear excitation energy directly to an orbital electron
Ionization / energy-deposition characteristics	Directly ionizing; high ionization density and high LET	Directly ionizing; generally lower LET than α particles	Indirectly ionizing; generally low LET	Indirectly ionizing; energy deposition occurs mainly through secondary charged particles	Directly ionizing; electron-like energy-deposition behaviour
Penetration characteristics	Very limited range in matter	Greater than α particles but energy-dependent	High and strongly dependent on photon energy and material properties	Strongly dependent on neutron energy and material composition	Energy-dependent; generally comparable to electrons of similar energy
External exposure relevance	Usually limited for intact skin; may affect superficial tissues under specific conditions	Relevant, particularly to skin and superficial tissues	Important because of relatively high penetration	Important; strongly dependent on neutron energy and exposure conditions	Dependent on source location and electron energy
Internal exposure relevance	Potentially important when α-emitting radionuclides are incorporated	Potentially important following incorporation of β-emitting radionuclides	Depends on radionuclide distribution, photon energy, and exposure conditions	Depends on the exposure scenario; internal neutron-emitting sources are uncommon	Relevant when produced by radionuclides incorporated within the body
Energy considerations	Discrete energies characteristic of the radionuclide	Continuous β spectrum up to a radionuclide-specific endpoint energy	Discrete photon energies characteristic of nuclear transitions	Broad energy range depending on production mechanism	Discrete energies determined by nuclear transition energy and electron binding energy

Principal shielding principle	Minimal material is sufficient for external α particles; prevention of intake is particularly important	Low-Z materials are generally preferred initially to reduce bremsstrahlung production	Sufficient thickness of dense materials is generally required; shielding depends on photon energy and attenuation properties	Hydrogen-rich materials are important for slowing neutrons, often combined with neutron-absorbing materials	Similar considerations to electron shielding; dependent on electron energy
Representative contexts / applications	Radionuclide research, targeted alpha therapy, contamination monitoring	Nuclear medicine, tracers, thickness measurements, contamination monitoring	Nuclear medicine, radiotherapy, industrial radiography, radiation monitoring	Reactor physics, neutron activation analysis, research, and dosimetry	Nuclear spectroscopy and nuclear decay-scheme studies

The comparative matrix provides a standardized scientific basis for distinguishing the principal radiation forms according to their physical properties, interaction mechanisms, exposure relevance, and shielding considerations. Importantly, these characteristics were interpreted in relation to radiation energy, source location, and exposure conditions rather than as fixed indicators of biological hazard. Penetration characteristics or ionization density alone do not determine the potential health significance of radiation exposure; their interpretation requires consideration of the exposure pathway, energy deposition, absorbed dose, radiation quality, and the characteristics of the irradiated tissues (1–3).

Natural background radiation was not included in the matrix as a separate radiation form because it represents a **source and exposure context** that may involve several forms of ionizing radiation. Within the instructional framework, it was therefore treated separately through naturally occurring sources such as cosmic radiation, terrestrial radionuclides, radon and its progeny, and radionuclides naturally present in the human body. This distinction establishes a clearer conceptual separation between **radiation form, radiation source, and exposure context**, while preserving their relationships within subsequent dosimetric and health-related interpretation.

The standardized matrix subsequently served as the scientific basis for the visual learning structures developed in the next stage of the framework. Directly comparable radiation characteristics were transferred to the Venn diagram, whereas broader relationships among radiation forms, their origins, exposure contexts, and protection principles were organized through the Mind Map. In this way, the tabular representation functioned as a transition from the scientific organization of radiation characteristics to their comparative and relational visualization.

2.3. Transformation of Tabular Information into Visual Learning Structures

The second methodological stage involved converting the standardized content matrix into visual structures. The rationale for this transformation was not merely to make the material more visually attractive. The purpose was to reorganize scientific information according to the cognitive operation expected from the learner.

Graphic organizers can facilitate the organization of complex information by making relationships among concepts spatially explicit. Earlier meta-analytic evidence in science instruction has shown that graphic-organizer-supported teaching can contribute to factual comprehension and vocabulary learning, although the magnitude and generalizability of such effects depend on instructional context and learner characteristics (12). More recent meta-analytic evidence involving 4,824 participants across 66 empirical studies also reported a positive overall association between graphic-organizer use and higher-order thinking ($g = 0.778$), with comparatively stronger effects observed for mind maps among the organizer types examined (7).

These findings provided a methodological rationale for using different visual structures for different learning operations. Accordingly, the present framework was designed around three sequential functions:

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comparison → integration → reconstruction.

The Venn diagram was assigned to the comparison stage, the Mind Map to the integration stage, and the Flower Grid to the reconstruction stage. This functional differentiation was introduced to avoid using several visual tools merely as alternative illustrations of identical information.

2.4. Comparative Analysis Using the Venn Diagram

The first visual transformation involved α-, β-, and γ-radiation because these three forms of radiation provide a clear basis for comparing particulate and electromagnetic radiation, electric charge, penetration, ionization, and exposure characteristics.

A three-set Venn diagram was constructed from the standardized content matrix. Radiation-specific characteristics were positioned in the non-overlapping regions, whereas common or related characteristics were placed in the corresponding intersections. This structure allowed the scientific information to be reorganized according to **similarity and difference** rather than according to the order in which it appeared in a conventional table.

The original instructional material identified several limitations of tabular presentation, including information density, repeated reading, difficulty in immediately recognizing common characteristics, and the tendency for all properties to appear visually equivalent. It consequently proposed the Venn diagram as an alternative mechanism for analysis and synthesis of α-, β-, and γ-radiation.

Within the revised methodology, the Venn diagram was used through a three-stage procedure:

Stage 1 – Identification.
Students identify individual physical characteristics of α-, β-, and γ-radiation.

Stage 2 – Classification.
Each characteristic is assigned to the radiation type or types to which it applies.

Stage 3 – Comparative interpretation.
Students explain the physical reason for the observed similarities and differences, particularly with respect to charge, penetration, ionization, exposure pathway, and shielding.

This final stage is essential because correctly positioning information within a diagram does not necessarily demonstrate conceptual understanding. The instructional objective is therefore not simply to complete the diagram, but to explain the relationships represented by it.

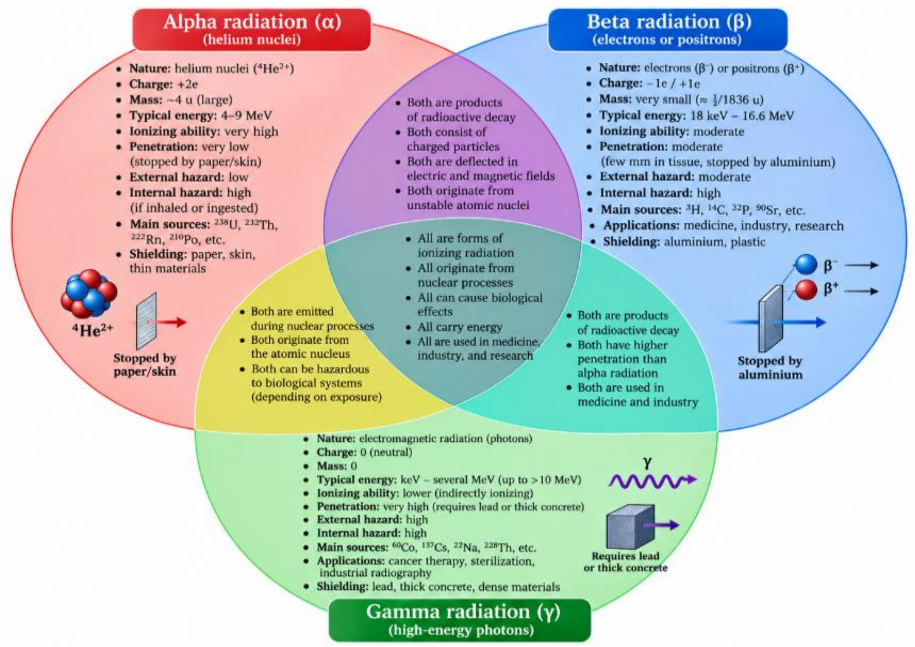

Figure 1. Venn diagram for the comparative analysis of α-, β-, and γ-radiation.

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The use of the Venn diagram at this stage establishes the first transition from descriptive knowledge toward relational reasoning. It also prepares learners for the subsequent Mind Map activity, in which the number of conceptual relationships is expanded.

2.5. Conceptual Integration Using Mind Mapping

Following comparative differentiation, the instructional sequence progressed to conceptual integration using a Mind Map. In contrast to the Venn diagram, which was restricted primarily to identifying common and distinguishing properties, the Mind Map was designed to represent the broader conceptual architecture of ionizing radiation.

The central node was defined as **Ionizing Radiation**. From this node, first-level branches represented the principal radiation categories, while secondary branches represented their physical characteristics, origins, interactions, penetration behaviour, exposure relevance, and shielding principles.

The methodological purpose of this structure was to allow individual concepts to be interpreted within a network rather than as isolated facts. For example, *penetration ability* was connected not only to a radiation type but also to external exposure and shielding, while *ionizing ability* was related conceptually to interaction with matter and subsequent biological significance.

This approach is supported by contemporary evidence concerning visual knowledge organization. The meta-analysis discussed in the Introduction showed a positive association between concept mapping and achievement in science education (6), while more recent evidence indicates that graphic organizers, particularly mind maps in the studies analyzed, may also support higher-order cognitive processes (13).

The Mind Map was constructed according to three principles:

hierarchical organization, in which general concepts precede more specific characteristics;

relational consistency, in which branches reflect scientifically meaningful associations rather than arbitrary visual grouping; and **conceptual economy**, in which only information necessary to explain the relationship between radiation physics and health-related interpretation is retained.

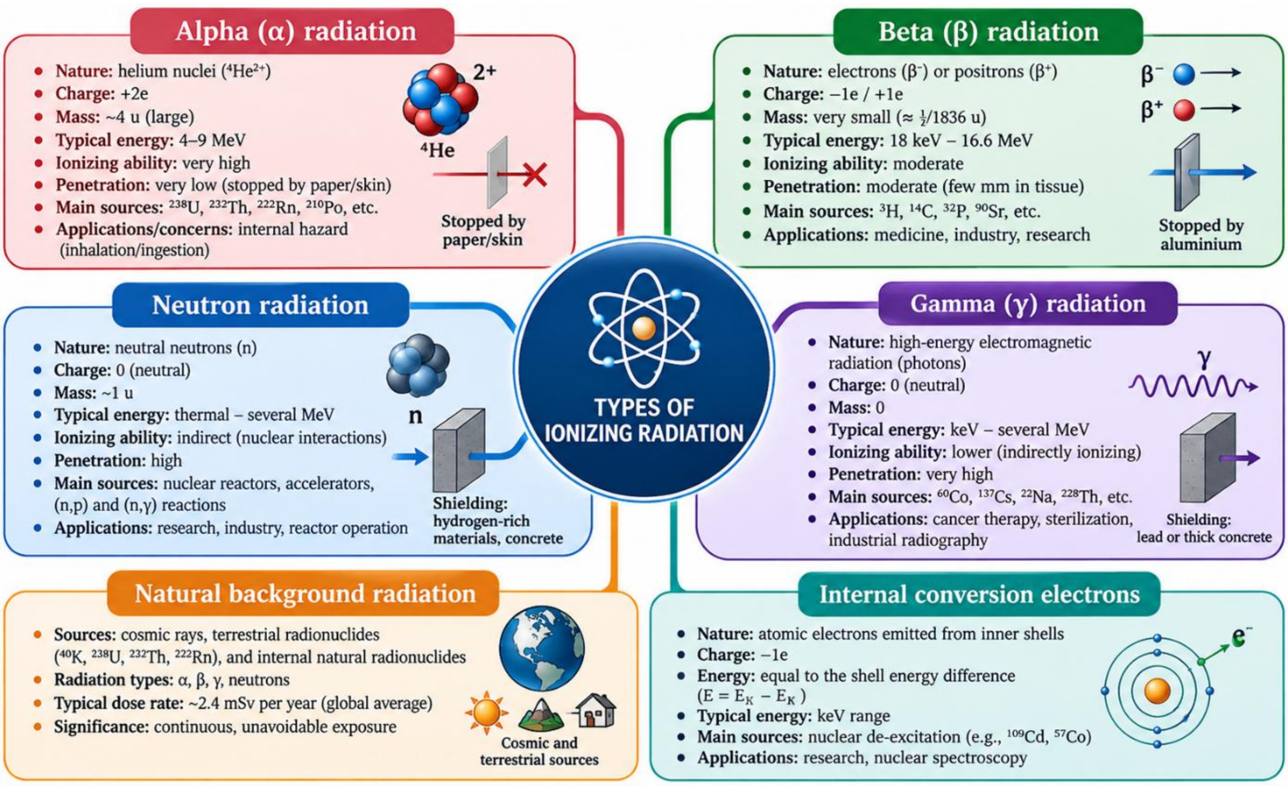

Figure 2. Mind Map representing the conceptual relationships among the principal forms and characteristics of ionizing radiation.

These principles were introduced to prevent the Mind Map from becoming an overloaded illustration. Its function was to make the internal organization of the topic visible and to prepare learners for the subsequent reconstruction stage.

2.6. Interactive Reconstruction Using the Flower Grids Method

The third stage employed the Flower Grids method. In the source material, the Flower Grid is proposed as a graphic organizer in which a central concept is surrounded by elements representing its principal characteristics. The original methodology further proposes separating these components and requiring learners to restore the correct structure.

In the revised framework, this feature was developed into an explicit **retrieval-and-reconstruction procedure**.

A radiation type was positioned in the central cell. Its associated characteristics—including physical nature, charge, origin, penetration, ionization, exposure relevance, and shielding—were placed in surrounding cells. After initial study, the peripheral elements could be removed from their original positions and presented in a mixed order.

Learners were then required to:

1. identify the radiation type represented by the central concept;
2. retrieve its relevant characteristics from memory;
3. distinguish correct characteristics from distractors;
4. associate each characteristic with the appropriate conceptual category;
5. reconstruct the complete Flower Grid; and
6. justify selected relationships verbally or in written form.

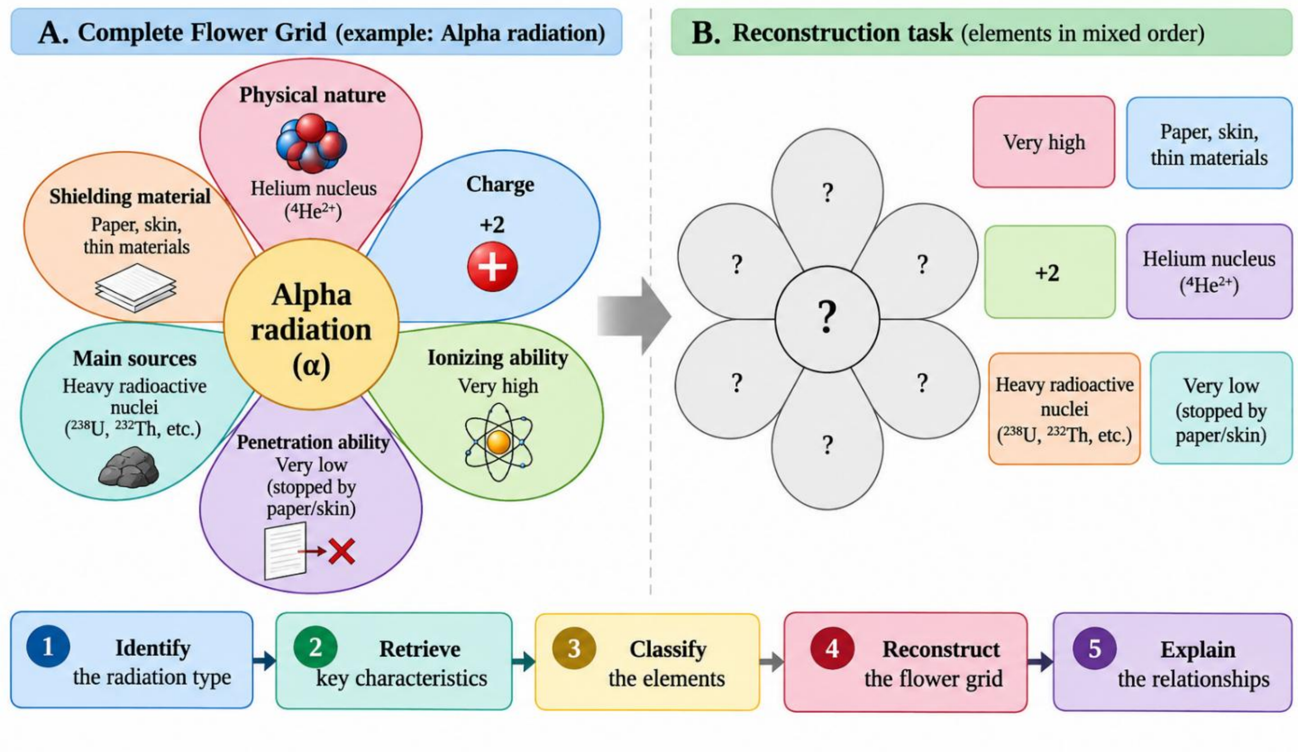

Figure 3. Flower Grid structure used for retrieval, classification, and reconstruction of radiation characteristics.

This modification provides a pedagogically grounded basis for using the Flower Grids method as a retrieval-and-reconstruction activity rather than solely as a static visual aid. Retrieval practice has been consistently associated with improved learning and longer-term retention across classroom and educational settings (14, 15). Agarwal et al. (14), in a systematic review of applied school and classroom research, concluded that retrieval practice generally benefits student learning across a range of educational conditions. Carpenter et al. (15) similarly emphasized retrieval practice as one of the well-supported strategies for strengthening learning and retention.

The present methodology does not claim that the Flower Grid itself has been experimentally demonstrated to produce these effects. Rather, its reconstruction procedure incorporates a learning operation—active retrieval—that is independently supported by educational research. This distinction is important for avoiding attribution of established retrieval-practice effects to a specific graphic organizer without direct empirical evidence.

2.7. Integration of Radiation Physics, Dosimetry, and Biological Effects

After the visual and reconstruction stages, the instructional sequence was extended from radiation characteristics to dosimetric and biological interpretation.

The original material includes exposure-related quantities, absorbed dose, equivalent dose, effective dose, somatic and genetic consequences, and deterministic and stochastic effects. It also describes the progression from ionization and physicochemical changes to cellular and biological effects.

Rather than presenting these elements as a separate section, the revised methodology incorporated them into a continuous causal-conceptual pathway:

radiation source
→ radiation type and energy
→ interaction with matter
→ ionization/excitation
→ energy deposition
→ absorbed dose
→ biologically relevant dose interpretation
→ cellular and tissue response
→ potential health consequence
→ radiation-protection decision.

This sequence represents a central methodological improvement over the original descriptive organization. It allows the learner to move progressively from a nuclear-physics concept to its biological interpretation while preserving the intermediate physical processes required to understand that relationship.

The framework also explicitly distinguishes **hazard** from **exposure and risk**. A radiation type is not characterized as universally "safe" or "dangerous" solely on the basis of penetration or ionization. Instead, its potential biological significance is considered in relation to energy, exposure route, dose, tissue characteristics, and duration of exposure. This distinction is particularly important when comparing α- and γ-radiation: limited external penetration of α-particles does not imply negligible biological significance following internal incorporation, just as the high penetration of γ-radiation does not by itself specify the magnitude of health risk without information about exposure and dose (1–3).

2.8. Instructional Implementation Sequence

The complete teaching procedure was organized into six consecutive phases.

Phase I – Scientific orientation.
Learners are introduced to the principal radiation types and the physical meaning of ionization, penetration, energy, and interaction with matter.

Phase II – Standardized comparison.
The radiation categories are examined using the common parameters presented in the content matrix.

Phase III – Comparative differentiation.
The Venn diagram is used to classify common and distinctive properties of α-, β-, and γ-radiation.

Phase IV – Conceptual integration.
The Mind Map is used to connect radiation types with their origins, physical properties, interactions, exposure relevance, and shielding.

Phase V – Active reconstruction.
Flower Grid elements are reorganized and reconstructed so that learners retrieve and re-establish conceptual relationships rather than merely reread them. The use of retrieval at this stage is consistent with evidence showing that active retrieval can enhance retention relative to passive restudy (14–16).

Phase VI – Health-related interpretation.
The reconstructed physical concepts are connected with dosimetric quantities, biological responses, human-health implications, and radiation-protection principles.

The methodological sequence can therefore be summarized as:

Scientific orientation → Comparison → Differentiation → Integration → Retrieval and reconstruction → Biological interpretation → Radiation-protection reasoning.

Unlike the original presentation, this sequence defines not only **which tools are used**, but also **when they are used, why they are used, and what cognitive operation each tool is intended to elicit**.

2.9. Conceptual Assessment Framework

Assessment was aligned with the conceptual structure of the instructional methodology. Rather than restricting assessment to the recall of definitions, the framework distinguishes several levels of understanding.

At the **factual level**, learners identify radiation types, physical properties, and basic shielding materials.

At the **comparative level**, they distinguish characteristics of α-, β-, γ-, and neutron radiation.

At the **relational level**, they explain relationships between ionization, penetration, exposure pathway, and shielding.

At the **reconstruction level**, they restore incomplete or disordered Flower Grid structures using conceptual knowledge.

At the **interpretive level**, they connect radiation properties with dose, biological effects, and radiation-protection decisions.

Accordingly, conceptual understanding can be assessed through classification tasks, incomplete Venn diagrams, partially constructed Mind Maps, Flower Grid reconstruction exercises, and short explanatory questions.

For example, instead of asking only:

"What is alpha radiation?"

a relational assessment may ask:

"Why can alpha radiation represent a limited external irradiation hazard but a substantial concern following internal incorporation of an alpha-emitting radionuclide?"

The latter requires integration of penetration, ionization, exposure route, and biological interpretation rather than simple recall.

This assessment structure is also consistent with evidence that retrieval-based learning is most educationally useful when students are required to actively reconstruct previously learned information rather than simply reread it (14–16).

2.10. Methodological Boundaries and Statistical Analysis

No quantitative statistical analysis was performed because the present study does not include a defined participant sample, randomization procedure, control or experimental groups, pre-test/post-test scores, or individual-level quantitative learning data. Consequently, inferential statistics, p-values, confidence intervals, and effect sizes are not applicable to the present methodological investigation.

The study should therefore be interpreted as the development and theoretical substantiation of an instructional framework rather than as a controlled educational intervention demonstrating its effectiveness. The analysis focused on the scientific consistency, conceptual organization, instructional sequencing, and functional integration of the proposed framework components.

Empirical evaluation of the framework through defined participant groups, validated assessment instruments, and quantitative measures of learning outcomes represents a subsequent stage of research and is considered in Section 3.11.

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3. RESULTS AND DISCUSSION

3.1. Structural Outcome of the Proposed Instructional Framework

The principal methodological outcome of the present study is a structured instructional framework that connects the physical foundations of ionizing radiation with exposure, dosimetry, biological response, human-health implications, and radiation protection. These components are organized as a continuous conceptual sequence rather than as isolated instructional topics, as illustrated in Figure 4.

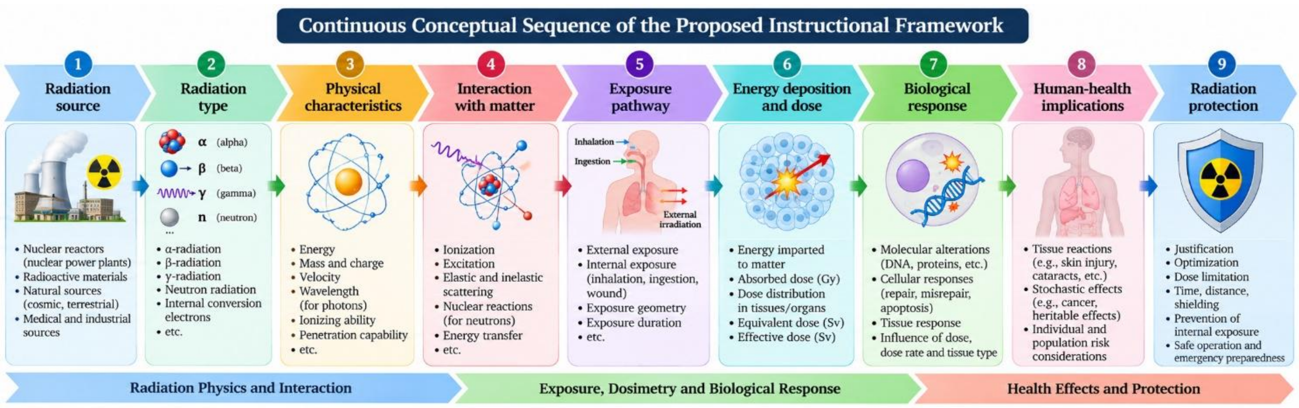

Figure 4. Continuous conceptual sequence of the proposed instructional framework linking radiation physics, exposure, dosimetry, biological response, human-health implications, and radiation protection.

As shown in Figure 4, the framework establishes a progression from radiation sources and radiation forms to their physical characteristics, interactions with matter, exposure pathways, and energy deposition. These relationships provide the basis for dosimetric interpretation and for connecting absorbed energy with biological responses, potential health consequences, and appropriate radiation-protection decisions. The resulting structure therefore links four domains that are frequently considered separately in instruction: radiation physics, dosimetry, biological effects, and radiation protection.

A central feature of the framework is that progression between these domains requires more than factual recognition. For example, knowing that alpha particles have limited penetration represents factual understanding, whereas explaining why internal incorporation can substantially change their biological significance requires consideration of exposure pathway, energy deposition, absorbed dose, and irradiated tissue. Likewise, the penetration characteristics of gamma radiation acquire greater interpretive meaning when considered together with exposure geometry, shielding, absorbed dose, and biological response (1–3). Thus, the framework shifts the instructional emphasis from the isolated recognition of radiation properties toward relational interpretation of their radiological and health significance.

Within this architecture, the three visual–interactive tools perform distinct but complementary functions. The Venn diagram in Figure 1 supports comparative differentiation of α, β, and γ radiation; the Mind Map in Figure 2 organizes broader relationships among radiation forms, sources and exposure contexts, physical characteristics, and protection principles; and the Flower Grid in Figure 3 converts previously organized information into a retrieval and reconstruction activity. Accordingly, these tools are not alternative representations of the same content but function as sequential components within the integrated instructional framework.

This functional differentiation is consistent with evidence indicating that visual knowledge structures are most educationally meaningful when they are incorporated into purposeful processes of comparison, organization, and conceptual integration (6, 12, 13). Evidence from retrieval-based learning further supports the value of requiring learners to actively reconstruct previously encountered information rather than relying solely on repeated inspection of completed representations (14–16). Within the proposed framework, these principles provide the pedagogical basis for progressing from visual organization toward active reconstruction and subsequent interpretation.

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3.2. Comparative Interpretation of Radiation Characteristics

The comparative structure developed in Figure 1 reveals that the properties of α-, β-, and γ-radiation should not be interpreted independently. In particular, ionizing ability, penetration, exposure pathway, and shielding form an interconnected group of concepts.

Alpha particles are massive charged particles relative to beta particles and produce dense ionization along relatively short tracks. Their penetration through external barriers is limited; however, this property should not be interpreted as indicating universally low biological significance. If an alpha-emitting radionuclide is incorporated into the body, energy may be deposited directly within tissues over a short range. Beta particles have greater penetration than alpha particles but generally less penetration than gamma photons, while their interaction and energy-deposition characteristics also depend strongly on particle energy. Gamma radiation consists of uncharged photons and can penetrate substantially deeper into matter, making exposure geometry and shielding particularly important considerations (1–3).

The educational implication is that **penetration and hazard are not synonymous concepts**. A simple ranking such as "alpha < beta < gamma" may describe penetration under specified conditions, but it does not constitute a corresponding universal ranking of biological risk. Radiation risk depends on dose and exposure conditions as well as radiation quality and the biological target (1–3).

The same reasoning applies to shielding. Paper, low-density materials, aluminium, dense materials, concrete, or hydrogen-rich shielding may be appropriate in different radiation contexts, but shielding should not be taught as a collection of isolated radiation–material pairs. The physical interaction mechanism must be considered. This is particularly important for neutron radiation, for which shielding principles differ substantially from those used for charged particles or photons.

Thus, the comparative representation in Figure 1 is valuable primarily because it enables students to move from the question **"What are the properties of this radiation?"** toward **"How are these properties related, and what do they imply under a given exposure condition?"**

3.3. Conceptual Integration beyond α-, β-, and γ-Radiation

Figure 2 extends the instructional content beyond the three radiation categories compared in the Venn diagram. The Mind Map integrates α-radiation, β-radiation, γ-radiation, neutron radiation, internal conversion electrons, and natural background radiation within a common conceptual structure.

This broader representation provides an opportunity to resolve an important classification issue. These six categories are not equivalent taxonomic entities. Alpha particles, beta particles, gamma photons, and neutrons describe forms of radiation, whereas **natural background radiation** refers primarily to the environmental origin and context of exposure and may contain contributions from several radiation types. Internal conversion electrons, in turn, originate from a particular mechanism of nuclear de-excitation rather than beta decay. Making these distinctions explicit prevents visual simplification from producing scientific oversimplification.

The Mind Map therefore serves not merely to display additional information but to organize different conceptual levels. Radiation **type**, **source**, **mechanism of production**, **physical characteristic**, **exposure context**, and **application** are separated while remaining visually connected.

This is particularly relevant because misconceptions in radiation education may arise from inappropriate relationships between concepts rather than complete absence of factual knowledge (4). A learner may, for example, know the definitions of radioactive decay and ionizing radiation while failing to distinguish radioactive material from the radiation emitted by it. The conceptual structure developed in Figure 2 provides an instructional basis for explicitly addressing such relationships.

The result is a transition from a list-based representation toward a network-based understanding:

What is emitted? → How is it produced? → How does it interact? → How far can it penetrate? → Under what conditions does exposure occur? → What protection principle follows?

The framework therefore treats conceptual organization as an intermediate stage between initial comparison and subsequent active reconstruction.

3.4. Retrieval and Reconstruction as an Active Learning Stage

The Flower Grid presented in Figure 3 represents the transition from visual organization to active knowledge reconstruction. In its completed form, the Flower Grid displays the properties associated with a selected radiation type. In its reconstruction form, however, these relationships are deliberately removed, requiring the learner to restore them.

The activity is organized around five operations:

Identify → Retrieve → Classify → Reconstruct → Explain.

The final operation—**explain**—is particularly important. Correctly placing "high ionizing ability" or "limited penetration" around alpha radiation may result from memorization. Explaining why these properties occur and how they influence external and internal exposure provides stronger evidence of conceptual understanding.

Retrieval practice has an established empirical basis in educational research. Trumble et al. reviewed 56 eligible studies containing 63 experiments in health-professions education; 43 reported significant benefits of distributed and/or retrieval practice compared with control or comparison conditions, although study designs and implementation strategies were heterogeneous (17).

The relevance of this evidence must nevertheless be stated carefully. It supports **retrieval practice as a learning mechanism**, not the Flower Grid itself. No experimental evidence available in the present study establishes that Flower Grid reconstruction produces a specific effect size or that it is superior to another retrieval format. The contribution of the present framework is therefore to adapt the Flower Grid as a practical mechanism through which retrieval, classification, reconstruction, and explanation can be incorporated into radiation instruction.

This distinction prevents an important methodological error: evidence supporting a cognitive process should not automatically be presented as evidence supporting every instructional tool in which that process is embedded.

3.5. Integration of Radiation Physics with Dosimetry

Once learners have established the relationships among radiation types and their physical properties, the framework proceeds toward dosimetric interpretation. This stage is necessary because the potential biological significance of radiation cannot be inferred solely from its physical identity.

The conceptual progression is:

Radiation field → Interaction with matter → Energy deposition → Absorbed dose → Protection-related dose quantities → Biological interpretation.

Absorbed dose represents energy imparted to matter per unit mass and is expressed in gray (Gy). Equivalent dose and effective dose are protection quantities expressed in sievert (Sv), although their purposes and appropriate applications differ. ICRP Publication 147 identifies absorbed dose, equivalent dose, and effective dose as central quantities used in radiological protection and emphasizes the role of effective dose in managing protection against stochastic effects, principally cancer (18).

A scientifically important clarification is required here. **Effective dose should not be interpreted as an exact prediction of an individual person's cancer risk.** Individual risk estimates depend on organ- and tissue-specific doses as well as factors such as age at exposure, sex, and population characteristics. Effective dose is therefore primarily a radiological-protection quantity rather than a substitute for individualized risk assessment (18). The relationship between energy deposition, absorbed dose, radiation and tissue weighting, and radiological-protection interpretation is summarized in **Figure 5**.

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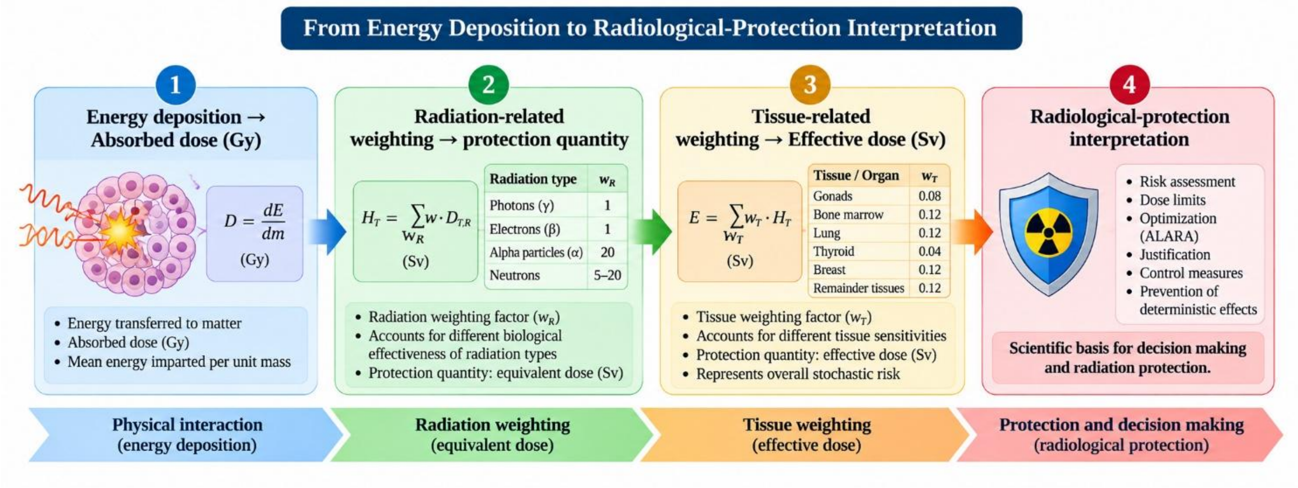

Figure 5. Conceptual pathway from energy deposition and absorbed dose to radiation- and tissue-weighted quantities and radiological-protection interpretation.

As illustrated in Figure 5, the dosimetric pathway begins with the physical deposition of energy in matter, expressed as **absorbed dose (Gy)**. Radiation weighting is subsequently applied to account for differences in radiation quality when deriving equivalent dose, while tissue weighting integrates the relative contribution of individual organs and tissues to effective dose. This progression enables learners to distinguish the physical quantity of absorbed dose from protection quantities expressed in sieverts and to understand their different roles in radiological protection (18).

Importantly, the sequence links each dosimetric quantity to the physical or protection-related concept from which it is derived rather than presenting **Gy and Sv as isolated units**. In the proposed instructional framework, this provides the conceptual bridge between radiation interaction, energy deposition, biological significance, and subsequent radiation-protection interpretation.

Table 2. Conceptual differentiation of the principal dose quantities

Quantity	Primary meaning	Unit	Principal instructional interpretation
Absorbed dose	Energy imparted per unit mass	Gy	Physical energy deposition in matter/tissue
Equivalent dose	Radiation-weighted organ/tissue dose	Sv	Protection-related consideration of radiation type
Effective dose	Tissue-weighted combination of organ/tissue doses	Sv	Overall radiological-protection quantity for stochastic risk management

This table also corrects a weakness of purely descriptive teaching: the quantities are differentiated according to **what they represent**, not merely their symbols and units.

3.6. Linking Dosimetry to Biological Response

The next conceptual result is the establishment of a continuous pathway between energy deposition and biological effects:

Ionization/excitation → Physicochemical changes → Molecular alterations → Cellular response → Tissue response → Potential health consequence.

The first stage occurs when ionizing radiation transfers energy to biological matter. Subsequent physicochemical processes may alter biologically important molecules and cellular structures. Whether such changes ultimately produce clinically meaningful consequences depends on numerous variables, including radiation quality, dose, dose rate, exposed tissue, irradiated volume, and biological characteristics of the exposed individual.

This sequence is important pedagogically because it prevents students from interpreting the biological effect as an immediate and inevitable consequence of the mere presence of radiation. Instead, the framework inserts the intermediate physical, dosimetric, and biological processes required for scientifically meaningful interpretation.

The approach is particularly relevant to discussions of nuclear power plants. A learner should be able to distinguish among **the existence of a radioactive material, emission of ionizing radiation, human exposure, absorbed dose, and health effect**. These concepts are related but not interchangeable. Failure to distinguish them can contribute to inaccurate interpretations of radiation risk.

3.7. Tissue Reactions and Stochastic Effects

A further scientific refinement concerns the classification of radiation-induced health effects. The original material distinguishes deterministic and stochastic effects. For contemporary terminology, however, the term **tissue reactions** should be introduced alongside the traditional term *deterministic effects*.

ICRP Publication 118 explains that effects previously called deterministic effects are now referred to as tissue reactions and provides updated information concerning threshold doses for radiation-induced injury in different tissues and organs (19). ICRP guidance also distinguishes tissue reactions from stochastic effects: tissue reactions are generally associated with threshold behaviour, whereas for stochastic effects the probability of occurrence, rather than severity, is treated as dose-related for radiological-protection purposes (20).

Accordingly, the educational classification should be presented as:

Radiation-induced health effects

A. Tissue reactions (traditionally termed deterministic effects)
– generally associated with threshold-type behaviour;
– incidence and/or severity increases as dose rises above the relevant range;
– examples depend on the irradiated tissue and exposure conditions.

B. Stochastic effects
– principally cancer and heritable effects in the conventional radiological-protection framework;
– probability is considered dose-related for protection purposes;
– severity of an individual stochastic outcome is not considered dose-dependent in the same way (20).

This terminology is more scientifically current than retaining only the deterministic/stochastic labels.

ICRP Publication 118 further emphasizes that threshold values vary according to the tissue and exposure circumstances and discusses, among other endpoints, cataracts and circulatory effects. It therefore would be scientifically inappropriate to teach one universal "deterministic-effect threshold" applicable to all organs and all exposure situations (19).

3.8. An Integrated Interpretation of Human-Health Effects

Combining the preceding physical, dosimetric, and biological components resulted in an integrated pathway linking the characteristics of ionizing radiation with potential human-health effects and the corresponding radiation-protection response. As illustrated in Figure 6, the pathway begins with the type and energy of radiation and subsequently considers its interaction with matter, the relevant exposure pathway, energy deposition and absorbed dose, biological response, and the possible development of tissue reactions or stochastic effects.

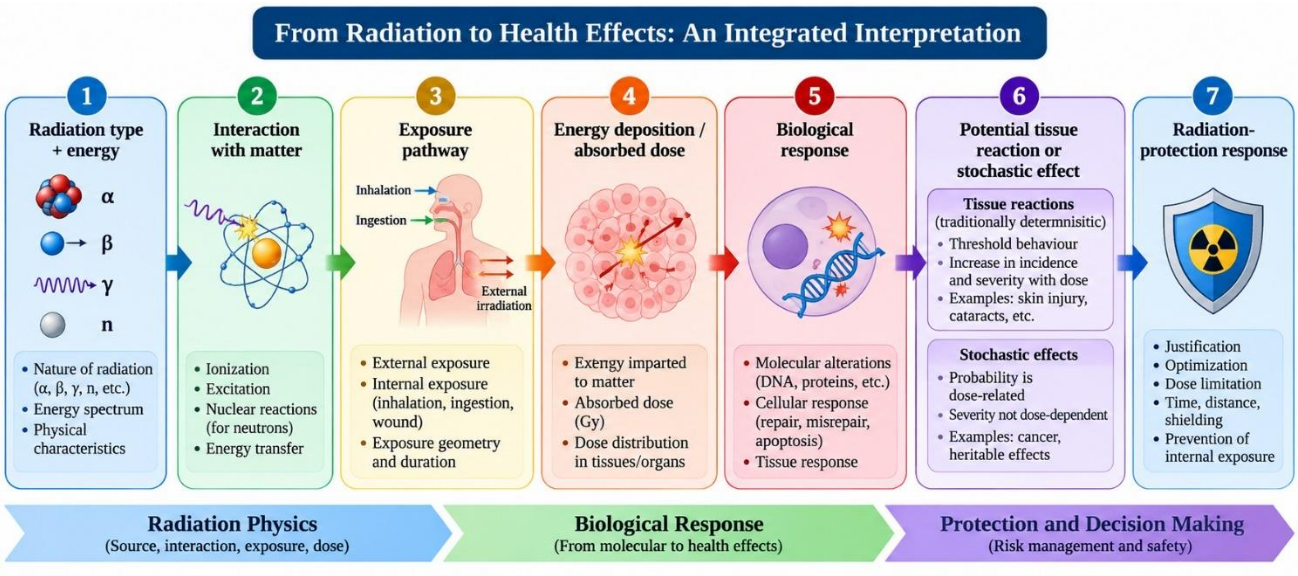

Figure 6. Integrated pathway from radiation type and energy to human-health effects and radiation-protection response.

The pathway presented in Figure 5 emphasizes that the biological significance of ionizing radiation cannot be determined from radiation type alone. The initial physical characteristics of α-, β-, γ-, or neutron radiation influence their interaction with matter and energy-transfer mechanisms; however, the resulting health implications also depend on the exposure pathway, exposure geometry and duration, the amount and spatial distribution of absorbed dose, and the characteristics of the irradiated tissues. Consequently, the same radiation type may have substantially different radiological significance under different exposure conditions (1–3, 18).

An important feature of the proposed framework is the explicit separation of **radiation hazard**, **exposure**, **dose**, and **biological effect**. The presence of an ionizing-radiation source does not by itself imply that a biologically significant dose has been received. Radiation must first interact with matter and transfer energy to biological tissues before dose-related biological processes become relevant. At the cellular level, such energy deposition may initiate molecular alterations involving DNA and other cellular structures, followed by repair, misrepair, cell death, or other biological responses. The eventual outcome depends on both physical and biological factors rather than on a single radiation characteristic.

Figure 5 also provides a logical transition from biological response to the contemporary distinction between **tissue reactions** and **stochastic effects**. Tissue reactions are generally associated with threshold-type behaviour and become increasingly relevant as dose increases above tissue-specific ranges, whereas stochastic effects are considered primarily in terms of the probability of occurrence for radiological-protection purposes (19, 20). This distinction demonstrates why dose information and biological context must be incorporated before radiation-related health consequences are interpreted.

The final stage of the pathway is the **radiation-protection response**. Protection measures are therefore presented as the outcome of the preceding scientific analysis rather than as an isolated collection of safety rules. Depending on the exposure scenario, appropriate measures may include optimization of exposure conditions, limitation of exposure duration, increasing distance from an external source, application of radiation-specific shielding, or prevention of radionuclide intake. In this way, the framework connects fundamental radiation physics directly with health-related interpretation and practical radiation-protection decision making.

3.9. Radiation-Protection Reasoning as the Final Learning Outcome

The final stage connects conceptual understanding with radiation protection. The learner is expected to move from recognition of radiation properties toward interpretation of an exposure scenario and selection of an appropriate protection principle.

For external irradiation, protection may involve combinations of **time, distance, and shielding**. For internal exposure, preventing or limiting radionuclide intake becomes particularly important. Shielding selection must also follow the physical properties of the radiation rather than a universal “stronger material is always better” rule.

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Consequently, the complete reasoning sequence becomes:

Identify the radiation → determine the exposure pathway → interpret interaction and penetration → consider dose → evaluate biological significance → select an appropriate protection principle.

This represents the highest level of the instructional sequence developed in the study. The student is no longer expected merely to reproduce characteristics but to apply them within a physically and biologically meaningful context.

3.10. Pedagogical Significance of the Developed Sequence

Taken together, the proposed approach establishes the following progression:

Remember → Compare → Differentiate → Organize → Retrieve → Reconstruct → Explain → Interpret → Apply.

The Venn diagram supports the transition from remembering to comparing and differentiating. The Mind Map moves the learner toward organization and integration. The Flower Grid introduces retrieval and reconstruction. Dosimetric and biological interpretation subsequently requires explanation and application.

The resulting contribution is therefore not the isolated use of three graphic organizers. The novelty lies in their **functional sequencing around a scientifically coherent radiation pathway**.

Importantly, this interpretation remains consistent with the limitations of the available evidence. The present study establishes an instructional framework; it does not demonstrate experimentally that the framework improves learning by a particular percentage. Existing research on concept mapping, graphic organizers, and retrieval practice provides a theoretical and empirical rationale for the selected learning mechanisms (6, 12–17), but those results cannot be transferred directly to the present framework as if they were outcomes of this study.

3.11. Limitations and Directions for Further Validation

The principal limitation of the present study is that the proposed instructional framework has not yet been evaluated through a controlled educational intervention. Accordingly, the findings establish the conceptual and methodological structure of the framework but do not provide quantitative evidence of its effects on student learning outcomes.

Future empirical validation should examine whether the proposed framework supports learning across four complementary dimensions: factual knowledge, including recognition of radiation forms and their physical characteristics; comparative understanding, including differentiation according to ionization and energy-deposition behaviour, penetration characteristics, exposure relevance, and shielding principles; relational understanding, including the ability to connect radiation form and energy with exposure pathway, dosimetric interpretation, and biological response; and transfer and application, including the interpretation of unfamiliar radiation-exposure and radiation-protection scenarios.

A controlled pre-test/post-test design using clearly defined participant groups and validated assessment instruments would enable quantitative evaluation of learning gains and between-group differences. Because retrieval and reconstruction constitute an integral component of the proposed framework, the inclusion of a delayed post-test would also be valuable for examining retention beyond immediate post-instruction performance. Such validation should consider not only factual recall but also learners' ability to reconstruct conceptual relationships and apply them to new radiation-related situations. Evidence from retrieval-practice research provides a methodological rationale for examining both the characteristics of the retrieval task and the interval between learning and subsequent assessment (16).

Until such empirical validation is completed, the contribution of the present study should be understood as a scientifically structured and theoretically grounded instructional framework that integrates radiation physics, visual comparison, conceptual organization, retrieval-based reconstruction, dosimetric interpretation, biological effects, human-health implications, and radiation-protection reasoning.

4. CONCLUSION

This study developed an integrated instructional framework for teaching ionizing radiation and its potential human-health effects in the context of nuclear power plants. Rather than presenting radiation forms, physical characteristics, dosimetric quantities, biological effects, and radiation-protection principles as separate topics, the framework organizes them into a continuous conceptual pathway linking radiation physics with exposure conditions, dose interpretation, biological response, and protection-related decision making.

A distinctive feature of the methodology is the functional sequencing of three complementary instructional tools. The Venn Diagram supports comparison and differentiation of radiation characteristics; the Mind Map organizes broader relationships among radiation forms, sources, exposure contexts, and protection principles; and the Flower Grid promotes active retrieval and reconstruction of previously organized knowledge. Together, these tools establish a progressive learning sequence rather than functioning as interchangeable graphic organizers.

The resulting instructional progression comprises eight interconnected stages: comparison, differentiation, organization, retrieval, reconstruction, explanation, interpretation, and application (Figure 7). These stages guide learners from identifying and organizing radiation characteristics to reconstructing conceptual relationships and applying them to dosimetric, health-related, and radiation-protection scenarios.

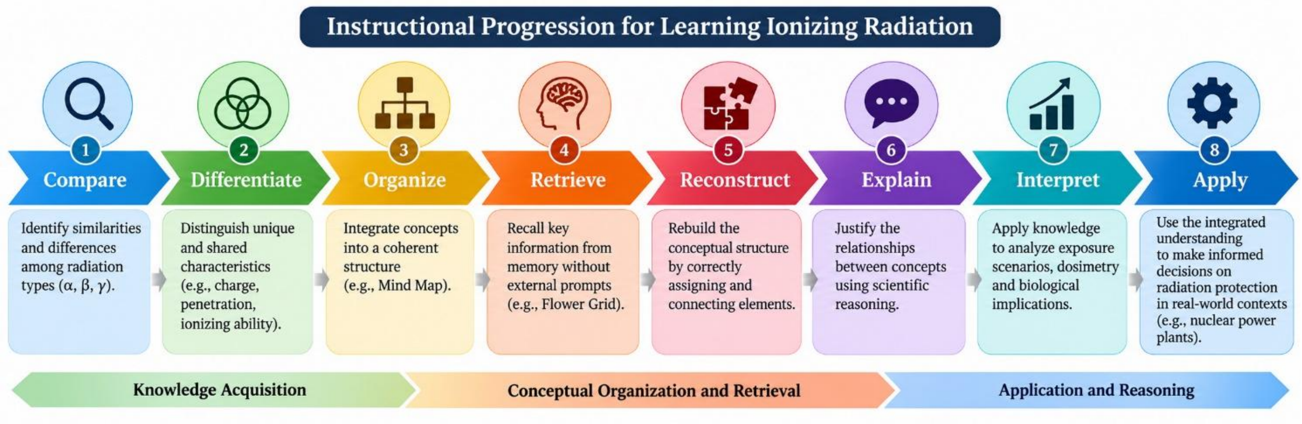

Figure 7. Instructional progression from comparative analysis and conceptual organization to retrieval, reconstruction, interpretation, and application of knowledge about ionizing radiation.

Overall, the methodological contribution of the study lies in the functional sequencing of complementary learning strategies within a unified pathway connecting radiation physics, human-health effects, and radiation-protection reasoning.

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AUTHOR CONTRIBUTIONS

Asror X. Ramazanov: Conceptualization, Methodology, Investigation, Writing—Original Draft, Visualization.

Erkin X. Bozorov: Conceptualization, Methodology, Validation, Writing—Review & Editing.

Ganiboy Rakhmanov: Investigation, Resources, Formal Analysis, Writing—Review & Editing.

Sanobar Reymbayeva: Investigation, Literature Review, Visualization, Writing—Review & Editing.

Mariya Malysheva: Methodology, Formal Analysis, Validation, Writing—Review & Editing.

Makhmudjan A. Tulametov: Methodology, Validation, Resources, Writing—Review & Editing.

All authors reviewed and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this manuscript.

ETHICS STATEMENT

Ethical approval was not required for this study because the research focused on the development and theoretical analysis of an instructional framework and did not involve human participants, patient data, biological samples, or experimental procedures involving humans or animals.

DATA AVAILABILITY STATEMENT

No primary experimental or participant-level dataset was generated or analyzed in this study. The study is based on the development and scientific analysis of an instructional framework using established concepts of ionizing radiation, dosimetry, biological effects, and radiation protection. All information supporting the proposed framework is presented within the article and its cited references.

REFERENCES

[1] International Commission on Radiological Protection (ICRP). The 2007 Recommendations of the International Commission on Radiological Protection. *ICRP Publication 103. Annals of the ICRP*. 2007;37(2–4):1–332.

[2] Hall EJ, Giaccia AJ. *Radiobiology for the Radiologist*. 8th ed. Philadelphia: Wolters Kluwer; 2019.

[3] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). *Sources, Effects and Risks of Ionizing Radiation: UNSCEAR 2020/2021 Report, Volume III, Scientific Annex C: Biological Mechanisms Relevant for the Inference of Cancer Risks from Low-Dose and Low-Dose-Rate Radiation*. New York: United Nations; 2022. ISBN: 978-92-1-139208-1.

[4] Prokop AT, Nawrodt R. Energy as a source of preservice teachers' conceptions about radioactivity. *Physical Review Physics Education Research*. 2024;20(1):010155. doi:10.1103/PhysRevPhysEducRes.20.010155.

[5] Healthcare students' knowledge and awareness on ionizing radiation and radiation protection. *Journal of Radiation Research and Applied Sciences*. 2024;17(4):101180. doi:10.1016/j.jrras.2024.101180.

[6] Anastasiou D, Wirngo CN, Bagos P. The effectiveness of concept maps on students' achievement in science: A meta-analysis. *Educational Psychology Review*. 2024;36:39. doi:10.1007/s10648-024-09877-y.

[7] Lei H, Ding Y, Chiu MM. The effect of graphic organizers on cultivating higher-order thinking: Evidence from a meta-analysis. *Educational Research Review*. 2026;52:100822. doi:10.1016/j.edurev.2026.100822.

[8] Sajadi AS, Babajani A, Sedigh Maroufi S, Sarraf N. Using the mind map method in medical education, its advantages and challenges: A systematic review. *Journal of Education and Health Promotion*. 2024;13:483. doi:10.4103/jehp.jehp_1323_23.

[9] Kefalis C, Skordoulis C, Drigas A. A systematic review of mind maps, STEM education, algorithmic and procedural learning. *Computers*. 2025;14(6):204. doi:10.3390/computers14060204.

[10] Picardal MT, Sanchez JMP. Students' performance, satisfaction, and experiences in graphic organizer integrated online instruction of astronomy. *Science Education International*. 2023;34(4).

[11] Imam BT, Olorundare AS. Comparative effect of use of graphic organizers on students' learning outcomes in organic chemistry. *Unnes Science Education Journal*. 2023;12(1). doi:10.15294/usej.v12i1.55511.

[12] Dexter DD, Park YJ, Hughes CA. A meta-analytic review of graphic organizers and science instruction for adolescents with learning disabilities: Implications for the intermediate and secondary science classroom. *Learning Disabilities Research & Practice*. 2011;26(4):204–213. doi:10.1111/j.1540-5826.2011.00341.x.

[13] Agarwal PK, Nunes LD, Blunt JR. Retrieval practice consistently benefits student learning: A systematic review of applied research in schools and classrooms. *Educational Psychology Review*. 2021;33:1409–1453. doi:10.1007/s10648-021-09595-9.

[14] Carpenter SK, Pan SC, Butler AC. The science of effective learning with spacing and retrieval practice. *Nature Reviews Psychology*. 2022;1:496–511. doi:10.1038/s44159-022-00089-1.

[15] McDermott KB. Practicing retrieval facilitates learning. *Annual Review of Psychology*. 2021;72:609–633. doi:10.1146/annurev-psych-010419-051019.

[16] Trumble E, Lodge J, Mandrusiak A, Forbes R. Systematic review of distributed practice and retrieval practice in health professions education. *Advances in Health Sciences Education*. 2024;29(2):689–714. doi:10.1007/s10459-023-10274-3.

[17] International Commission on Radiological Protection (ICRP). Use of dose quantities in radiological protection. *ICRP Publication 147. Annals of the ICRP*. 2021;50(1).

[18] Stewart FA, Akleyev AV, Hauer-Jensen M, Hendry JH, Kleiman NJ, MacVittie TJ, Aleman BM, Edgar AB, Mabuchi K, Muirhead CR, Shore RE, Wallace WH. ICRP Publication 118: ICRP statement on tissue reactions and early and late

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effects of radiation in normal tissues and organs—threshold doses for tissue reactions in a radiation protection context. *Annals of the ICRP*. 2012;41(1–2):1–322. doi:10.1016/j.icrp.2012.02.001.

[19] Cousins C, Miller DL, Bernardi G, Rehani MM, Schofield P, Vañó E, Einstein AJ, Geiger B, Heintz P, Padovani R, Sim KH. Radiological protection in cardiology. *ICRP Publication 120*. *Annals of the ICRP*. 2013;42(1):1–125. doi:10.1016/j.icrp.2012.09.001.

[20] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). *Sources, Effects and Risks of Ionizing Radiation: UNSCEAR 2020/2021 Report, Volume I, Scientific Annex A: Evaluation of Medical Exposure to Ionizing Radiation*. New York: United Nations; 2022. ISBN: 978-92-1-139206-7