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ORIGINAL ARTICLE

REAL-LIFE RADIOACTIVE MEN: THE ADVANTAGES AND DISADVANTAGES OF RADIATION EXPOSURE

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ABSTRACT

In contemporary society, there's a pervasive belief that any level of radiation exposure is inherently detrimental and should be rigorously avoided. However, within the realm of fictional superhero narratives, radiation often serves as a catalyst for transforming ordinary individuals into super powered beings. For instance, Dr. Chen Lu, a Nuclear Physicist who becomes the formidable Radioactive Man, deliberately exposes himself to escalating doses of radiation, ultimately gaining extraordinary abilities. Similarly, Bruce Banner's accidental exposure to intense gamma radiation results in his transformation into the Incredible Hulk. While it is true that the human body can tolerate low levels of radiation without immediate harm, significant exposure can lead to severe health consequences. This article delves into the principles of radiation safety, detailing the various types of damage inflicted on the human body by radiation. It also explores the mechanisms of cellular mutation caused by radiation, examines the potential for organisms to develop resistance to its harmful effects, and highlights the beneficial applications of radiation in medical diagnostics and cancer treatment.

PROLOGUE

Chen Lu hesitated, his hand hovering over the door handle. The Geiger counter in his palm buzzed urgently, its clicks merging into a relentless drone—a stark warning of the peril within the laboratory. With a steadying breath, he braced himself, turned the handle, and stepped into the room, knowing this moment would define his fate.

INTRODUCTION

In the realm of science fiction, radiation has long fascinated enthusiasts as a mystical catalyst for superpower development [1]. It consists of unseen, intangible "rays" devoid of sensory clues, yet possessing enigmatic qualities that defy easy comprehension by laypeople. This ambiguity allows radiation in the world of fiction to be attributed as the origin of any imaginable superhuman ability.

Introduced in Marvel's "Journey into Mystery #93" in 1963, Dr. Chen Lu emerges as a Chinese nuclear physicist renowned for his exploration into using radiation to trigger extraordinary powers in humans [2]. Supported by his government, he subjects himself to prolonged, controlled exposure—details of which remain unspecified—to render himself immune to radiation's harmful effects. This exposure, though not fatal immediately, is presumed to induce genetic mutations. His goal: to wield any resulting powers against Thor, who thwarted a Chinese military incursion into India.

Over time, Lu acquires a suite of superhuman abilities: manipulation of radiation across the electromagnetic spectrum, emission of thermal energy, projection of high-energy radiation causing radiation sickness, absorption of radiation for personal energy, and accelerated healing. In battle, he dons a specialized radiation suit to safeguard allies from his emissions, though he can briefly reduce his radiation levels to blend in without it.

In the realm of superhero lore, one of the most iconic figures deriving powers from radiation is Dr. Bruce Banner, better known as the Hulk, in various media iterations from the 1962 Marvel comics [3], the 1977-1982 TV series, and subsequent Hollywood films [4, 5]. Banner's origin story typically involves direct exposure to a potent gamma radiation blast (see Figure 1), which triggers a transformative response: when provoked by anger, he metamorphoses into the Hulk—a colossal green entity endowed with immense strength, speed, agility, and remarkable regenerative abilities.

Exploring the mechanism behind Banner's transformation suggests a link to emotional triggers such as anger, potentially tied to physiological changes like heightened testosterone or adrenaline levels, or reduced cortisol—a threshold in blood chemistry that catalyzes his change.

This study draws inspiration from characters like Dr. Chen Lu and Dr. Bruce Banner to address key inquiries in radiation science: "What renders radiation hazardous?" "Can even minimal exposure to X-rays or gamma radiation be detrimental?" "Is it feasible to develop immunity against harmful radiation effects?" "Could exposure to intense gamma radiation genuinely confer superhuman strength?" and "Do genetic mutations occur following high radiation exposure?"

Moreover, we examine themes where ordinary individuals gain superpowers post-radiation exposure, exploring why these narratives hold fascination within the realm of radiation science.

WARNING – RADIATION HAZARD!

Understanding the dangers posed by certain types of electromagnetic (EM) radiation to human health begins with distinguishing between ionising and non-ionising radiation. Ionisation occurs when atoms either gain or lose electrons, transforming into positively or negatively charged ions. Non-ionising radiation does not alter the electron count of atoms, while ionising radiation typically strips electrons from atoms.

In the human body, ionisation can directly damage DNA atoms or indirectly generate "free radicals," highly reactive molecules with unpaired electrons that can harm cellular components. More than 70% of cellular damage is attributed to free radicals [6]. These processes can lead to biological and physiological changes in cellular structures, potentially causing disruptions that manifest immediately or decades later. For instance, UV radiation from sunlight is known to cause sunburn shortly after exposure and increases the long-term risk of melanoma (skin cancer) [7]. High-energy forms of radiation such as ultraviolet rays, X-rays, and gamma rays are classified as ionising because they can ionise atoms within the human body (see Figure 1). In contrast, low-energy radiation such as visible light and radio waves do not ionise atoms and fall under nonionising radiation.

Additionally, radiation can also manifest as particles resulting from the interaction of ionising radiation with matter. These particles, including protons, neutrons, and electrons, are even more biologically reactive than radiation rays.

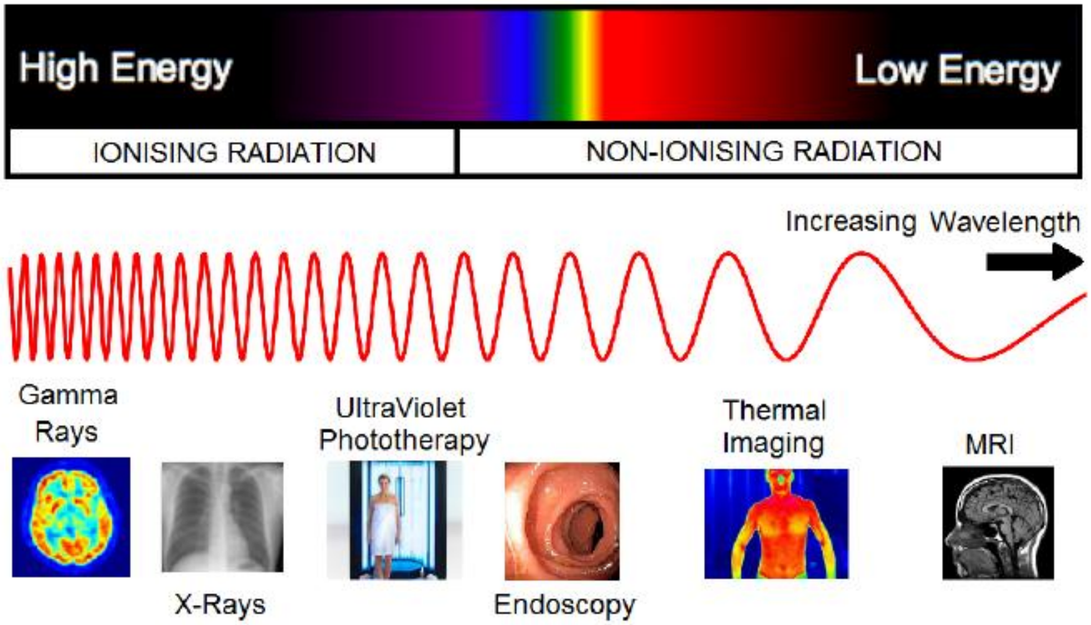


Figure 1: The electromagnetic (EM) spectrum, and applications in modern medicine. Ionising radiation is a term used to describe radiation with enough energy to cause damage to the cells of the human body while non-ionising radiation does not have enough energy to damage cells.

MEASUREMENT OF RADIATION EXPOSURE

When assessing radiation exposure, it's crucial to understand how it is measured and quantified. "Radiation exposure" refers to the potential damage caused by specific types of radiation, considering the sensitivity of biological tissues to that exposure. At its core, the fundamental measure is "absorbed dose," which quantifies the amount of radiation energy absorbed per unit mass (measured in Joules per kilogram, or Gray (Gy)). Another important parameter is "effective dose," derived from the absorbed dose and adjusted by a radiation weighting constant (e.g., 1 for X-rays, 20 for neutrons) and a tissue-weighting constant (e.g., 0.01 for skin, 0.12 for bone marrow). Effective dose is expressed in Sieverts (Sv) and serves as an internationally accepted albeit simplified measure to estimate the biological effects of radiation exposure.

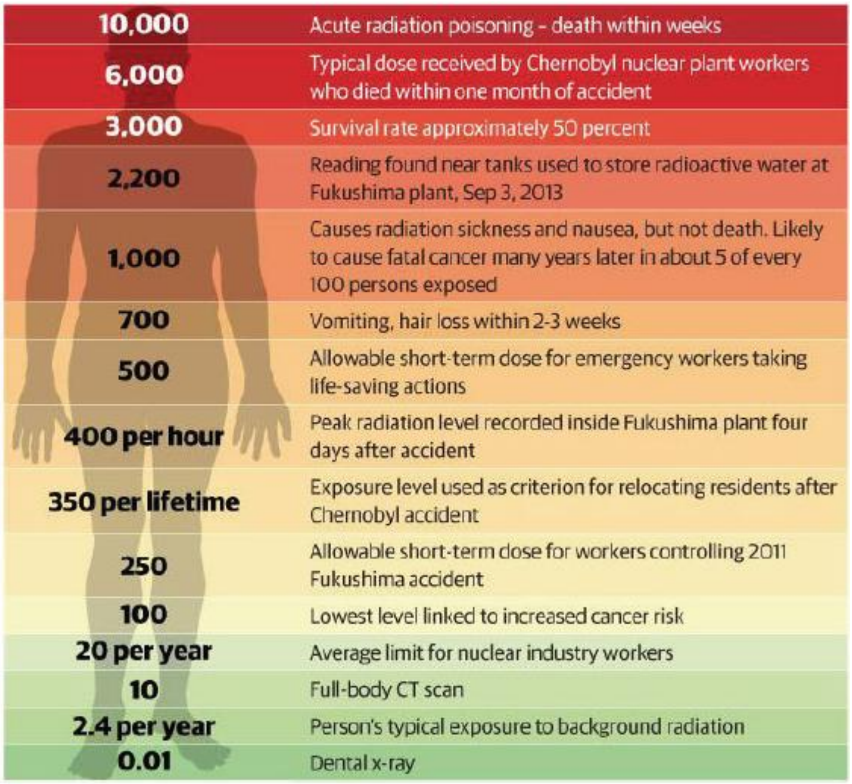
BIOLOGICAL EFFECTS OF RADIATION EXPOSURE

Exposure to ionising radiation can result in two distinct effects known as deterministic and stochastic effects, both of which are relevant to the radiation exposure scenarios of the Hulk and Radioactive Man. Deterministic effects manifest when an individual receives a high dose of radiation over a short period, surpassing a specific threshold where biological damage is certain to occur. Examples include skin reddening (at doses between 2-10 Gy), sterility (at doses above 2.5-6 Gy to the reproductive organs), and cataracts (at doses above 1.5 Gy to the eyes) [8]. Figure 2 summarizes deterministic effects in millisieverts (mSv), representing the effective whole-body dose, accompanied by a severity scale.

For Bruce Banner, estimating the effective or absorbed dose from his gamma ray exposure during the original 1962 comic [3] is challenging. It's noted that he was "many miles from the blast," and since he did not succumb within weeks, it suggests he likely received an effective dose of less than 6000 mSv. Despite radiation dose decreasing with distance from the blast, superhuman strength has not been observed as a side effect thus far.

In reality, individuals exposed to high doses of radiation in a single instance are highly likely to develop acute radiation sickness. Tragic incidents resulting in death from radiation exposure have occurred in accidents at nuclear power plants [9], aboard submarines [10], and through mishandling of radioactive sources intended for medical use [11]. More disturbingly, radiation has been employed for criminal purposes, as seen in the case of Alexander Litvinenko, who was fatally poisoned with highly radioactive Polonium-laced tea at a London restaurant [12]. His death, caused by multiple organ failure three weeks later, starkly illustrates the severe biological consequences of acute radiation sickness. Litvinenko's kidneys and bone marrow received absorbed doses 7-10 times higher than those known to cause critical organ complications [12].

Radiation poisoning commonly results in conditions such as leukopenia (reduced white blood cell count impairing infection resistance), thrombocytopenia (decreased platelet count affecting blood clotting), and aplastic anemia (decreased red blood cell production hindering oxygen transport) [13].



10,000	Acute radiation poisoning - death within weeks
6,000	Typical dose received by Chernobyl nuclear plant workers who died within one month of accident
3,000	Survival rate approximately 50 percent
2,200	Reading found near tanks used to store radioactive water at Fukushima plant, Sep 3, 2013
1,000	Causes radiation sickness and nausea, but not death. Likely to cause fatal cancer many years later in about 5 of every 100 persons exposed
700	Vomiting, hair loss within 2-3 weeks
500	Allowable short-term dose for emergency workers taking life-saving actions
400 per hour	Peak radiation level recorded inside Fukushima plant four days after accident
350 per lifetime	Exposure level used as criterion for relocating residents after Chernobyl accident
250	Allowable short-term dose for workers controlling 2011 Fukushima accident
100	Lowest level linked to increased cancer risk
20 per year	Average limit for nuclear industry workers
10	Full-body CT scan
2.4 per year	Person's typical exposure to background radiation
0.01	Dental x-ray

Figure 2: Summary of deterministic biological damage after radiation exposure to the entire body A very rough estimate would put Bruce Banner's exposure level at less than 6000 mSv (given that he didn't die) (1 milliSv = 0.001 Sv). Figure reproduced with permission [13].

In contrast to deterministic effects, which have a clear threshold of exposure leading to certain biological outcomes, stochastic effects are more challenging to quantify. These effects occur with a probability that increases with dose but never reaches zero, even at very low levels of exposure. This concept is encapsulated in the 'linear no threshold hypothesis' (LNTH), where the likelihood of such effects, like cancer from ionizing radiation or lung cancer from smoking, is considered to rise proportionally with exposure.

Consider the case of Radioactive Man, or Dr. Chen Lu, who subjected himself to ionizing radiation over an unspecified duration. Presumably, he took intermittent breaks during his exposure, allowing his body time to recover between sessions. This approach mirrors how certain organisms adapt to survive in radiation-rich environments like exclusion zones around nuclear accidents [15, 16]. However, if his cumulative effective dose exceeded 100 mSv (see Figure 2), the risk of chronic radiation sickness and cancer would significantly escalate due to sustained high-level exposure. Notably, this kind of exposure claimed the lives of early pioneers in Nuclear Physics such as Marie Curie, Pierre Curie, and Henri Becquerel, who, unaware of the dangers, succumbed to conditions like aplastic anemia directly linked to prolonged radiation exposure [17]. Even today, artifacts like Marie Curie's 1890 notebooks remain radioactive hazards, necessitating special protective measures for handling [17].

RADIATION AND MUTATIONS

When thinking of mutations, it's easy to associate them with superheroes like the Hulk, Radioactive Man, and the X-Men. DNA, the genetic code within every organism, resembles computer code but is vastly more intricate. Ionizing radiation alters this code by damaging atoms within specific segments. Because ionization occurs randomly, various parts of the genetic code can sustain damage during radiation exposure, affecting numerous cells in an organism, which number in the trillions.

After ionization-induced damage, several outcomes can occur: the cell may perish, repair itself, or experience a transcription error. This error means that when the cell divides, it passes the genetic flaw on to subsequent generations of cells. This process is commonly known as "mutation," where each alteration represents an error in the organism's genetic blueprint. Unfortunately, random mutations caused by radiation exposure are not coordinated enough to confer superpowers. Instead, these mutations are generally unpredictable and more likely to result in harmful health effects, as the chances of a random change benefiting the organism are exceedingly slim.

If one were to envision developing superpowers akin to Radioactive Man, a more plausible approach might involve deliberately transferring structured genetic information into cells before birth using specifically engineered stem cells. However, current research primarily focuses on employing stem cells to combat inherited genetic and metabolic disorders, rather than pursuing ethically contentious experiments aimed at creating humans with superhuman abilities.

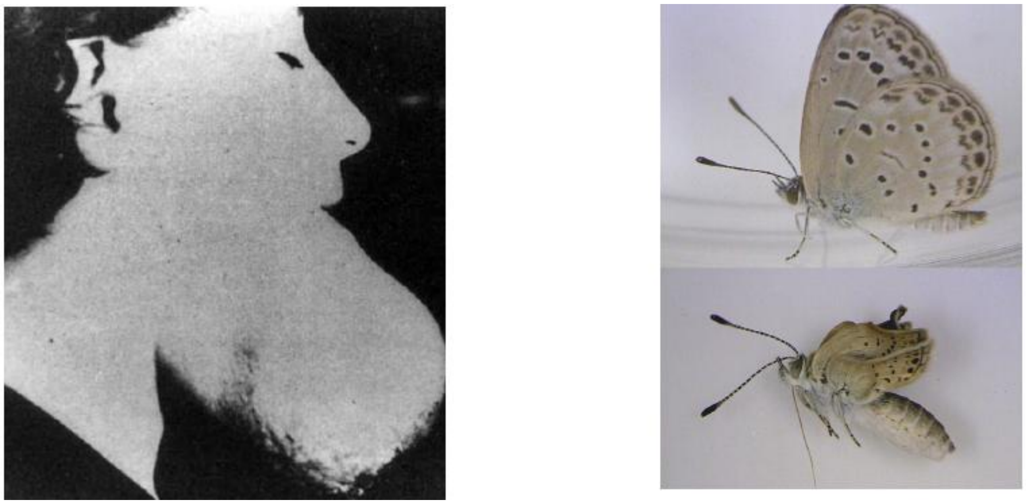


Figure 3: (Left): The resulting damage suffered by one of the "Radium Girls" from ingestion of radium in the 1920s [18]. (Right): Comparison of a pale bluegrass butterfly from the area directly surrounding Fukushima (bottom) and the same species from an unaffected area of Japan (top) [19]. Figures reproduced with permission.

Numerous instances illustrate the lasting impact of radiation exposure on individuals, both evident and unseen. However, none of these cases have resulted in individuals gaining superhuman abilities. Various groups have faced exposure to ionizing radiation from sources such as nuclear weapons testing in Kazakhstan, the United States, United Kingdom, and Russia, as well as from nuclear accidents in Chernobyl (Belarus), Fukushima (Japan), and Three-Mile Island (United States).

A poignant and peculiar example of radiation exposure is the tragic story of the “Radium Girls” employed at clock factories in the 1920s in the United States. These women used what was believed to be harmless self-luminous paint containing radium to paint dials, often licking the paintbrushes to achieve a fine point or even applying the paint as nail varnish. Unbeknownst to them, radium emits ionizing radiation and is particularly hazardous when ingested (at the time, small amounts of radium were erroneously considered beneficial and used in products like toothpaste, milk, and blankets). Over months and years, the women suffered from severe health issues including anemia, disintegration of jawbones, facial abscesses, mouth ulcers, tooth loss, bone cancers, and severe facial deformities due to prolonged radium exposure. These genetic mutations, though not understood at the time, were directly caused by radium. Because humans inherit genetic material from their parents, these mutations were passed down to the women's children through mutated DNA in ovarian stem cells. Even now, a century later, some descendants still experience conditions like syndactyly (fused fingers) and dental and digestive problems initiated by their ancestors' exposure to radium [22].

Flora and fauna also demonstrate vulnerability to the harmful effects of radiation.

In nuclear accident sites like Chernobyl, a variety of animals and insects across different taxonomic groups have shown observable effects such as smaller brains, reduced reproductive capacity, albinism, and eye cataracts [23]. Microbes in these areas exhibit unusual behaviors, and trees display slower growth rates along with abnormalities in growth and deformed pollen [24]. Following the Fukushima nuclear disasters of 2011, mutated butterflies with irregularly shaped wings and bodies have been discovered in the surrounding region, while spiders have been observed constructing ineffective and erratic webs [19]. As animals roam freely in human-abandoned areas, these mutations have the potential to disseminate throughout other populations in the environment.

Unfortunately, for those of us who might wish for superpowers from radiation exposure, the reality is far from promising. Many groups exposed to nuclear weapons, nuclear accidents, or the ensuing radioactive fallout face heightened cancer risks. For instance, cancer rates among adults near Hiroshima and Nagasaki increased by 10%, and childhood leukemia saw a 50% rise [25]. Concerns over the substantial radioactive fallout generated by nuclear weapon tests in the 1960s prompted an international ban on above-ground or surface nuclear testing [26].

FIGHT THE POWER – RADIATON RESISTANCE

In the 1960s, soldiers involved in nuclear tests (like Bruce Banner) faced approximately 14% higher mortality rates from leukemia, 20% higher from prostate cancer, and over 20% higher from nasal cancer compared to soldiers not part of those tests [27].

However, certain less complex organisms exhibit greater resilience to radiation than humans due to various factors. For instance, insects like wasps have a slower cell reproduction rate [28], single-cell organisms such as those that do not undergo division avoid issues with DNA damage, and bacteria possess remarkable abilities to regenerate their DNA even after exposure to high radiation levels [29]. In a recent experiment, Escherichia coli (E. coli) bacteria were subjected to intense radiation until 99% of the population perished, after which a new generation of E. coli was cultivated from the survivors. These new cells demonstrated a DNA repair rate four times faster than their ancestors, showcasing how radiation resistance can be naturally encoded through accelerated bio-adaptive evolution in simpler organisms [30].

The implications of this research for other species are intriguing, particularly if further studies can elucidate how such resistance mechanisms are encoded in DNA sequences. Future research might explore applying these principles to gene therapy aimed at enhancing human resistance to radiation, crucial for scenarios like astronauts who endure radiation doses ranging from 50 to 2000 mSv during sixmonth stays aboard the International Space Station [31]—vital data for future missions to Mars. Additionally, this knowledge could potentially lead to the development of new bacterial strains capable of decontaminating radioactive waste sites such as Fukushima in Japan [32].

ARE LOW DOSES OF RADIATION BAD FOR US?

No, the answer is no. The previous discussion primarily concerns serious health risks associated with high doses of radiation, such as nuclear fallout or explosions. However, when it comes to lower effective doses of radiation (typically less than 100 mSv), the situation becomes more nuanced. The prevailing international assumption is the Linear No Threshold Hypothesis (LNTH), which posits a linear relationship between radiation dose and the severity of biological effects, extrapolated from observations at high doses (refer to Figure 4). Despite applying the LNTH to low-dose regions (under 100 mSv effective dose), epidemiological studies lack robust statistical power to conclusively determine health risks from low-dose radiation exposure. Criticisms of the LNTH persist due to its shaky scientific foundation, though it still forms the basis of legal radiation safety regulations in countries with such legislation [33].

Radioactive Man's acquisition of superpowers after prolonged exposure to small amounts of radiation might not be entirely implausible and has been actively researched. This phenomenon, akin to "radiation hormesis," suggests that low doses of radiation could potentially stimulate beneficial effects by activating the body's repair mechanisms, similar to how vaccines work by strengthening immunity against specific microbes. Proponents of this theory argue that continuous low doses prompt protective responses, whereas high doses overwhelm the body's defenses [34].

The 2015 Nobel Prize in Chemistry, awarded to Tomas Lindahl, Paul Modrich, and Aziz Sancar, elucidated biological mechanisms through which cells repair DNA damage caused by UV radiation during DNA replication, thereby safeguarding genetic information via constant surveillance and adjustment [35]. Thus, there is a hypothesis that small amounts of radiation may not be as detrimental as once thought. However, this conclusion remains uncertain and warrants further investigation.

Despite the common belief that most people will never encounter radiation, we are exposed to varying levels of it daily. Environmental radiation originates primarily from naturally occurring radioactive elements like uranium, thorium, and radon, found in the bedrock beneath us. The amount of radiation one receives from these sources depends on geographical location, as some regions naturally contain higher concentrations of these elements than others.

For instance, individuals in the United Kingdom receive an average annual effective radiation dose of 2.2 mSv [36], while in the United States, it is around 3.0 mSv per year [37]. In China, the natural background radiation is estimated at 2.3 mSv annually [38]. However, there are regions with significantly higher natural radiation levels, such as Ramsar, Iran, where the local population has been exposed to approximately 260 mSv of background radiation each year for centuries [39].

Contrary to the assumption that all radiation exposure is harmful, evidence suggests the concept of radiation hormesis may hold merit. Genetic studies comparing populations from high and normal background radiation areas, such as Ramsar, reveal no significant differences. In fact, studies involving white blood cells from Ramsar residents exposed to high levels of ionizing radiation show fewer chromosome aberrations compared to cells from control groups [39]. This finding challenges earlier notions and aligns with the idea that small, chronic doses of radiation might stimulate adaptive responses within the body.

The notion that Radioactive Man's immunity to radiation, conceived in 1963 before research on radiation hormesis, could have some basis in reality is intriguing. It suggests that continuous, low-level radiation exposure might not necessarily be detrimental and could potentially confer protective benefits.

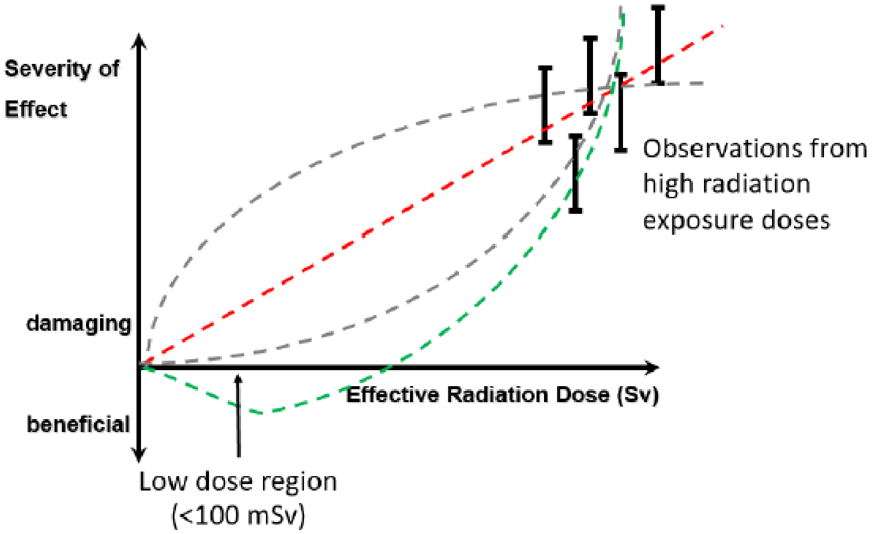


Figure 4: The "linear no threshold hypothesis" of radiation exposure (red line) stating that the severity of radiation exposure at high dose rates can be extrapolated linearly and used to predict radiation effects at lower exposure levels. However many other potential curves may fit the data (grey lines). For example, a case where low levels of radiation are actually good for humans (less severity of effect on the graph) is also included on the graph (green curve). This effect is called "radiation hormesis" [40].

MEDICAL USES OF RADIATION EXPOSURES

Thanks to pioneers like Wilhelm Röntgen, Henri Becquerel, and the Curies, the dual effects of radiation—both beneficial and potentially harmful—have found profound applications in medicine. X-rays, for example, are indispensable in computed tomography (CT) and conventional X-ray imaging, enabling non-invasive visualization inside the human body. Surgeons now routinely perform minimally invasive procedures guided by X-rays, which contribute to shorter hospital stays, reduced infection risks, and faster recovery times [41].

Moreover, the use of radioactive isotopes in imaging and high-energy X-rays in cancer treatment through radiotherapy has become standard practice in hospitals worldwide. Despite the slight increase in cancer risks associated with radiation exposure according to the Linear No Threshold Hypothesis (LNTH), the benefits of precise medical diagnoses and effective tumor reduction significantly outweigh the minimal risks posed by controlled and purposeful radiation exposure.

These advancements underscore the critical balance between harnessing the advantages of radiation in medical contexts while minimizing potential risks, thereby improving patient outcomes and quality of care.

In the realm of medicine, nuclear medicine stands out as a fascinating field closely tied to the concept of Radioactive Man. Here, patients receive injections of radiopharmaceuticals—a blend of a small amount of a radioactive isotope and a pharmaceutical agent. These compounds can be tailored to target specific biochemical pathways within the body, such as receptors found exclusively in tumors or specific organs. Once the radiopharmaceutical accumulates in the targeted tissue, specialized scanners like positron emission tomography (PET) or single photon computed tomography (SPECT) are used to create images showing its distribution [42].

This technology enables clinicians to investigate organ function in diseased states, including processes like glucose metabolism in organs, lung ventilation, brain neurotransmitter activity, and the imaging of various cancer-related proteins and heart metabolism. Moreover, when administered in higher doses, these radioactive agents can be employed to treat different types of cancer by selectively damaging tumor cells while minimizing harm to healthy tissue—a technique known as molecular radiotherapy. In such treatments, absorbed radiation doses to tumors can reach up to 200 Gy [43, 44].

Patients undergoing nuclear medicine procedures can be likened to real-life "Radioactive Men and Women." After receiving radiopharmaceutical injections, they remain radioactive for a period determined by the isotope's half-life. It's not uncommon for patients to carry residual radiation for several weeks after treatment. Despite this, there are no visible effects that they are radioactive—contrary to popular belief, they do not emit a green glow! This demonstrates how advanced medical technologies harness the power of radiation safely and effectively for both diagnosis and treatment, enhancing patient care without the sensationalized effects often associated with radiation exposure.

In radiotherapy, a similar principle applies where specialized machines called linear accelerators (Linacs) deliver high-energy X-rays to patients as part of their cancer treatment. These X-rays are precisely shaped to target the tumor site while minimizing exposure to surrounding healthy tissue. Typically, patients undergo multiple sessions of radiation therapy—sometimes up to 30 sessions over a month—because delivering the entire radiation dose in a single session would cause excessive damage to non-cancerous tissues [45].

Another form of radiotherapy, known as "total body irradiation (TBI)," exposes the entire body to high doses of ionizing radiation. This treatment is used to intentionally suppress the patient's immune system by destroying lymphocytes, a type of white blood cell that fights foreign invaders. This process helps prevent rejection of transplanted bone marrow or blood stem cells [46]. However, TBI also leads to high rates of infertility in both men and women, with only 10-20% of patients recovering proper reproductive function [47].

The scenario of TBI bears a striking resemblance to how Radioactive Man acquired his powers, possibly influenced by the advent of the linear accelerator. In contrast to Radioactive Man becoming impervious to radiation, it is actually beneficial for patients to become more sensitive to radiation over time during treatment, as heightened sensitivity often correlates with a more effective response to cancer therapy.

This highlights the nuanced application of radiation in medical settings, where precise delivery and understanding of its effects are crucial to optimizing treatment outcomes while minimizing adverse effects on patients' overall health.


[redacted]

Figure 5: (Left): A PET scan of a patient showing the distribution of a radioactive tracer for glucose metabolism. The PET scan (in orange) is overlaid onto a computed tomography (CT) scan for anatomical localization. The image shows normal use of glucose in the brain but abnormal distribution in the mouth cavity. Middle – a linear particle accelerator (Linac) used in radiotherapy treatments of cancer. The entire unit rotates around the patient, which allows the X-ray beam to conform to the tumour volume as

accurately as possible. Image courtesy of Varian Medical Systems. (Right): A patient about to undergo total body irradiation (TBI) to greatly reduce their immune system for bone marrow transplant.

CONCLUSION

In the cases of both Radioactive Man and the Incredible Hulk, exposure to ionizing radiation resulted in their damaged DNA reacting in a coordinated manner, granting them abilities far beyond those of ordinary humans. However, in the realm of actual biological effects of radiation on humans, this scenario remains confined to science fiction. The reality of radiation-induced mutations encompasses not only visible physical changes like those observed in the blue grass butterfly and the tragic outcomes suffered by the Radium Girls, but also functional abnormalities such as increased cancer incidence and hereditary effects passed to future generations. Given that DNA in trillions of cells performs diverse functions, its response to radiation varies widely.

Human beings theoretically possess some degree of resilience to radiation due to background exposure from natural sources. Yet, the precise relationship between radiation dose and clinically observable effects remains unclear. Establishing threshold levels of ionizing radiation through clinical trials could provide clarity, but such trials are deemed unethical due to the well-documented harmful effects of high radiation doses and are unlikely to receive regulatory approval. Therefore, the Linear No Threshold Hypothesis (LNTH), depicted in Figure 4, continues to guide global radiation regulation until comprehensive understanding of the effects of low-dose radiation emerges.

In conclusion, radiation serves society in beneficial ways when managed with care and precision, such as in established fields like nuclear power generation, medical diagnostics through nuclear medicine, and critical life-saving procedures like radiotherapy and interventional radiology. While there are some truths to concepts like radiation resistance and hormesis, which are actively researched for potential applications such as enhancing resistance or understanding DNA damage mechanisms, the idea of harnessing ionizing radiation to grant humans superpowers remains firmly in the realm of science fiction for the foreseeable future.

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