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ORIGINAL PAPER

Simulated nuclear contamination scenario, solid cancer risk assessment, and support to decision

**Sergio X. Lima,
Karolina P. S. Costa,
Zelmo R. Lima,
Fagner C. Rother,
Olga M. O. Araujo,
Helio C. Vital,
Tercio Brum,
Wilson F. R. S. Junior,
Jose Carlos C. Amorim,
Matthew J. F. Healy,
Edson R. Andrade**

Abstract. The detonation of an (hypothetical) improvised nuclear device (IND) can generate atmospheric release of radioactive material in the form of particles and dust that ultimately contaminate the soil. In this study, the detonation of an IND in an urban area was simulated, and its effects on humans were determined. The risk of solid cancer development due to radiation was calculated by taking into account prompt radiation and whole-body exposure of individuals near the detonation site up to 10 km. The excess relative risk (ERR) of developing solid cancer was evaluated by using the mathematical relationships from the Radiation Effects Research Foundation (RERF) studies and those from the HotSpot code. The methodology consists of using output data obtained from simulations performed with the HotSpot health physics code plugging in such numbers into a specific given equation used by RERF to evaluate the resulting impact. Such a preliminary procedure is expected to facilitate the decision-making process significantly.

Keywords: improvised nuclear device (IND) • induced cancer • risk assessment • decision

S. X. Lima, H. C. Vital, T. Brum, J. C. C. Amorim
Defense Engineering Graduate Program, Military Institute of Engineering, (IME), Rio de Janeiro, Brazil

K. P. S. Costa, Z. R. Lima
Nuclear Engineering Institute (CNEN/IEN)
Rio de Janeiro, Brazil

F. C. Rother
Institute of Radioprotection and Dosimetry (CNEN/IRD)
Rio de Janeiro, Brazil

O. M. O. Araujo
Nuclear Engineering Graduate Program
Federal University of Rio de Janeiro (COPPE/UFRJ)
Rio de Janeiro, Brazil

W. F. R. S. Junior
Faculty of Engineering, Rio de Janeiro State University and IBRAG, Rio de Janeiro, Brazil

M. J. F. Healy
Cranfield Forensic Institute, Cranfield University and Defence Academy of the United Kingdom
Shrivenham, SN6 8LA, United Kingdom

E. R. Andrade✉
Defense Engineering Graduate Program, Military Institute of Engineering (IME), Rio de Janeiro, Brazil and Nuclear Engineering Institute (CNEN/IEN)
Rio de Janeiro, Brazil
E-mail: fisica.dna@gmail.com

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Introduction

The terms improvised nuclear device (IND) and hypothetical nuclear device (HNED) are both used to describe a potential nuclear bomb created by a terrorist or emerging rogue state. There are significant challenges in HNED procurement and construction; however, it would not be impossible for a terrorist group to produce a nuclear explosion, and it should be considered a genuine threat given that the potential extreme devastation arguably outweighs the low probability that it will occur. Although theft of a functioning weapon cannot be ruled out, in 2005 a group of 85 subject matter experts marginally concluded that a terrorist group would more likely acquire fissile material and then fabricate its own weapon [1]. Should a terrorist group make its own weapon, it is most likely to follow the tested well-documented path of the allied programme during World War II, which gave rise to the two designs detonated at Hiroshima and Nagasaki [2]. The implosion design could use abundant reactor-grade plutonium, but it is a severe technical challenge, whereas the 'gun-type' design is quite simple to construct if highly enriched uranium (HEU) were available.

The availability of fissile material and the access to it through targeted theft or the opportunistic disaffected insider would be a factor in a terrorist's weapon design and potential yield to be faced. The review of fissile material stockpiles by Mian and Glaser [3] looks at the abundance of civilian, as well as the more commonly considered military fissile material. Bunn and Wier discussed in detail the technical challenges that the terrorists face in constructing a weapon and how that may influence their choice of material and weapon design [4].

The Hiroshima 'Little Boy' bomb used the gun--type design where a 38.9 kg cylinder of optimal weapons-grade (>90% ^{235}U) HEU was propelled onto a 25.3 kg plug of weapons-grade HEU at the high velocity of a modified artillery gun [1]. Such an effort required state-level resources and engineering and resulted in the designers being so confident of a sufficient fission yield that would completely destroy the weapon that no full trial was made before dropping the valuable material over enemy territory. This gun design was also chosen by the South Africans during their period of isolation, for their clandestine weapon programme from 1973 to 1991 [5]. The simple implosion weapon has been shown to increase with the spontaneous neutron rate and decrease with increasing assembly speed [6]. Hippel and Marka [7, 8] calculated that the minimum fission yield would be 2.7% of the maximum for the design yield, corresponding to a fizzle yield of about 0.5 kT for a feasible terrorist device, compared to the yields of 15 kT and 22 kT at Hiroshima and Nagasaki. Nation states, including the US, have occasionally delivered sub kiloton yields when testing new designs. Perhaps, the most relevant state test is the 2006 North Korean one whose intended design yield was 4 kT [9], but actually achieved between 0.2 and 0.7 kT [8] and a best estimate of 0.48 kT [10]. Even nations attempting their first explosion may not achieve high yields, especially if the fissile material available is insufficient or if its isotopic composition fails to meet the requirements. Although the yields of nuclear weapons can be overwhelmingly large, there are many credible low yield explosion scenarios where epidemiological effects will be significant among blast and thermal effects.

The scenario under evaluation in this work considers an explosion of an IND at a populated urban site. Although preparedness is the most important phase toward an effective response [11], special attention was drawn to provide fast information about future detriments for the public due to potential radiation exposure and responders. Significant amount of radioactive material is expected to be deposited on the soil after the IND explosion. Therefore, assessment, rescue, and cleanup operations might result in whole--body (external) radiological exposure of personnel that would significantly add to occupational levels [12]. Furthermore, activities related to personnel risk communication should also be considered.

The detonation of an IND can release various radioactive materials in particle and electromagnetic form such as gamma rays. Casualties are primarily caused by blasting and thermal effects and may also be due to exposure to ionizing radiation at high doses. Some time-dependent effects can also occur years later not only due to radiation exposures but also due to other potential carcinogens, such as tobacco and environmental pollution.

This work aims at evaluating the main immediate consequences of an IND detonation over a populated urban area. Using the convergence methodology, different methods are combined, providing means for a fast evaluation of the time-dependent damage due to the blast explosion and also the amount of exposure to ionizing radiation. It is expected that this methodology can contribute to improve the efficiency of the decision-making process when such events occur.

Methods

The consequences of an explosion of an IND might transcend political and economic boundaries [11, 13]. Risk perception and risk communication are major concerns since they are crucial particularly during the initial phase of response. Risk formulation and its communication to the public are complex tasks. In addition, the fact that the decision-making process is often performed when the general public is not able to understand complex situations must be taken into account [14]. According to Greenberg *et al*., the factors that can determine the risk in the context of a radiological or nuclear event are related to the: (a) ability to cause real damage, (b) radiation quantities involved, (c) likelihood of release, (d) dispersion profile, (e) net exposed population, and (f) radiation absorption by the body. All these factors contribute to panic, specially misconception and lack of information. To further complicate things, there are other sources of injuries, such as the blasting, electromagnetic pulse (EMP) and thermal effects from the explosion. Exposed individuals are expected to receive immediate health assistance at the medical triage site.

Risks arising from exposure to ionizing radiation have been studied by the Radiation Effects Research Foundation (RERF) [15–17], which provides technical data to the United Nations Scientific Committee, including the Effects of Atomic Radiation (UNSCEAR) on induced cancer risk for the population and responders. The model estimates the excess relative risk (ERR) of developing cancer as a result of total body exposure to radiation. It has been developed using the epidemiological follow-up of Japanese atomic bomb survivors, the Life Span Study (LSS) showing that the risks of developing cancer for males and females due to the same radiation exposure are different. Consequently, different sex- and age-dependent risks can give rise to different radiation exposure legislations and operational guidance.

Evaluating actual risk in such type of event is a very complex and challenging task mostly due to poor information likely to be gathered from the scenario at first sight. However, by applying a fast and conservative model that is capable of simulating (or replicate) the scenario of interest from a minimum amount of available information, a great deal of valuable data can be generated to assist the decision-making process. In order to find out a way to shortly foresee consequences on public due to the IND explosion, the methodology that includes the use of the HotSpot program and the biostatistical model for radiation effects based on the RERF stand was implemented. This technique, which combines different methodologies targeting a unique objective, has been called convergence methodology.

The HotSpot code uses a semiempirical Gaussian model that quickly provides a first-order approximation of radiation effects associated with the atmospheric release of radioactive materials [18]. For more accurate but time-demanding results, other dispersion models exist such as NAMEIII [19] developed by the UK meteorological office. However, HotSpot is fast, widely accessible, and suitable for the early response stage. HotSpot conservatively evaluates contamination in an affected area and calculates the total effective dose equivalent (TEDE) by accounting for external contributions to the absorbed dose. It is justified because internal contamination is more easily prevented by simple procedures, and dose from external contamination is more in line with emergency triage timescale of convergence methodology. Such data are needed to conduct effective risk assessments and optimize safety [20]. Also, HotSpot was used to simulate the main scenario features and the initial screening not only for radiological releases but also for blasting and thermal radiation. Equations used from RERF were used to estimate cancer development arising from radiation exposure in such a scenario [21, 22].

Modelling techniques

The HotSpot Health Physics Code was used to simulate an IND detonation. The results from simulations performed by HotSpot have been found to be mostly in good agreement with the well-established literature [23]. The radioactive material producing the equivalent radiation dose is considered to be external to the body, and no internal contamination is assumed in this study. In addition, the contamination plume rise can be considered as varying according to the stack emission speed and the differential temperature between the stack effluence and the surrounding air. As the plume rises, lower integrated concentrations can be observed at the ground level.

Scenario

In the computer simulations, an IND (hypothetical IND) is assumed to have been detonated at a crowded area of a city having a population of 2 million people. The electrical power grids are also assumed to have been damaged by the EMP and the major communication systems (land lines, internet, and cell phones) become non-functional. Survivors near the epicenter, ground-zero (GZ), were heavily exposed to radiation and radioactive contamination must also be a source of concern. The distribution and severity of the injuries depend on device yield, height of burst, atmospheric conditions, body orientation, protection afforded by shelter, and the general nature of the terrain. The main parameters chosen for the scenario are as follows: (a) nuclear yield (10 kT), (b) cloud top (8.2 km), (c) cloud radius (2.3 km), (d) cloud bottom (5.1 km), (d) stem radius (0.8 km), (e) wind direction (270 degrees from the West), (f) multistory-upper floor including prompt gamma transmission factor = 0.90, prompt neutron transmission factor = 1.00, fallout gamma transmission factor = 0.01, no weathering correction factor, and ground roughness correction factor = 0.70, and (g) effective wind speed (2 m/s) before detonation.

Simulation and risk modelling

Right after the IND explosion, the most important dose component is gamma radiation, referred to as prompt radiation. The total energy of the initial neutrons and gamma rays is about 5% of the total explosive energy. The effective wind shear (speed and direction) varies with the height of the top and bottom of the stabilized cloud debris. HotSpot fallout predictions assume a fixed wind shear of 15 degrees, and for this simulation we assume an effective wind speed of 2 m/s. Dose calculation due to fallout has been assumed to be independent of the atmospheric stability classification [18, 23].

Initial casualties are mostly due to the blast and thermal radiation. The severity of the physical injuries depends on additional variables such as nuclear yield, height of burst, atmospheric conditions, human body orientation, and sheltering and terrain characteristics. The severity of biological harm due to exposure to ionizing radiation can vary depending on the radiation type. As a consequence, equal absorbed doses due to different types of radiations may produce different biological effects [18]. In this work, radiation doses are taken as an equivalent dose, which is expressed in sieverts (Sv).

Basically, two sets of models can be used for evaluating radiation risks under an epidemiological perspective. The first one is based on generalized relative risk models fitted to the Japanese atomic bomb survivor LSS mortality data by the Committee of the Biological Effects of Ionizing Radiations (BEIR) [24]. The second one focused on the generalized relative and absolute risk model fitted to the Japanese LSS incidence data by the RERF [15, 25]. It has been used by the UNSCEAR [26] in the assessment of cancer risk in populations. The RERF model was used in this study because the focus was on the incidence of morbidity. The models are being continuously tested by researchers worldwide in an effort to generate additional improvements to the models [27].

The term ERR is commonly used in epidemiological studies being a regression model that can be used to evaluate the risk for different end points. In general, ERR represents a risk comparison between exposed and unexposed individuals regarding incidence in this study. The data assume that the bone marrow dose remains below the mean lethal dose for humans, $LD_{50/30}$ (~4 Sv) the whole-body exposure of gamma rays to kill 50% of the individuals within 30 days. This approach considers the fact that 50% of the population exposed to a whole-body dose of 4 Sv is expected to survive [28]. The model used by RERF fits data for all solid cancers as a group [29]. In this study, such equation from RERF was modified to calculate ERR instead of RR (Eq. (1)). The baseline value was considered as the unit for simplification purposes since this work addresses a fictitious population and not a real epidemiological scenario. This procedure does not change the shape of the risk-based curves.

$$\text{ERR}(D,s,e) = \alpha_s D \exp(\beta(e - 25)) \quad (1)$$

where α_s [Sv^{-1}] (male = 0.45, female = 0.77) is the age-specific linear ERR per Sv, s is the sex, D is the dose (RBE for neutrons = 10), e is the age at exposure time in years, and β (age-at-exposure effect = –0.026 for both male and female) is the coefficient accounting for the modifying effect of age at exposure time. The equation is limited to the whole-body radiation dose of 4 Sv, which is the estimated $LD_{50/30}$ for humans [29].

By evaluating the effects of age and sex on the risk emerging from the scenario, the ratio (R) between male and female ERR ($R = ERR_M/ERR_F$) was determined. Therefore, the parameter R can assume the following values: (a) $R > 1$, (b) $R = 1$ and (c) $R < 1$. The cases with $R < 1$ suggest that the ERR_F is more impacting on decision-making for a specific location. The same rationale can be applied for the cases with $R > 1$, suggesting greater importance for ERR_M. Considering the locations where $R = 1$, both ERR_M and ERR_F would identically influence the decisions to be taken based on the risk perspective of all forms of solid cancers. The ERR variations and their impacts on decisions for any location can be observed in the light of the standard deviation (SD) applied to the age distribution for each sex at a specific location. The SD may be useful for the decision makers as the qualifier for ERR distribution at a particular location. The SD may be valuable for evaluating the age susceptibility to risk.

Results

Blast effects

Casualties due to blast effects may occur in several ways. Direct action of the wave pressure, impact of fragments, and whole-body translation facing toward the epicenter can be fatal. Blasting destructiveness is characterized by its overpressure peak and duration of the positive pressure wave (or impulse). The explosion of the IND can produce 100% lethality within a distance of 0.27 km from GZ. Damages to ear drum and lung, besides injuries associated with shattered window glasses, might occur up to a distance of 4.1 km.

Thermal radiation effects

Damage from burning might be due to the absorption of thermal radiation energy by the skin and heating or ignition of clothing as side effects of air blasting. Eyes exposed to thermal wave can permanently become blind, especially at night when the diameter of the pupil is increased. Even at daytime, such explosion may produce temporary flash blindness from scattered light up to a distance of 22 km. Individuals who directly view the initial fireball could experience retinal burns up to a distance of 23 km. Unprotected individuals might experience third-degree burns when located up to a distance of 1.4 km from GZ.

Electromagnetic pulse

The EMP range for the simulated IND detonation was calculated to be approximately 4 km. This range is the outer extent that any EMP effects are expected to occur. Not all equipment within the EMP-effects circle will fail. The amount of failure will increase such that the closer to GZ the equipment is located, the larger the effects will be on its antenna. In addition, such effects largely depend on the sensitivity of the equipment to EMPs. Solid-state devices are more sensitive than vacuum tube devices. Least affected by EMP are electromechanical devices such as electric motors, lamps, heaters, etc. Cell phones and hand-held radios have relatively small antennas and if they are not connected to electrical power supplies during the EMP pulse, they are likely not to be significantly affected by the EMP.

The effects of an EMP occur at the instant of the nuclear detonation and end a few seconds later. Thus, equipment damage is expected to happen only within that short period of time. Electronic equipment entering the area after the detonation will function normally as long as they do not rely on previously damaged equipment, e.g., repeaters, power supplies, etc. Table 1 summarizes the main effects other than radiological.

Ionizing radiation effects

Prompt ionizing radiation consists of X-rays, gamma rays, and prompt neutrons. Unprotected individuals might receive doses associated with a 50% chance of lethality within weeks up to a distance of 1.4 km from GZ. The mortality rate is 100% on the first day for those located up to 0.3 km from GZ. Additional deaths might occur within the following weeks. Delayed ionizing radiation is produced by fission prod-

Table 1. Main effects of the IND other than radiological

Distance from GZ [km]	Major effects
0.27	100% death
1.25	Third-degree burns
4.09	Ear drum and lung damage
22.00	Temporary blindness
23.00	Retinal burns
4.00	EMP pulse range

EMP – electromagnetic pulse. GZ – ground-zero. IND – improvised nuclear device.

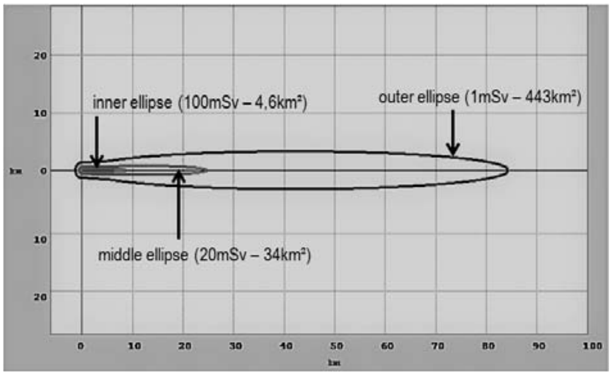

Fig. 1. The simulated radiation profile of the inner, middle, and outer ellipse (plume) from HotSpot codes showing the external dose after the first week due to fallout ground deposition. Wind direction 270 degrees from the West with effective wind speed of 2 m/s.

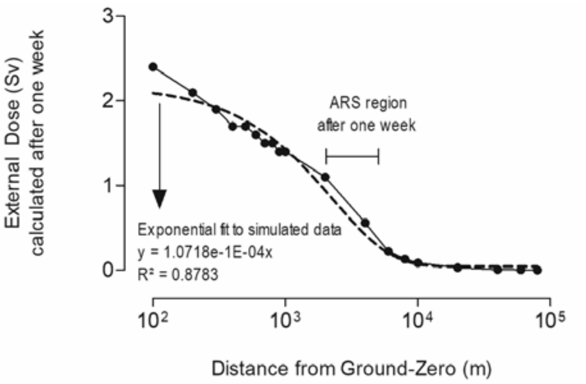

Fig. 2. The simulated dose distribution along the straight line from the ground-zero 1 week after the event. The exponential fit of the representative curve is also shown in dotted line.

ucts and neutron-induced effects on the surrounding materials. As the contaminated cloud travels, the radioactive material falls down on the ground, creating a footprint of contamination (fallout). Exposure to fallout is the dominant source of radiation exposure, and absorbed dose is the quantity used in this work. Unprotected individuals remaining in the contamination zone up to a distance of about 5 km during the first hour might absorb fallout dose with 50% chance of lethality within weeks. Figure 1 shows the simulated radiation profile from HotSpot. The ellipses are calculated with basis on the contour values assumed as follows: (a) inner (100 mSv), normally accepted value for emergency starting limit; (b) middle (20 mSv), occupational annual limit for workers, and (c) outer (1 mSv), average radiation exposure limit for public.

Figure 2 shows the simulated dose distribution along the straight line from the GZ.

Calculations for all solid cancer developments are shown in Fig. 3 according to Eq. (1). Results show differentiated ERR for males (Fig. 3A) and females (Fig. 3B) for the first week of the IND event. Figure 3C shows the ERR/Sv ratio (male/female), and Fig. 3D refers to the SD for the ERR/Sv ratio.

In addition, inspection of Figs. 3A and 3B allows one to conclude that children and females seem to be at higher risks in all circumstances when compared to adult males. This trend is in agreement with the findings from the Nuclear Research Council background for this sort of event [30]. The ERR ratio is presented in Fig. 3C as well as the SD profile, which is shown in Fig. 3D. Exposure to whole-body radiation doses from natural radiation sources diminishes the importance of dose-response relationship for very small doses that will ever be confused with the background doses. As rates become moderately above the background, a linear relationship between dose and likelihood of a deleterious effect may be a suitable approximation whatever the form of the relationship between dose and risk [31].

Discussion

The effects on the area affected by the explosion of the IND have spatiotemporal dependence [18, 23]. Initially, there is the immediate risk involving the mechanical consequences of the explosion and affecting both the physical structures as any equipment dependent on electricity. Table 1 shows that serious human deleterious effects may occur up to a distance of 23 km from GZ. All distances are referred to GZ.

After the mechanical effects of explosion, the effects of environmental contamination by radioactive elements in the environment now and overlapping the material damage ending up to a poisoning scenario to not only humans as itself but also the local food chain are considered. Calculation shows that the exposed individuals subjected to higher doses of radiation are located up to 0.27 km, and so the redemption of shares must be to withdraw immediately survivors of the area and provide comfort and palliative care.

For those located between 2 and 4 km have chances of survival, even if they have been exposed to higher levels of radiation exceeding 4 Sv whole--body exposure. Screening these individuals should consider this condition and refer to treatment considering potential evolution of clinical conditions of acute radiation syndrome (ARS). The damage to the bone marrow and depletion of peripheral circulating lymphocytes from ARS begin typically with an acute whole-body exposure on the order of 0.7 Sv [32].

The results provided in Fig. 1 provide valuable information on likely geographical limits, the radiological exposure profile, and the estimated areas potentially affected by contamination plumes. It is important to notice that this study matches a 10 kT nuclear explosion with superimposed mechanical, thermal, and electromagnetic effects. These effects have a negative impact for any location until 4 km in a straight line downwind from the GZ triggering point (Fig. 1). Therefore, any measure that is necessary within this geographical limit should consider a worsened environment response. Such an allocation might include the phenomena of simultaneous injuries due to radiological and mechanical effects combined.

An important variable can be inferred from the curve shown in Fig. 2. The evaluation of the external dose profile due to the fallout phenomenon is of value for determining geographical limits and priorities during the initial phase of the response. All risk evalu-

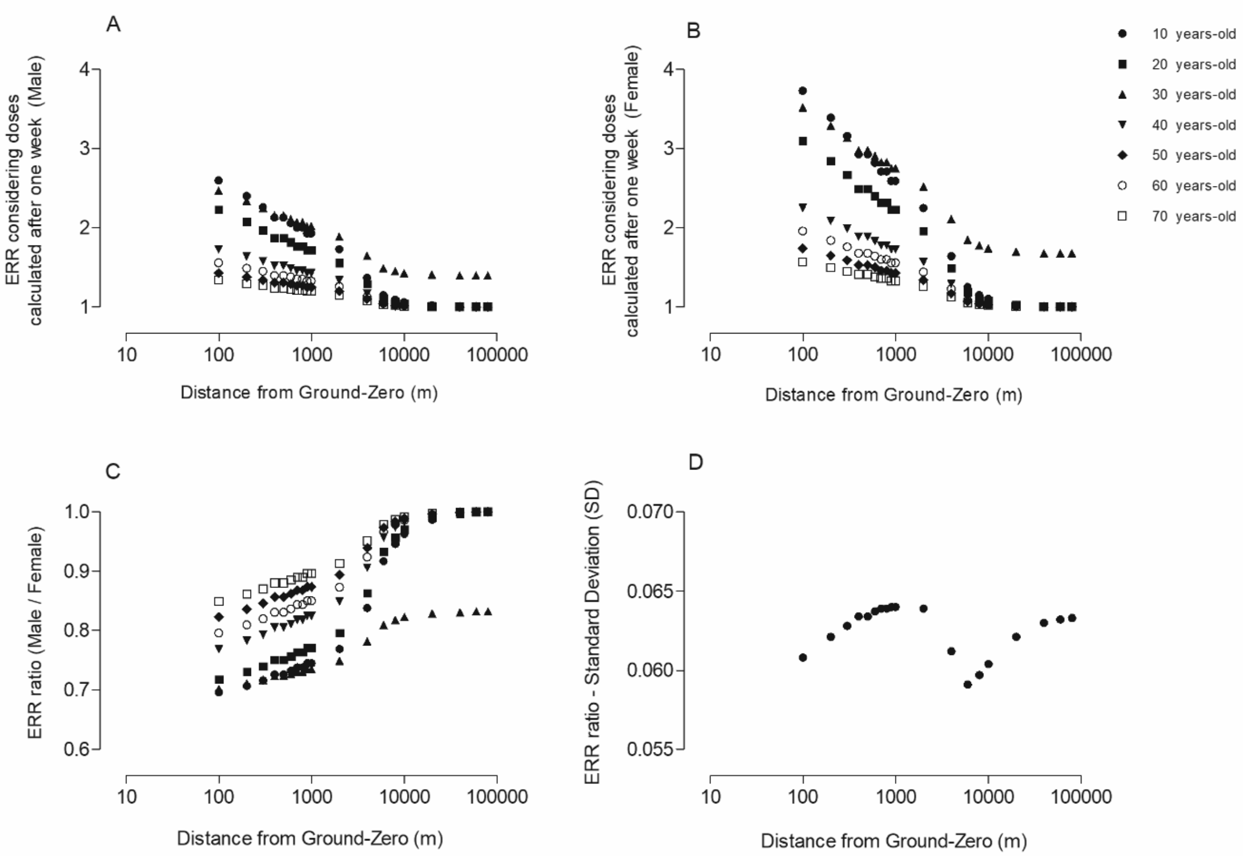

Fig. 3. Excess relative risk (ERR/Sv) for all solid cancers as a function of age (10–70-year old), sex, and distance from ground-zero (GZ). (A) and (B) refer to ERR/Sv considering doses calculated after 1 week for males and females, respectively. (C) shows ERR/Sv ratio (male/female) and (D) refers to the standard deviation (SD) for the ERR/Sv ratio.

ations may come from this first-level information. Additionally, the best exponential fit of the representative curve for the simulated data is also shown in Fig. 2.

According to Figs. 3A and 3B, there are differences for risk coefficients considering sex and age, most significantly for young women and children. The difference in risk between men and women is no longer significant for distances above 10 km. People who were located in this area (up to 10 km) should be recorded and included in follow-up epidemiological studies. These data may provide insights for targeting efforts in epidemiological monitoring programs.

From the personnel teams' perspective, risk assessment should be more rigorous. Qualified personnel seconded to the response to the scenario, in addition to meeting the stricter legislation, needs to work on radiation field at various levels of contamination and exposure, being exposed to risks that overlap. The results shown in Figs. 3A and 3B may positively impact the response team's strategy with respect to sex and age appearing as an additional occupational risk factor. Thus, depending on the location determined for a task to be performed, the team members could be selected by taking into account such specific vulnerabilities aiming at reduced occupational risk in accordance with the As Low As Reasonably Achievable (ALARA) principle [33].

Figure 3C shows that the contribution of age and sex loses strength as the sites of interest are increasingly further away from GZ. However, this fact does not seem to occur for 30-year-old individuals or near. Considering locations above 4 km away from the GZ, the R curve tends to approach asymptotically the value $R = 0.8$ instead of 1. This behaviour suggests that female subjects are under higher threatening and priority should be given to young adult women in such locations. Such an information can be valuable for not only triage purposes but also response team assembling. Following the interpretation criteria assumed for R, such cases with $R < 1$ suggest that the ERR_F is more impacting on decision-making. Therefore, for this specific location, a potential further implication on triage and response team assembling may take place with potential impacts on logistics.

The SD profile from Fig. 3D shows the SD calculated for the R values. The maximum and the minimum values of the SD curve can be valuable by suggesting limits of attention to be drawn regarding age and sex relevance to the response at a certain location.

The use of the proposed convergence methodology is expected to provide important information that could greatly facilitate the initial response, helping mitigate the harm to exposed individuals and responding personnel with improved efficiency and at lower costs as it is a very important issue from the long-term perspective [12]. Additionally, the simulations are also capable of providing radiological risk estimates, which can also be valuable for future decisions based on the studies of epidemiological monitoring.

Conclusions

The results further hint at the possibility of harmonic integration of different approaches (HotSpot and RERF) aiming at improving the simulation as well as the support to the decision-making process in case of an IND event. The proposed methodology can also provide support for optimizing radioprotection procedures during the initial phase. Additionally, it is important to highlight that the ERR is just an assumed prediction of radiation risk based on the exact model. A different risk model approach may drive to a different dose-response output. Further detailing and improvements are needed but the preliminary results indicate that there are indeed interesting ways to use in combination different capabilities to obtain an optimized joint response aimed at decision-making support for a radiological scenario.

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