Gender and Ionizing Radiation

Towards a New Research Agenda Addressing Disproportionate Harm

AMANDA M. NICHOLS • MARY OLSON

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Notes

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About the Authors

Amanda M. Nichols

Postdoctoral Researcher, University of California, Santa Barbara

Amanda M. Nichols, PhD, is a Postdoctoral Researcher in the Environmental Studies Program at the University of California, Santa Barbara. Nichols received her PhD in 2021 from the University of Florida. Her dissertation research focused on illuminating the role of women in the North American anti-nuclear movement and assessed whether ethical perspectives, informed by different social and religious ideologies, shaped their environmental perspectives and activism. Her ongoing research examines the histories and futures of nuclear technologies with an emphasis on the social and environmental justice implications of those technologies as we look to a climate insecure future. Nichols is the author of several book chapters and peer reviewed journal articles, including "Nuclear Energy" (Routledge, 2025); "Uranium and Religion: Toward a Decolonial Temporality of Extraction" (Religions, 2024); "Karen Coulter and the Religious Roots of Radicalism in North America" (*Journal of Radicalism*, 2023); and "Gender" (Routledge, 2023).

Mary Olson

Founder, Gender and Radiation Impact Project

Mary Olson is the founder of the non-government organization Gender and Radiation Impact Project. Olson holds a degree in Evolutionary Biology and has been an educator on radiation health impacts while serving nuclear-impacted communities. She has also been relied upon by States for independent counsel on radioactive waste policy. She served from 1991 to 2019 as Staff Biologist and Senior Radioactive Waste Policy Analyst at the US-based Nuclear Information and Resource Service, a non-government organization. Olson has been invited to speak at several high-level conferences on nuclear weapons, including the Vienna Conference on the Humanitarian Impacts of Nuclear Weapons (2014 and 2022) and the Nuclear Non-Proliferation Treaty Review conferences (2010 and 2015), among others.

Acronyms & Abbreviations

ABCC	Atomic Bomb Casualty Commission
BEIR VII	Biological Effects of Ionizing Radiation VII
CVD	Cardiovascular Disease
ICRP	International Commission on Radiological Protection
LSS	Life Span Study
NAS	National Academy of Sciences
NRC	National Research Council
TPNW	Treaty on the Prohibition of Nuclear Weapons
NPT	Non-Proliferation Treaty
UN	United Nations
UNIDIR	United Nations Institute for Disarmament Research

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Executive Summary

The detonation of a nuclear weapon in a populated area would cause devastating harm: it can kill thousands of people instantly, whether through the explosion itself, or through the intense heat and high levels of radiation. The mid- and long-term consequences from radiation exposure are less well understood, in part because they manifest differently for male and female survivors.

Robust evidence of differentiated health impacts emerged in 2006, when the US National Academy of Sciences published *Biological Effects of Ionizing Radiation VII* which reported 60 years of data from the Life Span Study of atomic bomb survivors of Hiroshima and Nagasaki.

Nearly 20 years after the publication of that report, this report speaks to the extent to which new evidence has been published regarding the correlation between harm from exposure to ionizing radiation and biological sex.

This report concludes the following:

- The post-2006 radiation research reviewed in this report provides clear evidence that radiation causes more cancer, heart disease, and stroke in women compared to men.
- Several studies present evidence that supports the hypothesis that a higher percentage of reproductive tissue in the female body could be one contributing factor to the greater rate of harm from radiation exposure in females compared to males.
- In addition to biological sex, some studies suggest that age at time of exposure may be an important factor in assessing radiation outcomes.
- Girls (ages 0–5 years) are the most at risk post-birth lifecycle stage for developing cancer and non-cancer related health consequences over the course of the lifetime from exposure to ionizing radiation.

These findings are important for discussions about nuclear non-proliferation and disarmament, given that sex-specific and gendered impacts of nuclear weapons are a prominent topic during the meetings of the Nuclear Non-Proliferation Treaty and the Treaty on the Prohibition of Nuclear Weapons.

More research is needed, however, that takes seriously the ways that age and intergenerational impacts inform discussions about radiological harm. This report concludes with an outline of a future research agenda and suggests research questions applicable across a number of disciplines and lines of inquiry.

1. Introduction

The detonation of a nuclear weapon in a populated area is known to cause devastating harm: it can kill thousands of people instantly, whether through the explosion itself, or through the intense heat and high levels of radiation. The mid- and long-term disease outcomes from radiation exposure are less well understood, in part because they manifest differently for male and female survivors.

Robust evidence of differentiated health impacts became available in 2006, when the US National Academy of Sciences (NAS) published *Biological Effects of Ionizing Radiation VII* (henceforth BEIR VII) which reported 60 years of data from the Life Span Study (LSS) of atomic bomb survivors of Hiroshima and Nagasaki.[1] The reported data evidenced disproportionate harm to girls and women from ionizing radiation exposure. Independent analyses of the BEIR VII data by Makhijani et al.[2] and Olson[3] showed that radiation harms female bodies more than males, particularly in childhood.

This knowledge, which was first reported widely in the BEIR VII report, has since informed discussions about nuclear disarmament, non-proliferation, and the peaceful use of nuclear technologies. Sex-specific and gendered impacts of nuclear weapons was a prominent topic during the conferences on the humanitarian consequences of nuclear weapons which led to the establishment of the Treaty on the Prohibition of Nuclear Weapons (TPNW) in 2017. The preamble of the TPNW acknowledges, without qualification, that nuclear weapons "have a disproportionate impact on women and girls, including as a result of [exposure to] ionizing radiation."[4]

In this report, we offer an overview of research published since the 2006 BEIR VII report that contributes additional evidence of the correlation between harm from exposure to ionizing

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1 NAS-NRC, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII – Phase 2* (National Academies Press, 2006), **http://www.nap.edu/openbook.php?isbn=030909156X**; see also NAS-NRC, "National Research Council – Committee on the Biological Effects of Ionizing Radiations: Health Effects of Exposures to Low Levels of Ionizing Radiation: BEIR V" (National Academy Press, 1990), **http://www.nap.edu/openbook.php?isbn=0309039959**.

2 Arjun Makhijani et al., "Science for the Vulnerable: Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk," Institute for Energy and Environmental Research (19 October 2006), **https://ieer.org/wp/wp-content/uploads/2006/10/Science-for-the-Vulnerable.pdf**; Arjun Makhijani et al., "Healthy from the Start: Building a Better Basis for Environmental Health Standards – Starting with Radiation," *Science for Democratic Action* 14, no. 4 (2007): 1–12, **https://ieer.org/wp/wp-content/uploads/2012/01/SDA-14-4.pdf**.

3 Mary Olson, "Disproportionate Impact of Radiation and Radiation Regulation," *Interdisciplinary Science Reviews* 44, no. 2 (2019): 131–39, **https://doi.org/10.1080/03080188.2019.1603864**; Mary Olson, "Atomic Radiation is More Harmful to Women," Nuclear Information Resource Services (2011), **https://www.nirs.org/wp-content/uploads/radiation/radhealth/radiationwomen.pdf**.

4 See "Treaty on the Prohibition of Nuclear Weapons," United Nations General Assembly, 7 July 2017: 1, **https://documents.un.org/doc/undoc/gen/n17/209/73/pdf/n1720973.pdf**. Although the term "survivor" is generally preferred over the term "victim," many of the key international instruments use the latter (see e.g., victim assistance in "Draft Vienna Action Plan," First Meeting of the States Parties to the Treaty on the Prohibition of Nuclear Weapons, 22 June 2022: 1–8, **https://documents.unoda.org/wp-content/uploads/2022/06/TPNW.MSP_.2022.CRP_.7-Draft-Action-Plan-new.pdf**.

radiation and biological sex. We examined a sample of extant research to understand whether, and if so to what extent, further research since the 2006 BEIR VII report has been conducted to verify, engage, or refine the findings that girls and women are more at risk of harm from ionizing radiation exposure.

We found that the literature that presented data about radiation harm disaggregated for biological sex was far more extensive than anticipated. Through our review, we identified two critical updates in post-2006 peer reviewed radiation research:

1. Several studies present evidence that supports a hypothesis made by Dr. Rosalie Bertell that a higher percentage of reproductive tissue in the female body could contribute to a greater rate of harm from radiation exposure in females compared to males.[5,6]
2. In addition to biological sex, some studies suggest that lifecycle stage may be an important factor in assessing radiation outcomes.[7]

It is important to note that the research findings are part of a much larger body of literature, not all of which was reviewed here. Further research is needed to support and verify these findings. Although many studies have begun to disaggregate data based on biological sex, there is still a prevalent gap in terms of the amount of extant radiation research that looks at biological sex as a factor in radiation harm.

In what follows, we provide an update on the findings on the correlation between harm from exposure to ionizing radiation and biological sex. After giving a brief overview of the background and framing of this discussion, we provide a review of a sample of post-2006 literature that has addressed questions pertaining to the correlation between harm from exposure and biological sex. The research methodology and the peer reviewed articles we examined are detailed in appendices A and B, respectively. In section 4, we provide an update on the findings and a brief analysis of the ongoing discussion about radiological protections. These findings speak to the need for future research to engage with the question of how biological lifecycle stages are impacted by radiation exposure in humans. We offer some broad questions in section 5, which we hope will help guide and inspire future radiation research and radiological protection standards.

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5 See, e.g., D. L. Preston et al., "Cancer Incidence in Atomic Bomb Survivors. Part III. Leukemia, Lymphoma and Multiple Myeloma, 1950–1987," *Radiation Research* 137 (1994): S68–97, **https://pubmed.ncbi.nlm.nih.gov/8127953/**; Kotaro Ozasa et al., "Studies of the Mortality of Atomic Bomb Survivors, Report 14, 1950–2003: An Overview of Cancer and Noncancer Diseases," *Radiation Research* 177, no. 3 (2012): 229–43, **https://doi.org/10.1667/RR2629.1**; Mai Utada et al., "Radiation Risk of Ovarian Cancer in Atomic Bomb Survivors: 1958–2009," *Radiation Research* 195, no. 1 (2021): 60–65, **https://doi.org/10.1667/RADE-20-00170.1**; Nadia Narendran et al., "Sex Difference of Radiation Response in Occupational and Accidental Exposure," *Front Genet* 3, no. 10 (2019): 260, **https://doi.org/10.3389/fgene.2019.00260**.

6 Rosalie Bertell, "A New Understanding of Breast Cancer and Alternatives to Mammography," *Canadian Woman Studies* 28, no. 2–3 (2010): 10–17, **https://cws.journals.yorku.ca/index.php/cws/article/view/31485/28909**.

7 See, e.g., Ozasa et al., "Studies of the Mortality," 2012; Utada et al., "Radiation Risk," 2021; D. L. Preston et al., "Studies of Mortality of Atomic Bomb Survivors. Report 13: Solid Cancer and Noncancer Disease Mortality: 1950–1997," *Radiation Research* 160 (2003): 381–407, **https://doi.org/10.1667/RR3049**.

2. Main Concepts

2.1 Ionizing Radiation

A brief explanation of ionizing radiation and how it affects the human body is necessary to understand the complexities of radiation research. Ionizing radiation is radiation that has enough energy to cause atoms or molecules to gain or lose electrons. This happens through a process called ionization, whereby an atom or molecule acquires a positive or negative charge and therefore becomes a charged particle called an ion. Ionization is the result of the decay of a radioactive atomic nucleus, which causes the emission of energy that takes the form of waves (i.e., gamma rays and photons) or particles (i.e., alpha and beta). These emissions knock electrons into other materials, which creates ions. This emission of energy is called radioactivity, and when it directly impacts materials (living or non-living) it is called radiation exposure.[8]

Ionizing radiation can harm the body in two ways. First, in large amounts, it can directly destroy cells through immediate physical effects such as radiation burns or acute radiation syndrome. These harms are evident in cases of high levels of radiation exposure, such as those that occur in the immediate aftermath of a nuclear detonation. Second, ionizing radiation (including at lower levels) may cause damage and mutations to DNA. If not repaired, this damage can result in stochastic, or random, effects including infertility, cancer, cardiovascular disease, and genetic effects. Although these stochastic effects can, in some cases, appear soon after exposure, they are most often not observed until many years later. While it is impossible to assess direct causality or compounding factors that contribute to specific medical conditions (i.e., cancers, heart attacks, etc.), evidence from the ongoing LSS shows that some people are still dying as a result of the exposure to ionizing radiation they received in the 1945 nuclear bombings on Hiroshima and Nagasaki.[9]

2.2 Biological Sex and Gender

We use the term "biological sex" to refer to the binary (male or female) assignment made by the LSS researchers and other research groups cited in this report. None of the papers reviewed contained any discussion of non-binary individuals or self-assignment of sexual identity.

It is important to acknowledge the various problems that this approach raises. The use of "biological sex" presumes a binary model of the sexes whereby intersex individuals born with phenotypic ambiguity in their sex organs or chromosomal combinations other than XX or XY (about 1.7% of the global population)[10] are either misrepresented or not represented in the dataset.

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[8] For more information about ionizing radiation, see appendix 2 on radiation terminology in J. Borrie and T. Caughley, *An Illusion of Safety: Challenges of Nuclear Weapon Detonations for United Nations Humanitarian Coordination and Response* (2014): 86–87, https://unidir.org/publication/an-illusion-of-safety-challenges-of-nuclear-weapon-detonations-for-united-nations-humanitarian-coordination-and-response/.

[9] Borrie and Caughley, *An Illusion of Safety*, 2014: 86–87.

[10] See Office of the United Nations High Commissioner for Human Rights, "Intersex People: OHCHR and the Human Rights of LGBTI People," (2024), https://www.ohchr.org/en/sexual-orientation-and-gender-identity/intersex-people.

In most cases, biological sex of research participants is assigned by the researcher with little, if any, consideration for gender self-identification. A binary framing of biological sex points to gaps in our current scientific research methods. Marginalization and exclusions are perpetuated, reinforced, and exacerbated when individuals that do not fit into the binary model are not represented in the data.

Biological sex is also often uncritically conflated with gender (woman/man), or "the various meanings that modern society attaches to individuals based on the ways that they look, act, dress, and perform."[11] This is an important distinction, in part because, as Whitney Bauman and Heather Eaton have written, "bodies matter" because they "shape how we experience the world."[12]

Some researchers have begun to explore how socially constructed characteristics and relationships have informed differentiated experiences with nuclear technologies. Author of this report, Amanda M. Nichols, for instance, has explored the important role of the use of gendered language in framing nuclear discourses.[13] Nichols has also written at length about the role of women in the North American anti-nuclear movement and how socially constructed gender norms informed their lived experiences and their activism.[14] Dalaqua et al. have also noted the cross-cultural tendency to blame women for sterility and genetic mutations related to nuclear bombings and accidents, even though, "in the general population, infertility problems tend to affect males and females at virtually equal rates."[15] Dalaqua et al. further noted that socially constructed beliefs about women, their bodies, "marriage, [and] reproduction seem to contribute to the intensified discrimination experienced by women exposed to radiation."[16]

These brief examples demonstrate how the category of "biological sex" interacts with notions of gender that are prevalent in a given society at a given time. Alert to the important distinctions between biological sex and gender, and to the various problems with imprecisely conflating terminology, we mark a clear distinction in the use of the terms "women" and "female" (and "men" and "male," respectively) in this report. We have retained the use of the terms female and male when discussing data specifically from peer-reviewed scientific research that uses the binary biological sex model. In all other cases, we use the terms "women/girls" and "men/boys" respectively, aware of the limitations of this terminology and the various problems with these binary categories and the socially constructed meanings that inform them.

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11 Amanda M. Nichols, "Gender," in *Grounding Religion: A Field Guide to the Study of Religion and Ecology*, volume 3, ed. Whitney A. Bauman, Richard Bohannon, and Kevin J. O'Brien (Routledge, 2023): 73.

12 Whitney Bauman and Heather Eaton, "Gender and Queer Studies," in *Grounding Religion: A Field Guide to the Study of Religion and Ecology*, volume 2, ed. Whitney A. Bauman, Richard Bohannon, and Kevin J. O'Brien (Routledge, 2017): 56.

13 Nichols, "Gender," 2023; Amanda M. Nichols, *Women on the Edge of Time: Grief and Power in the Nuclear Age*, (PhD Dissertation, University of Florida, 2021); see also John Wills, *Conservation Fallout: Nuclear Protest at Diablo Canyon* (University of Nevada Press: 2006).

14 Nichols, *Women on the Edge of Time*, 2021.

15 See Renata Hessmann Dalaqua et al., "Missing Links: Understanding Sex- and Gender-Related Impacts of Chemical and Biological Weapons," United Nations Institute for Disarmament Research (2019): 6, **https://doi.org/10.37559/WMD/19/gen1**.

16 See Dalaqua et al. "Missing Links," 2019: 6.

We make this distinction foremost because it is critical to acknowledge that there are both biological *and* social factors that inform disproportionate impacts of nuclear technologies. Despite these important distinctions, radiological exposures have been, and continue to be, understood as consistent for all individuals, no matter the age, biological sex, or other contributing factors. The question about disproportionate impacts is critical because different bodies bear the brunt of environmental and radiological hazards differently.

We find the terminology “women/girls” and “men/boys” fitting, in part, because our research is focused exclusively on human populations and does not consider disproportionate impacts to non-human organisms. Since the terms women/men and girls/boys have been exclusively applied to human populations, we employ them here to signal that there is still important work to be done in terms of looking at biological and lifecycle impacts of radiation exposure in non-human organisms. We also use these terms to underscore the humanitarian implications of nuclear technologies. The impacts of ionizing radiation affect the lives of real human beings with bodies and minds, who are more than just numbers in a data set.

Moreover, we intend these terms to be representative of a more diverse reality that takes seriously the ways that biological factors (e.g., sex organs) and environmental and social factors intersect and often produce compounding forms of radiological harm. In other words, by using the term “women” (for instance), we aim to acknowledge not only biological sex (XX chromosome) but also all of the social, cultural, and environmental factors that shape lived experiences in female bodies.

2.3 An Intersectional Approach to Understanding Radiological Harm

Many scholars working in the environmental humanities and social sciences have raised questions about the compounding effects of biological, social, and environmental factors, citing concerns about equity and social and environmental justice.[17] Among them, Angelon-Gaetz et al. found disproportionate radiological harm tied to ethnicity in the US nuclear weapons production process.[18] Folkers and Gunter have further shown that women (including pregnant women) and children “living near nuclear production facilities appear to be at disproportionately higher risk of harm from exposure” to radiation.[19] Importantly, they point out that “children in

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17 See, e.g., Jacob Darwin Hamblin and Linda Marie Richards, *Making the Unseen Visible: Science and the Contested Histories of Radiation Exposure* (Oregon State University Press, 2023); Lois Gibbs, *Love Canal: And the Birth of the Environmental Health Movement* (Island Press, 2011 [1982]); David Pellow, *Garbage Wars: The Struggle for Environmental Justice in Chicago* (MIT Press, 2004); David Pellow, *Resisting Global Toxics: Transnational Movements for Environmental Justice* (MIT Press, 2007); Dana Powell, *Landscapes of Power: Politics and Energy in the Navajo Nation* (Duke University Press, 2018); Sandra Steingraber, *Living Downstream: A Scientist’s Personal Investigation of Cancer and the Environment* (Vintage Books, 1997); Traci Brynne Voyles, *Wastelanding: Legacies of Mining in Navajo Country* (Minnesota University Press, 2015).

18 Kim A. Angelon-Gaetz et al., “Inequalities in the Nuclear Age: Impact of Race and Gender on Radiation Exposure at the Savannah River Site (1951–1999),” *New Solutions* 20, no. 2 (2010): 195–210, **https://doi.org/10.2190/NS.20.2.e**.

19 Cindy Folkers and Linda Pentz Gunter, “Radioactive Releases from the Nuclear Power Sector and Implications for Child Health,” *BJM Peadiatrics Open* 6, no. 1 (2022): 1, **https://doi.org/10.1136/bmjpo-2021-001326**.

poorer often Non-White and Indigenous communities with fewer resources and reduced access to healthcare are even more vulnerable – an impact compounded by discrimination, socio-economic and cultural factors."[20] These brief examples show that disproportionate impact is informed by factors beyond biological sex, and demonstrates the need for a more nuanced understanding of the effects of radiological harm.

In this regard, important work has been done by feminist and womanist scholars to underscore the importance of intersectional approaches to research. These approaches take seriously the ways that factors including ethnicity, socioeconomic status, and geographical location, among others, compound to create unique forms of oppression that exacerbate the risk of negative outcomes. Audre Lorde and others have shown that by understanding these differences we can gain more insight into how compounded oppressions impact individuals in different ways.[21]

Among other ongoing research that considers intersectionality and compounding factors in assessments of radiological harm, Cindy Folkers has examined the implications of "compounding generational damage" noting that this could "indicate increased sensitivity through heritable impact."[22] Intergenerational and intersectional harm are explicit in radiation exposure data. Yet, despite this evidence, these harms have not been widely addressed or discussed in the context of exposure at different life stages.[23] This suggests the need for dedicated research into these implications.

2.4 The Lifecycle Model

The question of generational damage and heritable impact is critical when we consider the human as a biological species with a lifecycle process. Reproductive cells (gametes) are present at all stages of the human lifecycle. Therefore, radiation exposure at any point during the human lifecycle has the potential (however small) to impact reproductive cells. If reproduction occurs, this impact has the potential to cause damage that appears in the next generation of offspring, thus causing intergenerational harm. This is why the lifecycle model is important: it includes all life stages and therefore lends itself to tracking intergenerational impacts of radiation exposure. These impacts include the biological, social, and emotional impacts at a level that an adult-only population model cannot address. The human lifecycle model is shown as a binary cycle in figure 1.

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20 Folkers and Gunter, "Radioactive Releases," 2022: 1.

21 Audre Lorde, *Sister Outsider: Essays and Speeches* (Crossing Press, 1984); see also, e.g., Kimberlee Williams Crenshaw, "Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Antidiscrimination Doctrine, Feminist Theory and Antiracist Politics," *The University of Chicago Legal Forum*, article 8 (1989): 139–67, **https://chicagounbound.uchicago.edu/uclf/vol1989/iss1/8**; P. H. Collins, "Gender, Black Feminism, and Black Political Economy," *Annals of the American Academy of Political and Social Science* 568, no. 1 (2000): 41–53, **https://doi.org/10.1177/000271620056800105**; bell hooks, *Feminist Theory: From Margin to Center* (South End Press, 2000 [1984]).

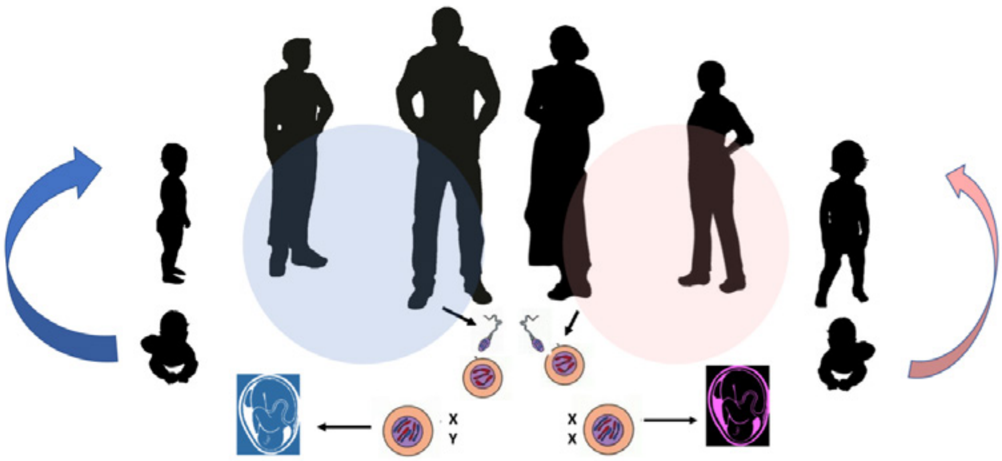
22 Cindy Folkers, "Disproportionate Impacts of Radiation Exposure on Women, Children, and Pregnancy: Taking Back our Narrative," *Journal of the History of Biology* 54 (2021): 31, **https://doi.org/10.1007/s10739-021-09630-z**.

23 One important exception to this is Hamblin and Richards, *Making the Unseen Visible*, 2023.

FIGURE 1.

A binary diagram of the human lifecycle

Reproductive cells carry heritable information, while somatic life stages constitute the life-time bodies of individuals.



Art credit: Mary Olson. Silhouette figures by Saro Lynch-Thomason.

3. Background

3.1 About the Life Span Study

In August 1945, the US bombing of the civilian cities of Hiroshima and Nagasaki resulted in the immediate death and fatal injury of approximately 210,000 people.[24] In addition to these victims, numerous survivors were exposed to the pulses of gamma and neutron radiation emitted from these detonations. In 1950, the Atomic Bomb Casualty Commission (ABCC)[25] instituted the Life Span Study (LSS), a long-term research programme that began after those who suffered the highest-level radiation exposure and other injuries in Hiroshima and Nagasaki had largely perished. The survivors from both cities were enrolled into this study and a control population was established.

The LSS continued under the ABCC until 1975. That year, Japan and the United States founded a jointly led research institute, called the Radiation Effects Research Foundation, to continue the study, which is still ongoing today.[26] The LSS is the only longitudinal study of the impact of radiation on human health that allows assessment of the consequences of ionizing radiation exposure in humans of all ages, differentiated by biological sex.[27]

The LSS followed approximately 120,000 individuals from Hiroshima and Nagasaki combined.[28] This number includes survivors (93,000 in 1950) and an assumed control group (27,000) that was believed, at the time, to have had no prompt radiation exposure from the nuclear detonations.[29] The data reported from initial interviews and follow-up surveys has enabled scientists and researchers to study and better understand the relationships between exposure to ionizing radiation and various health consequences, including rates of cancer and death, since the bombings.

It is important to note, however, that this dataset is limited in multiple ways. Foremost, as a critical research study, the LSS was focused on collecting data about one specific research question: the rate of harm from external exposure as a direct result of the gamma and neutron radiation

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24 This number is an estimate that is still widely debated. Masao Tomonaga, "The Atomic Bombings of Hiroshima and Nagasaki: A Summary of the Human Consequences, 1945–2018, and Lessons for *Homo sapiens* to End the Nuclear Weapon Age," *Journal for Peace and Nuclear Disarmament* 2, no. 2 (2019): 491–517, **https://doi.org/10.1521/psyc.67.1.43.31249**.

25 The ABCC was a commission established with funding from the US Atomic Energy Commission under the direction of President Harry Truman.

26 For a detailed history of the LSS, including the role of the ABCC, see M. S. Lindee, *Suffering Made Real: American Science and the Survivors at Hiroshima* (The University of Chicago Press, 1994); see also Radiation Effects Research Foundation, "Life Span Study," (2024), **https://www.rerf.or.jp/en/programs/research_activities_e/outline_e/proglss-en**.

27 NAS-NRC, "Health Risks," 2006; Radiation Effects Research Foundation, "Life Span Study," 2024. Exclusion of the early deaths means that any greater sensitivity to radiation that contributed to early death is not included in the LSS. This implies that the surviving population that was studied during the LSS may be more robust and radiation-resistant than a "general" population.

28 Radiation Effects Research Foundation, "Life Span Study," (2024).

29 Radiation Effects Research Foundation, "Life Span Study," (2024).

from a nuclear detonation. This exposure from the weapons is shared by those who were in Hiroshima and Nagasaki on 6 and 9 August 1945, respectively. The research question does not consider additional or compounding exposures that occurred in the aftermath of the detonation or at any subsequent life stage. Additional exposures may have contributed to the health outcomes of individuals, but the study was designed to find patterns among a large number of people who shared exposure from the detonations.[30]

Moreover, the LSS did not collect data about those individuals who experienced the most acute doses of radiation exposure – those who died immediately or within the first hours, days, and weeks after initial exposure. The study also did not collect data about exposed individuals who died between the time of the bombings in August 1945 and the beginning of the study in 1950. The term lifespan is accurate: the LSS tracked only survivors and did not directly include impacts to pregnancies in 1945 or to subsequent generations.

An additional limitation of the LSS is that it did not track internal radiation exposures that might have occurred from breathing contaminated air, drinking radioactive water or milk, or eating radioactive food. These limitations of the LSS have directly informed the design and findings of subsequent radiation protection and radiation research.

The LSS provided the largest available set of data that examines the health consequences of exposure to ionizing radiation from nuclear technologies in humans of all ages and both sexes. As such, it is unparalleled for radiation exposure data applied to human disease incidence in the general public. This appellation, while accurate, has allowed several generations of researchers to feel comfortable accessing and using data from civilian victims of the first nuclear strike directly on cities full of people. However, it is imperative to remember that the LSS secured no informed consent or other hallmarks of ethical study.[31] It must also be noted that, in other areas where nuclear fuel and weapons have been produced and tested, there are additional human radiation victims and survivors. Yet, there have been no other comparable, declassified research studies that incorporate statistical data derived from these communities.

The LSS is unique in that, to date, it is the only dataset about radiation health impacts associated with all ages (from birth to eighty years) and across both sexes. There are, however, some other concurrent epidemiological studies, including studies focused on atomic workers in the United States and elsewhere, that have looked at human health impacts and risks of exposure to ionizing radiation.[32]

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30 There has been some controversy about whether the control and/or study group members experienced additional radioactive fallout in the aftermath of the nuclear detonation and, if so, what impact, if any, this compounding exposure had on the data collected and reported in the LSS. It is our understanding that the primary research question of the LSS treats any additional radiation exposure (including from fallout in the aftermath of the nuclear detonation or any other source) as "random" in the data set. This means that these random exposures are not considered in the data reported in the LSS. Although subsequent radiation exposure may be part of an individual's lived experience, the LSS is designed to use epidemiology to look only at the large group and does not consider data at the level of the individual.

31 See, e.g., UNESCO, *Universal Declaration on Bioethics and Human Rights* (Paris, France: adopted 19 October 2005), **https://www.unesco.org/en/legal-affairs/universal-declaration-bioethics-and-human-rights**.

32 Angelon-Gaetz et al., "Inequalities in the Nuclear Age," 2010; Alexey V. Yablokov et al. *Chernobyl: Consequences for the Catastrophe for People and the Environment* (The New York Academy of Sciences, 2009).

It is also important to note that, although the BEIR VII report is now understood as the key source of data that shows disproportionate harm to girls and women, it neither highlights nor discusses the findings that females suffer more cancer than males, and that exposure of children will result in more cancer than the same-sex adults when exposed at the same rates. Nonetheless, this information is only available to the public because the National Academy of Sciences – National Research Council (NAS-NRC) published the LSS dataset in the BEIR VII report.

The LSS finding that outcomes caused by exposure to ionizing radiation depend on factors that include biological sex and the stage of the human lifecycle where exposure occurred has important consequences for our understanding of the ramifications of nuclear activities, both industrial and military. It is imperative to emphasize the importance of the LSS dataset: as a study that includes more than 120,000 subjects for which long-term epidemiological data has been collected, it remains the most cited and most depended upon radiation-focused research. The LSS also sheds new light on how we understand radiation itself: the study showed that the effects of exposure are not equally distributed, as previously assumed.

3.2 Known Health Consequences of Exposure to Ionizing Radiation

Exposure to ionizing radiation is known to cause detrimental human health impacts.[33] The effects of exposure tend to fall within two broad categories. The first is acute radiation exposure, or irradiation, where the body is exposed to high-dose radiation (as was the case with victims of the attacks on Hiroshima and Nagasaki), which results in adverse outcomes. The second is all other types of radiation exposure, which may include internal and external exposure. These exposures may occur at a wide range of levels, including as ongoing, or sustained, exposures from living in contaminated environments (e.g., uranium extraction zones).[34] Variability in the outcome of radiation exposure is now understood to include, among other factors, age, biological sex, and individual variability due to genetic makeup, epigenetic factors, and other indicators such as intergenerational health outcomes.[35]

When it comes to acute radiation exposure, level of harm and resulting health outcomes vary by the level and length of exposure. In the most extreme cases, burns, acute radiation syndrome, and death may occur. Radiation exposures that are lower and do not result in catastrophic damage to the body may be imperceptible at the time of exposure. Cancer and non-cancer outcomes from lower-dose radiation exposure may appear at any point during the life of the exposed individual, with some cancers taking as long as 30 years to present in the body.[36]

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33 See, e.g., NAS-NRC, "Health Risks," 2006; Ian Fairlie, "New Radiation Risks," *Campaign for Nuclear Disarmament* (Mordechai Vanunu House, 2024), https://cnduk.org/wp-content/uploads/2024/07/New-radiation-risks.pdf.

34 Stephanie A. Malin, *The Price of Nuclear Power: Uranium Communities and Environmental Injustice* (Rutgers University Press, 2015); Judy Pasternak, *Yellow Dirt: An American Story of a Poisoned Land and a People Betrayed* (Free Press, 2010); Sophie Rousmaniere (dir.), *Yellow Fever: Uncovering the Navajo Uranium Legacy*, Vision Maker Media, https://visionmakermedia.org/product/yellow-fever/.

35 See e.g., European Commission, "Radiosensitivity of Children – Health Issues After Radiation Exposure at a Young Age – EU Scientific Seminar 2020," (2021), https://data.europa.eu/doi/10.2833/769468.

36 Diana L. Nadler and Igor G. Zurbenko, "Estimating Cancer Latency Times Using a Weibull Model," *Advances in Epidemiology* (2014): 1–8, https://doi.org/10.1155/2014/746769.

Lower-level radiation exposure also has the potential to result in detrimental health outcomes at any point during the lifecycle of the exposed individuals' offspring.[37] Nevertheless, it is difficult to causally link radiation exposure to particular health consequences, since all of the consequences may also be caused by other agents.

Historically, radiation outcomes have been statistically assessed by comparing exposed populations to a "control population" of non-exposed individuals. In these analyses, scientists calculate the "excess" rate of cancer and non-cancer outcomes in the exposed population compared to the control population to assess the overall increased rate of health consequences from exposure to ionizing radiation. Recent developments in radiation research have shown that the adult population model (and the adult male model, specifically) is insufficient for accurately assessing and representing the risk of health consequences.[38] Researchers, including several cited in this report, have found that, among other factors, biological sex and age at time of exposure are key to accurately assessing the risk of harm from radiation exposure.[39]

In 2006, a shift began with respect to awareness of biological sex as a factor in the outcomes of radiation exposure. In the BEIR VII report, the US NAS presented data showing disproportionate harm to females (adults and children) from ionizing radiation, specifically, cancer.[40] Based on data from the LSS, the BEIR VII report documents that females exposed to ionizing radiation suffer a higher rate of health consequences, including cancer and death, over their lifetimes compared to males.[41,42]

Importantly, these findings also show that the highest rate of harm across the dataset is in the same-aged cohorts composed of young boys and girls. This means both that children (ages 0–5) are more at risk than adults, and that girls (ages 0–5) suffered two times more cancer (over the next 60 years) than boys exposed at the same age.[43]

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37 Folkers, "Disproportionate Impacts," 2021.

38 See, e.g., Olson, "Disproportionate Impact," 2019; W. Later et al., "Is the 1975 Reference Man Still a Suitable Reference?," *European Journal of Clinical Nutrition*, 64 (2010): 1035–42, **https://doi.org/10.1038/ejcn.2010.125**; A. Makhijani, "The Use of Reference Man in Radiation Protection Standards and Guidance with Recommendations for Change," Institute for Energy and Environmental Research (2009 [2008]), **https://ieer.org/wp/wp-content/uploads/2009/04/referenceman.pdf**; Makhijani et al., "Healthy from the Start," 2007; Arjun Makhijani et al., "Science for the Vulnerable," 2006.

39 See, e.g., European Commission, "Radiosensitivity," 2021; Narendran et al., "Sex Differences," 2019; Utada et al., "Radiation Risk," 2021; J. D. Matthews et al., "Cancer Risk in 680 000 People Exposed to Computed Tomography Scans in Childhood or Adolescence: Data Linkage Study of 11 Million Australians," *BMJ* 346 (2013): f2360, **https://doi.org/10.1136/bmj.f2360**.

40 NAS-NRC, "Health Risks," 2006.

41 It is important to note that the data in the BEIR VII report is disaggregated for females and males, and that the biological sex of participants was assigned by the researchers during the initial stages of the study.

42 Other post-2006 research, including non-LSS related studies, have reported similar findings. The study by Matthews et al., for instance, reported that "overall cancer incidence was 24% greater for exposed than for unexposed people, after accounting for age, sex, and year of birth." Moreover, they suggested not only that the incidence rate ratio (IRR) was "greater after exposure at younger ages" (para. 14) and that, in terms of "solid cancers other than brain cancer, the IRR was greater in female patients than in male patients…; [but] the EIR [excess incidence rate] was also significantly greater in female patients than for male patients" (Matthews et al. "Cancer Risk," 2013: para. 15).

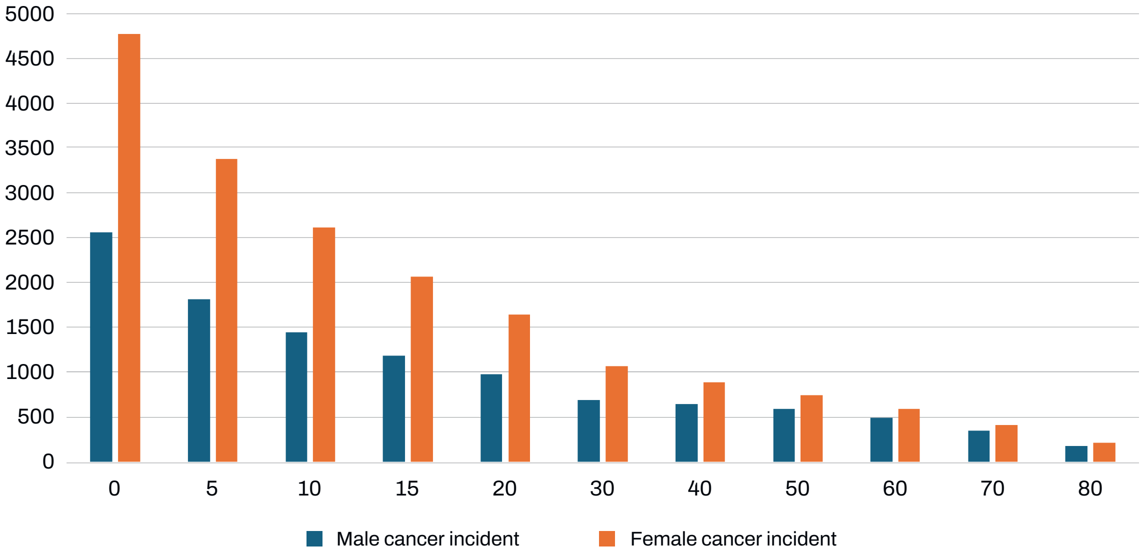
43 NAS-NRC, "Health Risks," 2006.

This data provides clear evidence indicating that girls between the ages of 0–5 years are the most at-risk post-birth lifecycle stage for cancer from ionizing radiation exposure.[44]

Though the data supporting these findings appears in tables presented in the appendices of the BEIR VII report, it does not highlight or discuss the female versus male difference in harm from exposure to radiation. Independent analysts, first Dr. Arjun Makhijani and his team, followed later by Mary Olson (co-author of this report), put the spotlight on these age- and sex-based differences in outcome.[45] In addition to showing a difference between males and females, the data in BEIR VII forces a re-evaluation of the basic premise that radiation exposure is a consistent, universal, interchangeable, indiscriminate event. Now, thanks to the data in BEIR VII, we know that age and biological sex influence the outcome of any radiation exposure (see figure 2).

FIGURE 2.

Cancer incidence by 100,000 by age at time of exposure



Based on Table 12D-1, NAS, 2006, Biological Effects of Ionizing Radiation (BEIR VII). This bar chart presents a hypothetical case of rate of cancer incidence by age at time of radiation exposure based on data presented in the LSS. Exposure rate (1 Gy) was consistent for each individual, which allows age of exposure and biological sex to be assessed as contributing factors in cancer incidence as a radiation outcome.

[44] NAS-NRC, "Health Risks," 2006; see also Olson, "Atomic Radiation," 2011; Olson, "Disproportionate Impact," 2019.

[45] Makhijani et al., "Science for the Vulnerable," 2006; Olson, "Disproportionate Impact," 2019.

3.3 Research Uptake in Nuclear Non-Proliferation and Disarmament Initiatives

This research made its way into policy discussions, as States and multilateral stakeholders participated in the Humanitarian Initiative on the Impact of Nuclear Weapons, which comprised three international conferences held between 2013 and 2014. The initiative highlighted scientific research on the potential risks and impacts of nuclear weapons and foregrounded the voices and experiences of individuals and communities directly harmed by nuclear detonations.[46] These conferences were rooted in humanitarian perspectives about nuclear impacts on individual human rights, civil society, and the environment and they paved the way for the adoption of the Treaty on the Prohibition of Nuclear Weapons (TPNW) in 2017.[47] The TPNW includes a clause mandating that States Parties "provide age- and gender-sensitive assistance" to "individuals under [their] jurisdiction who are affected by the use or testing of nuclear weapons" (article 6).[48] This assistance includes, but is not limited to, "medical care, rehabilitation and psychological support" and is also intended to consider "social and economic inclusion" (article 6).[49]

Since the Treaty's entry into force on 22 January 2021, States Parties have continued to work to integrate sex and gender analysis into TPNW implementation. As part of an Action Plan adopted in 2022, States Parties agreed to "establish a geographically diverse and gender balanced network of experts to support the goals and TPNW" (Action 34).[50] They also agreed to "establish a Gender Focal Point... to support the implementation of the gender provisions of the Treaty" (Action 48).[51] Additionally, States Parties aim to establish "guidelines for ensuring age- and gender-sensitive Victim Assistance" (Action 49), and for the "integration of gender perspectives in international cooperation and assistance" (Action 50).[52]

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46 John Borrie, "Humanitarian Reframing of Nuclear Weapons and the Logic of a Ban," *International Affairs* 90, no. 3 (2014): 625–46, **https://www.jstor.org/stable/24538512**; Becky Alexis-Martin et al., "Addressing the Humanitarian and Environmental Consequences of Atmospheric Nuclear Weapon Tests: A Case Study of UK and US Test Programs at Kiritimati (Christmas) and Malden Islands, Republic of Kiribati," *Global Policy* 12, no. 1 (2021): 106–21, **https://doi.org/10.1111/1758-5899.12913**; Sébastien Philippe et al., "Radiation Exposures and Compensation of Victims of French Atmospheric Nuclear Tests in Polynesia," *Science & Global Security* 30, no. 2 (2022): 62–94, **https://doi.org/10.1080/08929882.2022.2111757**; Matthew Breay Bolton, "Human Rights Fallout of Nuclear Detonations: Reevaluating 'Threshold Thinking' in Assisting Victims of Nuclear Testing," *Global Policy* 13, no. 1 (2022): 76–90, **https://doi.org/10.1111/1758-5899.13042**; Aiko Sawada et al., "Surviving Hiroshima and Nagasaki – Experiences and Psychosocial Meanings," *Psychiatry* 67, no. 1 (2004): 43–60, **https://doi.org/10.1521/psyc.67.1.43.31249**; Tomonaga, "The Atomic Bombings of Hiroshima and Nagasaki," 2019.

47 Alexander Kmentt, *The Treaty Prohibiting Nuclear Weapons (Routledge Global Security Studies) How it was Achieved and Why it Matters* (Routledge, 2021).

48 "Treaty on the Prohibition of Nuclear Weapons," 2017, 6.

49 "Treaty on the Prohibition of Nuclear Weapons," 2017, 6.

50 "Draft Vienna Action Plan," 2022, 6.

51 "Draft Vienna Action Plan," 2022, 8.

52 "Draft Vienna Action Plan," 2022, 8.

In 2023, the Scientific Advisory Group of the TPNW acknowledged that "cancer deaths attributable to radiation increases with dose, and [that] there are higher risks for younger individuals and women."[53]

Some States have also started to reference the disproportionate impact of ionizing radiation on the health of women and girls. These references have featured in national statements and working papers presented at meetings of the Nuclear Non-Proliferation Treaty (NPT).[54] In 2018, for example, the Chair's factual summary from the 2018 Preparatory Committee for the 2020 NPT Review Conference noted the disproportionate impact of ionizing radiation on women and suggested that the issue "should be factored into discussions in the current review cycle."[55] The Chair of the 2019 Preparatory Committee also proposed that the 2020 NPT Review Conference should "recognize the disproportionate impact of ionizing radiation on women and girls."[56]

In 2022, at the Tenth Review Conference of the NPT, a Joint Statement on Gender, Diversity and Inclusion was delivered by 67 States Parties.[57] The statement underscored the importance of full, equal and effective involvement of women in all aspects of the NPT, highlighted that nuclear weapons have different effects on different demographics, and noted that the intersections of race, gender, economic status, geography, nationality, and other factors must be taken into account as risk-multiplying factors in relation to nuclear weapons.

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53 "Report of the Scientific Advisory Group on the Status and Developments Regarding Nuclear Weapons, Nuclear Weapon Risks, the Humanitarian Consequences of Nuclear Weapons, Nuclear Disarmament and Related Issues," Second Meeting of States Parties to the Treaty on the Prohibition of Nuclear Weapons (Advance Unedited Version), 27 October 2023: 10, **https://docs-library.unoda.org/Treaty_on_the_Prohibition_of_Nuclear_Weapons_-SecondMeeting_of_States_Parties_(2023)/TPNW.MSP_.2023.8_SAG_nukes_advance_unedited.pdf**; see also, Ozasa et al., "Studies of the Mortality," 2012; Eric J. Grant et al., "Solid Cancer Incidence among the Life Span Study of Atomic Bomb Survivors: 1958–2009," *Radiation Research* 187, no. 5 (2017): 513–37, **http://doi.org/10.1667/RR14492.1**; Olson, "Disproportionate Impact," 2019.

54 "Gender, Development and Nuclear Weapons," 2017 Preparatory Committee for the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 10 May 2017: 1–4. , **https://documents.un.org/doc/undoc/gen/n17/132/22/pdf/n1713222.pdf**; "Impact and Empowerment: The Role of Gender in the Non-Proliferation Treaty," Preparatory Committee for the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 24 April 2018: 1–5, **https://documents.un.org/doc/undoc/gen/n18/120/86/pdf/n1812086.pdf**; "Integrating Gender Perspectives in the Implementation of the Treaty on the Non-Proliferation of Nuclear Weapons," Preparatory Committee for the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 18 April 2019: 1–5, **https://documents.un.org/doc/undoc/gen/n19/114/98/pdf/n1911498.pdf**; "Gender in the Non-Proliferation Treaty: Recommendations for the 2020 Review Conference," Preparatory Committee for the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 7 May 2019: 1–4, **https://documents.un.org/doc/undoc/gen/n19/133/49/pdf/n1913349.pdf**.

55 "Chair's Factual Summary (Working Paper)," Preparatory Committee for the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 16 May 2018: 2, **https://documents.un.org/doc/undoc/gen/n18/150/62/pdf/n1815062.pdf**.

56 "Recommendations by the Chair to the 2020 NPT Review Conference," Preparatory Committee for the 2020 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, 10 May 2019: 9, **https://documents.un.org/doc/undoc/gen/n19/138/50/pdf/n1913850.pdf**.

57 Reaching Critical Will. 2022. "Joint Statement on Gender, Diversity and Inclusion at the 10th NPT Review Conference (General Debate)," **https://reachingcriticalwill.org/images/documents/Disarmament-fora/npt/revcon2022/statements/4Aug_Gender.pdf**.

4. Updates

In this report, we have sought to answer the critical question of whether, and if so to what extent, further research since the 2006 BEIR VII report has been conducted to verify, engage, or refine the findings that girls and women are more at risk of harm to exposure from ionizing radiation. We reviewed a sample of peer-reviewed scientific research published since the 2006 BEIR VII report to assess what updates, if any, have been published on the correlation between biological sex and radiation harm. The research methodology is presented in appendix A and the systematization of results published in peer-reviewed articles is presented in appendix B.

4.1 Ongoing Discussions about the Correlations Between Biological Sex and Radiation Harm

The findings that radiation impacts are not uniform and that age and sex are factors in the outcome of a "same level" exposure have raised a variety of questions about the international standards for radiological protection.

Recent studies have called for further developments to adequately address disproportionate harm from ionizing radiation. Among them, the 2007 recommendations of the International Commission on Radiological Protection (ICRP) included calculations for effective dose guidelines for assessing radiation harm from internal and external exposures that standardized the data as an age- and sex-averaged value.[58]

Though our research did not include an exhaustive review of literature on radiological protections, we believe this update is critical to include. ICRP's recommendation initiated a shift from the use of "Reference Man" in assessing standards for radiological protection, to the use of "Reference Person" or "Reference Individual."[59] The "Reference Person" model is now being used in many countries but, critically, it has not yet been implemented in the United States where the federal regulator, and those under it, continue to use Reference Man exclusively.[60]

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58 ICRP, Publication 103: *The 2007 Recommendations of the International Commission on Radiological Protection* (2007), **https://journals.sagepub.com/doi/pdf/10.1177/ANIB_37_2-4**.

59 ICRP, Publication 103, 2007: 12–13. For a history of the development of "Reference Man" and updated use of Reference individuals see Wesley E. Bloch, "Reference Individuals Defined for External and Internal Radiation Dosimetry" in *Advanced Radiation Protection Dosimetry* (CRC Press: 2019): 169–214. For information on and discussions about the "Reference Person" models, see, e.g., ICRP, *Basic Anatomical and Physiological Data for Use in Radiological Protection Reference Values* (2002), **http://www.icrp.org/publication.asp?id=icrp%20publication%2089**; ICRP, *Publication 147: Use of Dose Quantities in Radiological Protection* 50, no. 1, (2021), **https://doi.org/10.1177/0146645320911864**; G. Tanaka et al., "Reference Man Models for Males and Females of Six Age Groups of Asian Populations," *Radiation Protection Dosimetry* 79, no. 1–4 (1998): 383–86, **https://doi.org/10.1093/oxfordjournals.rpd.a032432**; Gi-ichiro Tanaka and Hisao Kawamura, *Reference Man Models Based on Normal Data from Human Populations* (2000), **http://www.irpa.net/irpa10/cdrom/00602.pdf**; NAS-NRC, "Health Risks," 2006.

60 US Federal Code of Regulations, "Standards for Protections Against Radiation," chp. 10, part 20 (10cfr20, 2024), **https://www.ecfr.gov/current/title-10/chapter-I/part-20**.

BOX 1.

About “Reference Man”

The “Reference Man” model was formally established in 1974 by the ICRP as a standard for evaluating compliance with nuclear licenses as well as gauging the impact of routine and accidental releases of radiation on general populations. The original ICRP model stated:

> Reference man is defined as being between 20–30 years of age, weighing 70 kg, is 170 cm in height, and lives in a climate with an average temperature of from 10°C to 20°C. He is a Caucasian and is a Western European or North American in habitat and custom.[61]

It is critical to note that this reference model cannot accurately represent radiological harms to children, it excludes most men, and does not accurately represent the lived experiences of, or radiological harms to, women. Moreover, the Reference Man model is specifically framed as “white,” which actively erases impact to any other groups, including the numerous black, Indigenous, and people of colour involved in and impacted by the various stages of the nuclear production process. As such, it obscures any differences in harm from radiation exposure where ethnicity could be a factor.[62] Though the original ICRP model noted environmental and other non-biological factors (including land-based lifestyle and diet) in its definition, they have tended to be disregarded as contributing factors to the rate of harm from exposure.

The “Reference Man” model has been widely critiqued, especially in terms of its use for setting standards for safe levels of radiation exposure.[63] Radiation models, such as Reference Man, which represent radiation impacts to human health via an all-male population model of (near) same-age workers, fail to consider the important role that biological lifecycle and intergenerational impacts (among other factors) have in assessing radiation harm.

More recent studies, however, have criticized the use of the “Reference Person” model as failing to go far enough to make equitable recommendations for radiological protection. The Reference Person is created by blending male and female organs into a hypothetical hermaphrodite model. This effort to create a non-binary model for radiological protections uses sex-averaged values for impacts to males and females. This model is still problematic because averaging

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61 For the full report see Snyder et al., *Report of the Task Group on Reference Man*. [ICRP Publication] No. 23 (Pergamon Press, 1975; adopted October 1974). For a history of the development of “Reference Man” and updated use of Reference Individuals, see Bloch, “Reference Individuals,” 2019.

62 See, e.g., Folkers and Gunter, “Radioactive Releases,” 2022; Gabrielle Hecht, *Being Nuclear: Africans on the Global Uranium Trade* (MIT Press, 2014); Powell, *Landscapes of Power*, 2018; Voyles, *Wastelanding*, 2015.

63 See, e.g., Later et al., ““Is the 1975 Reference Man Still a Suitable Reference?,” 2010; Makhijani, “The Use of Reference Man,” 2009 (2008); Makhijani et al., “Healthy form from the Start,” 2007; Makhijani et al. *Science for the Vulnerable*, 2006; Olson, “Atomic Radiation,” 2011. This model has since been updated for various populations including sex-averaged “Reference Individuals” and Asian populations. However, there are still numerous issues with these models; see ICRP, Publication 147, 2021; Tanaka et al., “Reference Man,” 1998; Tanaka and Kawamura, *Reference Man*, 2000.

these values overestimates harm from exposure in males and *still* underestimates harm from exposure in females.[64]

Radiation experts involved in ICRP Task Group 111 have begun to engage in discussions aimed at confronting the challenge of finding an equitable model to implement as the standard for radiological protection. Among the important research that has been published by members of the Group, Applegate et al. critiqued the annual worker's dose limit exposure recommendations because they fail to differentiate between individuals based on age and sex.[65] That critical study showed that females are at a significantly higher risk for radiation-related stomach cancer than are males, thus demonstrating a need for specific protections that consider risks based on biological sex and age at time of exposure.[66]

In 2019, Mary Olson – a well-known researcher of radiation and co-author of this report – called for regulatory agencies to adopt a Reference Girl model to be universally applied.[67] Olson argued that a Reference Girl model would help to "shift public radiation safety regulations and limits to protect this most-impacted post-birth life phase," thus helping to "provide greater protection to all."[68] In a 2020 interview, Olson explained:

> It is more often acknowledged that children are at higher risk of disease and death from radiation, but it is rarely pointed out that the regulation of radiation and nuclear activity (worldwide) ignores the disproportionately greater harm to both women and children: "allowable" doses to the public do not incorporate this information.[69]

Olson's research was an independent second analysis which helped to confirm many of the findings first documented by Makhijani et al.[70] Her research has helped to affirm the need for protection and intervention calculations based on those populations (girls 0–5 years old) who are most at risk.[71] The rationale for the Reference Girl model is that representing those most at risk would result in greater protections when applied to all other parts of the human lifecycle.[72]

In 2021, the ICRP published a study on the "Use of Dose Quantities in Radiological Protection" which stands today as the international standard for evaluating risk from occupational radiation exposure.[73] This publication states clearly that biological sex and age at time of exposure are

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64 Makhijani et al., "Science for the Vulnerable," 2006; Olson, "Disproportionate Impact," 2019; Narendran, "Sex Differences," 2019.

65 K. E. Applegate et al., "Individual Response of Humans to Ionising Radiation: Governing Factors and Importance for Radiological Protection," *Radiation and Environmental Biophysics* 59 (2020): 185–209, https://doi.org/10.1007/s00411-020-00837-y.

66 Applegate et al. "Individual Response," 2020.

67 Olson, "Disproportionate Impact," 2019.

68 Olson, "Disproportionate Impact," 2019.

69 "Olson 13min UN Gender and Radiation," *YouTube*, 2017, https://www.youtube.com/watch?v=cgnWPxIP2m4; Nichols, *Women on the Edge of Time*, 2021.

70 Makhijani, "The Use of Reference Man," 2009 [2008]; Makhijani et al., "Healthy from the Start," 2007; for more details, see Nichols, *Women on the Edge of Time*, 2021.

71 Makhijani, "The Use of Reference Man," 2009 [2008]: 28–29.

72 Olson, "Disproportionate Impacts," 2019.

73 ICRP, Publication 147, 2021.

factors in radiation harm.[74] The use of an adult reference, however, precludes consideration of the BEIR VII insights that radiation exposures during childhood are significantly more harmful than in adulthood. Nowhere in the world is a regulatory model for public exposure based on the life stage most impacted: children, and particularly girls. In this regard, it should be noted that Mary Olson is currently initiating the development of a new model for a universal Reference Individual: a girl, not limited by the North American or European industrial habits and habitat of Reference Man.[75]

4.2 Literature Review Supports Early Hypothesis

While additional work is needed to address the question of why biological sex and age at time of exposure are factors in radiological harm, an early hypothesis regarding the cause of disproportionate impact of radiation exposure on girls and women was tendered by Dr. Rosalie Bertell. A Right Livelihood Award winner (1986) and public health advocate, Bertell conducted research that focused on radiosensitive reproductive tissue. She theorized that this “hot tissue” might be a factor in disproportionate impact because female bodies have a higher percentage of reproductive tissue (including the breasts) than males. Bertell offered this unpublished hypothesis at the end of her life and did not proffer any evidence to support or disprove this idea.[76]

Importantly, our review found research supporting the hypothesis that a higher percentage of reproductive tissue in the female body could contribute to greater risk of harm from radiation exposure in females.[77] This hypothesis and these findings reinforce the idea that being female cannot be read as an individual difference when assessing radiation harm. Rather, it understands biological sex as a factor that puts *all* females at a higher risk of harm from radiation exposure.

Though we find this hypothesis may be a useful starting point for determining the cause of disproportionate harm, there is one detail that needs to be critically examined by radiation researchers who engage this theory. The finding that reproductive tissue is harmed by radiation is supported by several studies reviewed in this survey (see appendix B). It is not clear, however, that female bodies having a higher percentage of reproductive tissue is an adequate explanation of the differences in impact based on biological sex that are found in the LSS dataset.

It is true that females have a higher proportion of reproductive tissue at all life stages than do males. It is also true, however, that during puberty both males and females develop more reproductive tissue than they had during childhood. A close examination of figure 2 shows a distinct pattern of divergence between male and female response (cancer outcomes) given the same rate of radiation exposure. Importantly, this dataset shows that the effects from exposure are greatest in the lowest age cohort (0–5 years). Those exposed during puberty (approximately

74 ICRP, Publication 147, 2021: 9, 11.

75 This research is ongoing through 2025.

76 Verbal communication with Mary Olson who enjoyed mentoring from Bertell in the final years of her life. Olson shared her findings about the BEIR VII data during a phone conversation with Bertell, which prompted her thoughts on causation. Bertell had written previously on breast cancer and other aspects of female-specific impacts of radiation. See: Bertell, “A New Understanding,” 2010.

77 See, e.g., Preston et al., “Cancer Incidence,” 1994; Ozasa et al., “Studies of the Mortality,” 2012; Utada et al., “Radiation Risk,” 2021; Narendran et al., “Sex Difference,” 2019.

8–14 years) show a convergence. By middle age, the difference between male and female outcomes is still there, but it is much smaller.

If higher percentage of reproductive tissue were the *only* factor in greater incidence of harm, we could expect the rate of harm to increase at the time of puberty (between approximately 8–14 years). Bertell's hypothesis does not account for this anomaly, nor does it explain why the data for male and female cancer outcomes begins to converge when the radiation exposure is at the age of puberty, or why the difference in outcomes decreases as age at time of exposure increases. Nevertheless, these observations do not make the hypothesis unequivocally wrong. Rather, they complicate our understandings of radiation exposure and radiological harm in human populations and evidence the need for further research into the question of disproportionate impacts. Based on current research, it is not yet possible to know what, if any, role reproductive tissue or other, disparate, factors have in disproportionate exposure outcomes.

4.3 Non-Cancer Outcomes

The non-cancer outcomes of exposure to ionizing radiation are extensive, and it is beyond the scope of this report to fully enumerate them.[78] Setting aside pregnancy and other reproductive impacts, which are female specific and worthy of a full and independent report, cardiovascular diseases (CVD) – including ischemic heart disease, heart attack, hardening and blockage of the arteries, and stroke – are the most prevalent non-cancer outcomes of radiation exposure. Research has shown that CVD outcomes are disproportionately tied to biological sex, where females exposed to ionizing radiation are more prone to develop CVD over the course of their lifetime than are males.[79] It is not yet clear why females are more prone to CVD outcomes.

4.4 Human Lifecycle Impacts

In our review of literature (see appendix B) we found that most of the reviewed research reports data about males and females separately and does not comment on different outcomes. Where analysis was included, we found that researchers tended to dismiss disproportionate impacts to female bodies when female-specific outcomes, such as breast cancer, were observed.

Radiation researchers have pointed to higher levels of breast cancer in females exposed to ionizing radiation as skewed on the basis of relative risk, or the higher rate of susceptibility of females to breast cancer as compared to males.[80] This approach considers being female as

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78 For a sample of additional research on non-cancer outcomes see, e.g., Rosalie Bertell, "Chernobyl: An Unbelievable Failure to Help," *International Journal of Health Services* 38, no. 3 (2008), https://doi.org/10.2190/HS.38.3.i; Angelon-Gaetz et al., "Inequalities in the Nuclear Age," 2010; Gillies et al. "Mortality from Circulatory Diseases," 2017; Keith Griffin et al., "Dosimetric Impact of a New Computational Voxel Phantom Series for the Japanese Atomic Bomb Survivors: Children and Adults," *Radiation Research* 191, no. 4 (2019): 369–79, https://doi.org/10.1667/RR15267.1; Narendran et al., "Sex Differences," 2019.

79 Gillies et al., "Mortality from Circulatory Diseases," 2017; Mark P. Little et al., "Ionising Radiation and Cardiovascular Disease: Systemic Review and Meta-Analysis," *BMJ* (2023): 380, https://doi.org/10.1136/bmj-2022-072924.

80 For example, Applegate et al., "Individual Response," 2020. The National Breast Cancer Foundation estimated that in 2024 "310,720 women and 2,800 men will be diagnosed with invasive breast cancer." Of the total number of cases, men make up approximately 0.9% of those diagnosed with invasive breast cancer; see National Breast Cancer Foundation, "Breast Cancer Facts & Stats," 1 August 2024, https://www.nationalbreastcancer.org/breast-cancer-facts/.

an individual affliction, or "confounding" factor. [81] This logic is flawed: greater harm to female bodies, no matter the site of harm, means that there is a disproportionate impact. Moreover, this approach fails to recognize the compounding risk of exposure to approximately half the human population who are already at higher risk for breast cancer. It is critical, in this respect, that policymakers think about disproportionate impact from radiation exposure in terms of absolute excess risk because, in every age cohort, there is greater absolute harm to females compared to males.

It is broadly the case that, when a scientific question is considered inconvenient, finding any form of causation can become a basis to dismiss that question as if it were resolved, rather than an indication that the question should be further engaged.[82] The question of disproportionate impact has been a problem for radiation researchers because, until 2006, the prevailing view was that ionizing radiation harm could be managed and regulated as "one size fits all." However, research has shown higher levels of breast and ovarian cancer among individuals exposed to radiation as compared to those not exposed, and significantly higher risk to those exposed during childhood. These findings shatter the idea that a "one size fits all" model is an acceptable standard for radiation exposure.[83] Such findings also add more weight to the hypothesis that a higher percentage of reproductive tissue in female bodies than in male bodies may contribute to disproportionate harm from radiation exposure.

In addition to the current dearth of research focusing explicitly on the causation and causal agents of disproportionate harm, we found that the broader point about the biological lifecycle of the human species has been altogether left out of discussions about radiation research, protection, and regulation.[84] A lifecycle perspective holds that every life phase is equally necessary for the lifecycle to continue.

As such, an exposure in one life phase harms all post-exposure life phases. Human reproductive cells (the primary germ cells) are present at every life stage, including during gestation. Healthy development is dependent on all previous stages. Radiation exposure at any life stage (including during gestation) may have adverse impacts at any point in the future lifecycle. However, there may also be impacts to the unique soma (in the sense of the individual body) at any age from radiation exposure that can be latent for long periods and may not appear as disease until much later in the human lifecycle.

This aspect of radiological harm was robustly documented in the LSS. The BEIR VII reports evidence the startling long-term difference in cancer rates between those exposed to radiation as children compared to the cancer rates among those exposed as adults. The BEIR VII data, which reports the raw data from the LSS, includes all cancer across the 60-year period, including childhood cancer and cancers that developed later in the lifecycle. It is worth noting that childhood exposure increases the overall rate of incidence of cancer across the 60-year study

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81 Applegate et al., "Individual Response," 2020.

82 See, e.g., Naomi Oreskes, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (Bloomsbury Press, 2010).

83 Ozasa et al., "Studies of the Mortality," 2012; Utada et al., "Radiation Risk," 2021.

84 Some studies, including the study by Ozasa et al. factor in age at exposure and attained age as essential for calculating harm from exposure. This is an important step toward a model that considers human lifecycle stage as a factor in measuring radiation harm; see Ozasa et al., "Studies of the Mortality," 2012.

period reported in BEIR VII, compared to adult exposure. For the same exposure level scenarios presented in figure 2, the dataset has been normalized to overall life expectancy. Every (non-lethal) radiation exposure to any human body takes place during a particular stage in the human lifecycle. Due to the latency of most radiation-based diseases, however, the outcome of that exposure will likely manifest at a later stage, if at all.

Understanding that early exposures to radiation are more harmful than later exposures underscores why variability in the age at time of exposure matters. Adult populations may be diverse in the sense that some adults were exposed as children and others were not. As such, the rates of cancers in adults can be understood differently if variability in the age of exposure is taken into account. Such a view does not diminish the potential for harm to adults and elders, but it does emphasize the greater and extended potential for disease originating from harm in children. Considering age at time of exposure is therefore vital to considerations about, and construction of, adequate radiation protections.

Understanding how the human lifecycle factors into conversations about radiological harm should be considered in any research on exposures that documents outcomes over time, and especially those that disaggregate data for biological sex. This question is of critical importance for understanding health and protecting the reproductive potential of our species.

There has been, to this point, inadequate scholarly attention to the correlation between biological sex and radiation health impacts. This includes, especially, research about human lifecycle impacts and related questions about causation of disproportionate harm. The dearth of scholarship on these topics reveals a critical gap in our knowledge about the effects of ionizing radiation. The literature that does address such issues speaks to the importance of and need for further critical engagement with the question of mechanisms for biological sex and ethnicity as causal factors in radiation outcomes, including questions of risk of exposure based on lifecycle stage.[85] Given this critical and evidenced need, we find that further failure on the part of international bodies of radiological protection to prioritize and engage these questions constitute what Wing identified as a continuing pattern of gender-based injustice characteristic of the entire history of nuclear impacts and technologies.[86]

We have demonstrated the need for additional research on this topic, especially in order that the States Parties can effectively implement solutions under the positive obligations of the TPNW and other facets of humanitarian assistance worldwide. Clearly more funding and support are needed to attract the rising generation of researchers to investigate the correlation between biological sex and radiation health impacts, including further research about human lifecycle impacts. The final section of this report suggests opportunities for further research to discern how and why biological sex may impact outcomes from radiation exposure.

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85 Bertell, "Chernobyl," 2008; Bertell, "A New Understanding," 2010; Steve Wing, "Ethics for Environmental Health Research: The Case of the U.S. Nuclear Weapons Industry," *New Solutions* 20, no 2. (2010): 179–87, **https://doi.org/10.2190/NS.20.2.b**; Angelon-Gaetz, et al., "Inequalities in the Nuclear Age," 2010; Folkers, "Disproportionate Impacts," 2021; Folkers and Gunter, "Radioactive Releases," 2022; Narendran et al., "Sex Difference," 2019.

86 Wing, "Ethics for Environmental Health Research," 2010: 180.

5. Conclusions and Agenda for Future Research

The research reviewed for this report provides clear evidence that radiation causes more cancer, heart disease, and stroke in women compared to men.[87] Moreover, that research clearly documents that, of any post-birth lifecycle stage, girls (ages 0–5 years) are the most at-risk for developing cancer and non-cancer related health consequences over the course of their lifetimes.

More research is needed, however, that takes seriously the ways that human lifecycle and intergenerational impacts inform discussions about radiological harm. The call for more inclusive and equitable research methods that take into consideration not only how gender, biological sex, and ethnicity (among other factors) impact results, but also how they influence the very questions we ask in research, has been echoed by numerous scholars. Tannenbaum et al. have argued that incorporating analyses based on sex and/or gender can help to offer "new perspectives, pose new questions, and importantly, enhance social equalities" in research.[88] Moreover, ensuring that researchers, regulators, and policymakers incorporate considerations about sex and/or gender into their research and analyses "can improve reproducibility and experimental efficiency, help to reduce bias, enable social equity in scientific outcomes, and foster opportunities for discovery and innovation."[89] Below, we suggest some critical questions for researchers engaging these issues.

5.1 Questions Arising from BEIR VII- and LSS-Related Research

- Why is biological sex a factor in radiation harm (including cancer and non-cancer outcomes)?
    - Are there multiple mechanisms? If so, which, if any, of these mechanisms are developmental?
    - Why is the impact of sex difference on radiation harm greatest in young children?
    - How much of the sex-based difference is tied to cancer in reproductive organs which are sex-specific?
    - Is disproportionate harm to females from radiation due to a higher percentage of radiation-sensitive reproductive tissue (Bertell's hypothesis)?
    - Are non-cancer, sex-linked outcomes also tied to age of exposure?

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87 See also Nanette K. Wenger et al., "Call to Action for Cardiovascular Disease in Women: Epidemiology, Awareness, Access, and Delivery of Equitable Health Care: A Presidential Advisory from the American Heart Association," *Circulation* 145, no. 23, https://doi.org/10.1161/CIR.0000000000001071.

88 Cara Tannenbaum et al., "Sex and Gender Analysis Improves Science and Engineering," *Nature* 575 (2019): 137, https://doi.org/10.1038/s41586-019-1657-6.

89 Tannenbaum et al., "Sex and Gender Analysis," 2019: 137.

5.2 Questions Arising from Non-LSS-Related Research

- Is the percentage of fat tissue in human bodies a factor in radiation harm?
- Does immunosuppression play a role in sex-based response to radiation?
- Is rate of maturation, including rate of mitosis, different in females and males? If so, is that a factor in sensitivity or resistance to radiation harm?
- Are there differences in females and males in cellular radiation repair mechanisms and, if so, do they play a role in cancer resistance?
- Are there genetic markers that indicate a higher or lower susceptibility to radiation harm and, if so, are they different for males and females?
- Internal decay of radioactivity (from ingestion and inhalation of contaminated food, water, and air) is not part of the research question studied in the LSS. Given this:
  - Does biological sex matter in outcomes of internal radiation exposures?
  - Does gender (social factors and behaviours) matter in internal radiation exposure?

5.3 Novel Questions

- How does factoring in the human lifecycle help to define research questions about biological sex and the outcomes of radiation exposure?
  - What is the lifecycle context for assessing risk or rate of cancer outcome in relation to attained age versus assessing risk or rate of cancer tied to age of exposure?
- Biological sex is generally assigned by the researcher. How can conversations about gender identity and gender expression be incorporated into this discussion?
  - How are non-binary and intersex individuals represented in the literature?
  - How could study of lifecycle and life stage also be more inclusive of a non-binary model?
- Does oestrogen impact disproportionate harm from exposure to ionizing radiation, including rates of carcinogenesis in human populations?
- Does testosterone provide any resistance to radiation harm?
- Are there environmental exposures to radiation where biological sex can be factored?
- Are medical professionals trained to consider biological sex when using or prescribing medical imaging, devices, medications, and treatments that deliver ionizing radiation?
- What are the gendered dimensions/biases that frame discussions about biological sex as a factor in radiation harm, and what are the implications and solutions for future funding and research on these topics?
  - Do the standardized units of radiation exposure or units of cellular harm impede gendered research?
  - Do these units contain implicit sex bias? Are assumptions based on the male body built-in?

5.4 Questions Concerning Reproductive Impacts

- Is the female foetus more sensitive to radiation harm, compared to the male?
- Since impacts on reproduction can originate from the mother, father, or both, where do we track exposure of reproductive cells to radiation throughout the lifespan for both females and males?
- What impacts are observed in second and third generation offspring when the parent has a known radiation exposure?
- Do women who have a history of current or intergenerational radiation exposure suffer pregnancy complications, including more post-partum depression in excess of those not exposed? Does awareness of this history change the outcome for the mother?
- In the years before childbearing, do people suffer greater anxiety about pregnancy or becoming a parent in areas and families with radiation impacts compared to those without?
- Are individuals who have known radiation exposure incidences more likely to avoid reproduction? Where avoidance is characterized, is it different in measurable ways for women and for men?
- Is there a sex difference in radiation-related childhood cancer rates? What about birth defects?
- Are there other developmental impacts that could be tied to radiation exposure of either children or parents? Is there a sex factor in these?
- Is radiation exposure a factor in infertility?
- What experience and knowledge do women bring from radiation-impacted areas?[90]

5.5 Final Questions

- How do we, as a society, prioritize preventative care?
- What differences in health outcomes could be obtained by gaining a better understanding of disproportionate harm through analysis of lifecycle impacts?
  - How does looking at disproportionate harm to children and to females of all ages inform the ways that we understand exposure of the general public?
  - How does looking at disproportionate harm factor into how allowable dose is calculated in radiation regulations, especially when considering infants, pregnant women, and elders?
  - How would differential findings on children and women change clinical care if they were incorporated into medical education and practice?

These questions, we believe, are all critical for the future of radiation research and radiological protection standards. Our research is an open call to the community of rising researchers who we invite and encourage to engage these questions.

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90 For instance, Tewa Women United promote protections for the most harmed in their Nava-Toi-Yiya project; see Tewa Women United, "Nava T'o | Yiya: Protecting the Most Vulnerable," (2024), https://tewawomenunited.org/nava-toi-yiya-protecting-the-most-vulnerable.

Appendix A. Research Methods

In order to assess whether, and if so to what extent, post-2006 research focused on correlations between biological sex and radiation health impacts were available, we set out to identify a list of primary keywords that could be used as search terms to identify relevant literature. These keywords included "male," "female," "gender," "biological sex," "sex," "radiation," "ionizing radiation," "risk," "impact," and "harm." Initial searches were conducted through Google Scholar using combinations of these keywords (e.g., "female + radiation + risk"; "biological sex + radiation") and the results were reviewed and collated.

Through this initial search, we found that in the literature published in English that presents data about radiation harm that was disaggregated for biological sex was far more extensive than anticipated, and the breadth of research spanned a number of disciplines and lines of inquiry. It became clear that an exhaustive review of the literature was not feasible within the scope of this study. We then set out to identify key areas of radiation-related research that focused on risk of exposure and radiation harm, especially those that presented data that was disaggregated for biological sex. Two primary databases of relevant information were identified: BioOne Digital Library and the journal *Radiation Research*. An exhaustive search of those databases was subsequently conducted for relevant research published since 2006, and the results were integrated and collated. During this search, we also began to identify a list of key authors, researchers, and organizations and subsequently conducted a comprehensive review of their published work for relevant data and the results were also collated.

In addition to our review of literature, we were also invited to present our provisional research in two meetings facilitated by the United Nations Institute for Disarmament Research (UNIDIR) which took place on 26 October and 9 November 2023. A number of leading experts in nuclear and radiation research as well as leaders in regulatory bodies were invited to attend these meetings, give feedback about the proposed research agenda, and share resources that might be relevant to the study.

Data Examined in this Study

The review of literature detailed below includes peer-reviewed scholarly research that was published after the 2006 BEIR VII report. The data presented is not exhaustive; rather, it includes a representative sample of the available research focused on, or simply reporting, correlations between biological sex and human health impacts from exposure to sources of ionizing radiation on Earth.

Among those studies detailed below, there are several key areas of inquiry which we have categorized to help organize the data. We identified two main categories: 1) research that used the dataset from the Lifespan Study (LSS) of survivors of the US nuclear attacks on Hiroshima and Nagasaki; and 2) research that used data sources distinct from the LSS study, which includes, but is not limited to, the International Nuclear Workers study, the Mayak Workers study, and medical sources of radiation exposure. Subcategories were identified according to specific areas of inquiry: 1) cancer impacts, which included research focused primarily on solid cancers of every kind and research focused on specific subtypes of cancer (i.e., breast, lung, respiratory specific cancers); and 2) non-cancer impacts, which was predominantly concerned with cardiovascular impacts and other disease.

After a preliminary assessment of the collated results, we chose to bound the data examined to exclude all non-scholarly sources and any scholarly sources that had not been peer-reviewed, as well as any sources published prior to the 2006 BEIR VII report. Moreover, we decided to further limit the data examined to include only that focused on radiological science, thus excluding work focused on radiation regulation.

A further limitation was made to exclude studies of non-terrestrial (e.g., space) and terrestrial non-Earth based (e.g., Mars) sources of radiation exposure. Though there is certainly valuable information being generated in the renewed exploration of space, we chose to exclude this subgroup as it did not address health risks to humans exposed to ionizing radiation related to the use of nuclear technologies here on earth, which was our main point of focus. We also do not include any studies using laboratory animal subjects, as an ethical choice.

It is important to note that much of the research that deals with non-terrestrial sources of radiation exposure does consider biological sex as a factor when assessing radiation harm. These studies tend to be focused on the estimated health risks from radiation exposure on astronauts that travel outside of Earth's low orbit. Though beyond the scope of this study, we suggest such work may have promising implications for ongoing discussion about radiological protections and the future of radiation regulation.[91]

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91 Alex Wilkins, "Space Test Dummies will Measure Female Radiation Risk for the First Time," *New Scientist*, 29 April 2022, **https://www.newscientist.com/article/2318260-space-test-dummies-will-measure-female-radiation-risk-for-first-time/**.

Appendix B. Literature Reviewed

We reviewed post-2006 radiation research for consideration of biological sex as a factor in the health consequences of those exposed to ionizing radiation. The data summary below is not exhaustive, but rather provides a representative sample of the available literature.[92]

LSS-Related Research

Cancer Impacts

AUTHORS	YEAR	SUMMARY OF RELEVANT CONCLUSIONS / UPDATES
Cologne et al.	2019	Found that "treating all incidents of solid cancer as a single outcome might not be the most effective approach for determining the shape of the radiation dose response, especially at low-dose levels" (p. 397).
Egawa et al.	2012	Showed that smoking and radiation exposure, in combination, led to a minor increase in harm to males compared to females of adenocarcinoma and squamous cell carcinoma. However, of those who smoked more, females suffered more small cell type cancer.
European Commission	2021	Found that sex, age at time of exposure, and attained age are key factors in accurately predicting risk from ionizing radiation exposure.
Grant et al.	2011	Found that "ionizing radiation may lead to changes in serum levels of cancer-related hormones and proteins in cancer-free women and that these changes are dependent upon either the menopausal status at the time of collection or the menarche status at the time of exposure" (p. 686).
Grant et al.	2021	Found that both urinary tract cancer (UTC) and kidney cancer show biological sex to be a factor in cancer outcomes. In both cases, females suffered cancer at a higher rate, which increased with increasing rates of exposure. For UTCs, the cancer rate was 3.4 times higher in females than in males.
Hwang et al.	2008	Suggested that cumulative, low-dose radiation exposure from cobalt-contaminated steel is correlated with increased risk of breast cancer and leukaemia.
Ozasa et al.	2012	Demonstrated "increased cancer risks throughout the [LSS] survivors' lifetimes" (p. 241), including "(17% more cancer deaths [overall]), especially among those under age 10 at exposure (58% more cancer deaths)" (p. 229).

92 Full citations for all papers discussed in the review of literature (those detailed in the table below) are marked with a double asterisk (**) in the references section.

		Also showed that "the relative risk of radiation for solid cancer was largest among those exposed at young ages" (p. 241). The risk of mortality from cancer also "increased significantly for most major sites including [the] stomach, lung, liver, colon, breast, gallbladder, esophagus, bladder and ovary" (p. 229).
Preston et al.	1994	Showed major differences between females and males for specific types of solid cancers, including lung and bronchus cancers (8.3% in females and 13.8% in males) and thyroid cancer (3.6% in females and 0.7% in males). A stand-out finding in this study is the rate of breast cancer in females (12.2%) compared to males (0.1%).
Preston et al.	2007	Found that "exposure as a child may increase risks of cancer of the body of the uterus" and that there was "a significant radiation-associated increase in the risk of cancer occurring in adolescence and young adulthood" (p. 2).
Sadakane et al.	2019	Showed liver cancer as an outcome in the study group, and at a higher rate for total males than total females. The findings on Biliary Tract Cancer Cases are reversed – the cases and rates are approximately twice as high in total females compared to total males, while pancreatic cancer results show near parity between total cases in females and males.
Utada et al.	2021	Found that the exposed LSS study group in general had a higher rate of ovarian cancer compared to the unexposed population. Also found that the outcomes were correlated between age-of-exposure, where those under the age of 20 had a higher risk, and those who were under the age of 10 when exposed had the highest incidence of ovarian cancer over their lifetime.

Non-Cancer Impacts

AUTHORS	YEAR	SUMMARY OF RELEVANT FINDINGS
Griffin et al.	2019	Provided an update on the computational "phantoms" used in the BEIR VII report, for dose reconstruction and simulation into a Voxel (3-D digital data storage) format for atomic bomb survivors. Suggested that the phantoms developed in the study offer not only "greater anatomical detail and age resolution," but "could help ... to more accurately characterize the dose to members of the atomic bomb survivor cohort" (p. 378).
Narendran et al.	2019	Noted that "demographic factors such as age, sex, genetic susceptibility, comorbidities, and various other lifestyle factors influence the radiosensitivity of different subpopulations" (p. 1).

Non-LSS-Related Research

Cancer Impacts

AUTHORS	YEAR	SUMMARY OF RELEVANT FINDINGS
Matthews et al.	2013	Reported that "overall cancer incidence was 24% greater for exposed than for unexposed people, after accounting for age, sex, and year of birth." Moreover, suggested not only that the incidence rate ratio (IRR) was "greater after exposure at younger ages" (para. 14) and that, in terms of "solid cancers other than brain cancer, the IRR was greater in female patients than in male patients...; [but] the EIR [excess incidence rate] was also significantly greater in female patients than for male patients" (para. 15).
Radiation Research Society (Conference Presentations)	2008	Suggested that "risk ... from radiotherapy for first breast cancers is inversely related to age at exposure to radiation and is dependent on dose" (p. 393). Found a "borderline significant association overall ... that was much stronger in women who reported a family history of breast cancer in first- or second-degree relatives" (p. 398). Showed that "multiple radiographic examinations of the spine at young ages [were] associated with increased breast cancer risk" (p. 398).

Non-Cancer Impacts

AUTHORS	YEAR	SUMMARY OF RELEVANT FINDINGS
Angelon-Gaetz et al.	2010	Reported that when taking into account race, black female workers had significantly higher doses than non-black female workers and found that their rates were actually comparable to those of non-black males.
Bracelet et al.	2016	Suggested that at low-dose levels of exposure there may be evidence of cardiovascular disease associated health risks, but these risks are complicated by gender and incidence of specific types of cancer and other diseases.
Gillies et al.	2017	Found that external radiation exposure may increase the risk for non-cancer diseases (including ischemic heart disease and cerebrovascular disease). The small sample size for female workers in this study is a confounding factor, but the excess relative risk (ERR) per unit of exposure for cardiovascular disease is important to note, since it shows that females suffered a higher rate of harm than males.
Scherthan et al.	2016	Found that shortened telomere length in male workers was associated with shortened lifespans, but that this was not the case among female workers, among those exposed to low-dose radiation. However, the sample size of this study was relatively small, and it is unclear whether males and females had the same, or similar, types of radiation exposure or whether other differences were a factor.

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