Brunel University of London

CHRC

Centre for Health Effects of Radiological and Chemical Agents

Effects of Nuclear Test Participation on UK Veterans and Families.

The British Government conducted a series of nuclear tests at sites in the South Pacific between 1952 and 1958. Alongside these atmospheric tests was an experimental programme, conducted largely at Maralinga in Australia, in which radioactivity was dispersed into the environment. This programme ended in 1963 although clean-up operations continued through to 1967. In addition, UK personnel took part in a series of American tests on Christmas Island in 1962. According to the Ministry of Defence (MoD), 22,347 veterans participated in at least one of these British or American tests.

Concerns about the health of veterans and their children first emerged in the early 1970s. Initial epidemiological studies reported no major health problems among veterans. However, more recent analyses, up to 2017, identified modest but statistically significant increases in illness and mortality compared to a control group of veterans. No formal epidemiological studies have examined the health of descendants, although anecdotal reports suggest adverse outcomes.

The Centre for Health Effects of Radiological and Chemical Agents (CHRC) was established in 2017 as a research initiative funded by the Nuclear Community Charity Fund (NCCF), through resources provided by the Armed Forces Covenant Aged Veterans Fund and, Brunel University of London.

CHRCs purpose is to generate, integrate, and share new multidisciplinary research focused on the British nuclear test veteran community, their genomic health, and the broader impact of uncertainty on wellbeing.

I am profoundly grateful to all the staff, researchers and PhD students who worked collaboratively on this programme. All contributors are recognised either as authors or acknowledged collaborators in the peer-reviewed publications included in this report. Most importantly, I extend my sincere thanks to the many families who generously participated in all our studies. Their involvement has advanced our understanding of critical questions affecting both the nuclear test veteran community and the broader field of radiation effects.

This report brings together all the outputs generated under this programme to provide a comprehensive overview of the research, its key findings, and the recommendations that emerge from them.

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Executive Summary

For decades, British nuclear test veterans and their families have expressed concerns about potential health risks from radiation exposure during nuclear test operations. Specifically, they have questioned whether they may have received sufficient radiation to cause harm in themselves and whether genetic damage might have been passed down, affecting the health of future generations. The CHRC's interdisciplinary research programme was established to, in part, investigate these concerns. This report brings together findings from cytogenomic, psychosocial, and wellbeing studies.

Cytogenomic research

A major component of the programme—the Genetic and Cytogenetic Family Trio (GCFT) Study—was designed to explore whether a heritable genetic legacy associated with radiation exposure existed among British nuclear test veterans. To address this, we recruited family trios comprising a veteran, the child's mother, and an adult child conceived after the veteran's final deployment to a nuclear test site. Veteran participants were selected based on their likelihood of exposure to ionising radiation and matched with veterans who served in tropical regions but did not participate in nuclear testing.

Using advanced genetic techniques, including whole-chromosome painting and whole-genome sequencing, the study aimed to answer two primary questions:

1. Is there chromosomal evidence of past radiation exposure in nuclear test veterans?
2. Is there evidence of genetic changes—either inherited or acquired—in the adult children of these veterans?

Key Findings:

- Overall, the results are reassuring. We found no chromosomal evidence of past radiation exposure in the sampled cohort of nuclear test veterans. Specifically, there were no significant differences in simple or complex chromosomal aberrations between nuclear test and control veteran cohorts.
- Similarly, we found no significant difference in de novo (newly arising) germline mutations between children of nuclear test and control veterans, and no evidence of constitutional chromosomal abnormalities in children of nuclear test veterans.
- Cytogenetic indicators of genomic instability did not differ significantly between adult children of nuclear test veterans and control cohorts.

Certain nuclear test sub-groups did exhibit notable findings, particularly in veteran families with higher radiation exposure risks:

- A small subset of veterans with higher potential for radiation exposure (e.g., Maralinga veterans, N=5) exhibited increased average frequencies of complex aberrations—a possible indicator of historical internal contamination with alpha-emitting radionuclides such as plutonium-239.

- A small group of adult children (N=4) born to veterans with higher exposure potential showed a weak statistical increase in chromatid-type aberrations, a cytogenetic indicator of genomic instability. This observation was not statistically robust and should be interpreted with caution.
- Mutation signature analysis identified a specific DNA mutation pattern (signature SBS16) appearing more frequently in the germline of a small number of families (N=8; 6 nuclear test and 2 control). This subgroup showed a weak association with higher average frequency of complex chromosomal aberrations in veterans and a stronger trend between unstable aberrations in fathers and chromatid-type aberrations in their adult children. These findings require further research to determine biological significance, if any.

Although more nuclear test veteran families reported congenital anomalies in children or grandchildren compared to controls—likely reflecting participation bias—we found no statistically significant relationship between veterans' chromosomal aberration burden, germline mutation frequency, adult child genomic instability, and reported family health issues. This suggests that if any effect exists, it may be too small to detect with current methods or is unrelated to radiation exposure and/or genetic damage.

Summary: For most British nuclear test veterans and their families, the GCFT study found no chromosomal or genomic evidence of radiation exposure or heritable changes. A small group of veterans with high exposure potential did show more complex chromosomal aberrations, consistent with internal contamination observed in other exposed populations. The meaning of the observations involving mutation signature SBS16 in a small subset of families is not known and requires further investigation in larger known radiation-exposed cohorts.

Somatic DNA mutations accumulate in all human cells throughout life. To assess the somatic mutational landscape in veterans, we analysed publicly available whole-genome sequencing data generated as part of the GCFT study. Our aim was to identify DNA variants in veterans present at nuclear test sites and compare these with age-matched controls.

Findings:

- No significant differences in somatic mutation burden were observed between nuclear test veterans and control cohorts.
- This corresponds with earlier findings which showed no difference in overall chromosome aberration frequency between the two veteran cohorts.
- Age-related mutational signatures (SBS1, SBS5) dominated across both cohorts, reinforcing ageing as the primary driver of somatic variation.

Other radiation-exposed populations

To broaden our understanding, we systematically reviewed published research (1988–2022) on whether parental exposure to ionising radiation can lead to adverse effects in unexposed children. Published studies were assessed for bias, including the timing of exposure—

particularly instances where post-conceptional exposure (e.g. in utero or postnatal) could not be ruled out—and grouped by health outcomes: pregnancy outcomes, genomic anomalies, cancers, and other diseases. Exposure scenarios included occupational, medical (non-cancer related), environmental, and atomic bomb.

Findings: For most health outcomes, evidence was insufficient to formally assess radiation-related effects in offspring. Variability in study design and inconsistent reporting were major limitations. A possible association was noted for congenital abnormalities in offspring of occupationally exposed individuals, but methodological weaknesses reduced confidence in this finding. Overall, if adverse health outcomes occur in unexposed children of exposed parents, they are likely small and difficult to measure reliably. Harmonised research protocols and expanded cohort studies are needed.

Psychosocial and wellbeing

The programme also examined psychological impacts of being a nuclear test veteran. A review of published literature found that perceived radiation exposure—even at low doses—can cause persistent psychological stress, which may negatively affect cognitive functioning. Inflammation is mechanistically relevant in both psychological stress and low-dose radiation exposure.

Among 89 British nuclear test veterans, 34% showed clinically significant anxiety—more than double the expected rate (~15%) in older men. Interviews revealed distress linked to perceived exposure and uncertainty about health consequences, including effects on future generations. This observation reflects the potential participation bias in the GCFT study where more nuclear test families self-reported health concerns.

Health perceptions and the causal attributions of physical health conditions were explored in interviews with 19 veterans. Some veterans expressed dissatisfaction when health issues were attributed solely to ageing, viewing this as dismissive given their unique historical context.

The research highlights that the healthcare experience may be improved by clinicians' understanding of the context and listening to veterans' beliefs or perceptions about their health conditions or symptoms.

Life histories from 29 members of the nuclear community highlighted themes of identity, isolation, and wellbeing. While many veterans remain active and socially engaged, others struggle with unresolved health concerns and loneliness. Understanding these experiences is essential for shaping inclusive public health and veteran support strategies.

Education and Engagement

Evidence-based resources have been developed to inform non-scientific audiences and are disseminated via www.chrc4veterans.uk, stakeholder magazines, events, and outreach initiatives.

Conclusion

This report deepens understanding of the impact of nuclear test participation on British veterans and their families. Although no definitive genetic harm was identified, further research is needed to interpret observations. The psychological burden of perceived exposure and the complexities of ageing within this community, including within the descendants, underscore the importance of ongoing scientific investigation and holistic support strategies. Policymakers and healthcare providers should integrate biological, psychological, and social dimensions to improve wellbeing for British nuclear test veteran communities and similar groups.

Recommendations to advance research and support

The research programme contributes valuable new evidence to the field of radiation genetics and the historical record of the British nuclear test programme. While we found no statistical evidence of heritable genetic changes, the GCFT study and the broader work at CHRC identified (a) a genetic feature in small subset of families that requires investigation to understand the biological meaning in relation to radiation and health, if any and (b) measurable psychological impacts on the community that requires addressing through policy and healthcare initiatives. The following recommendations are proposed:

1. Strategic investment in research on mutation signatures

Given the multiple observations involving families in the high-SBS16 subgroup, there is a compelling need for targeted research funding. This should prioritise:

- investigation of mutation signatures in populations with documented radiation exposures, including from α-particle emitters.
- investigation of co-occurring environmental, genetic, or lifestyle factors that may modulate these mutation profiles.

This evidence-based approach will not only enhance our understanding of mutational processes but also inform public health strategies.

2. Establish long-term health monitoring and support for descendants

Despite the absence of statistical evidence of heritable genetic changes, the higher levels of self-reported health concerns and persistent anxiety of intergenerational concerns among veterans and families underscore a need for proactive intervention. Policymakers should prioritise:

- Implementation of targeted, long-term health monitoring programmes for descendants, with a focus on early detection, mental health support, and tailored clinical follow-up.
- Development of family-centred support frameworks, including accessible information resources, psychosocial services, and community engagement initiatives to address ongoing concerns and reduce anxiety.

This approach acknowledges the lived experiences of affected families. It reinforces public trust in health governance by demonstrating a commitment to precautionary care and intergenerational wellbeing.

3. Training for Healthcare Providers on Radiation-Related Health Concerns

Psychosocial evidence clearly demonstrates that exposure-related anxiety is both real and measurable, yet many veterans report feeling dismissed or misunderstood in clinical settings. To address this gap, it is imperative that:

- General Practitioners and frontline clinicians receive training on the recognition and management of radiation-related health concerns, including psychosocial impacts and long-term risks.

- This training should be integrated into the Veterans Aware accreditation programme, led by the Veterans Covenant Healthcare Alliance, ensuring consistency across NHS Trusts.

By embedding this expertise within routine healthcare provision, trust can be improved to ensure that veterans and their families receive informed, empathetic care.

4. Strengthen public communication and scientific literacy on radiation concerns

While current scientific evidence does not support a link between pre-conception radiation exposure and serious health effects in offspring, public concern—particularly among affected families—is both understandable and persistent. To address this, policymakers should:

Invest in the co-creation of accessible, evidence-based communication resources, developed in collaboration with scientists, healthcare professionals, and affected communities.

5. Establish and expand multi-generational family trio cohorts for radiation research

To advance scientific understanding of the long-term and intergenerational effects of radiation exposure, it is essential to establish and expand structured cohorts of family trios—comprising exposed individuals, their partners, and offspring. Priority should be given to:

- Systematic recruitment of cohorts from known radiation-exposed populations, such as nuclear industry workers.
- Provision of sustained funding and infrastructure to support longitudinal data collection, biological sampling, and psychosocial assessments across generations.

This initiative will create a robust evidence base to inform future health policy, risk assessment, and public communication.

Conclusion

These five recommendations represent a comprehensive strategy to address the complex legacy of actual and perceived radiation exposure. As the use of medical radiation increases and global risks of nuclear exposure persist, their implementation is also essential for understanding intergenerational health risks in other radiation-exposed populations.

The Genetic and Cytogenetic Family Trio (GCFT) Study

This work was carried out by Ninoshka Barros, Kai Craenen, Frances Daley, Kirsty Lawrence, Jose Seixo, Martin Scholze, Jade Stephens and Rhona Anderson in collaboration with Laurette Bukassa, Clare Gilham, Christine Rake and Julian Peto from the Department of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine, London and Yuri Dubrova and Alex Moorhouse from the Department of Genetics and Genome Biology, University of Leicester, Leicester.

An overview of the key findings of this study is presented here. A more detailed account is given in the GCFT Study Report and open access publications Lawrence., et al (2024) [1], Moorhouse, et al., (2022) [2], Rake, et al, (2022) [3], Stephens et al., (2026) [4].

Background

The Genetic and Cytogenetic Family Trio (GCFT) Study was designed in response to long-standing concerns that veterans of the British nuclear testing programme may have received sufficient radiation exposure to cause genetic damage in themselves, and that these genetic changes could potentially be passed to their children affecting the health of future generations.

Aim of research

For this, we undertook a 'family trio' study that involved:

i. Recruitment of military veteran families
ii. Examination for any cytogenetic evidence of past exposure of the nuclear test veterans
iii. Examination for any evidence of genetic anomalies in 1st generation children of nuclear test veterans.

Recruitment of military veteran families

Eligible nuclear test and control veterans were identified from the UK Nuclear Test Veteran (NTV) cohort [5].

To select nuclear test veterans with the highest likelihood of radiation exposure, a long list of 1,459 nuclear test veterans was chosen if they were aged 80 or younger and had participated in two or more operations, including the GRAPPLE X, Y, and Z series or Maralinga tests, or were listed as special group members. An additional 42 veterans aged 82 or younger from specific high-exposure groups—such as the HMS Diana crew, Active Handling Flights, and Air Sampling Plume teams—were also included.

Using this list, NHS Digital obtained contact details for the veterans' general practitioners (GPs) for 908 nuclear test and 3,796 control veterans, enabling the team to invite participants via their GP practice. All 908 nuclear test and 2,741 control GPs were contacted with the request to forward invitation packs. Eligible veterans were asked to share study details with a child conceived after the veteran's last deployment to a nuclear test site. If the couple had more than one child, the first child conceived post-deployment was requested. Interested adult children were also screened and, with GP confirmation of eligibility, provided written consent. Participants were excluded if they had undergone chemotherapy or radiation therapy for any condition, as such treatments could cause genetic damage and confound the results.

After consent, blood was drawn by the participant's GP, shipped to Brunel University of London within 24 hours and processed under Human Tissue Authority guidelines. Cytogenetic analysis was performed at Brunel and whole genome sequence analysis at the University of Leicester. Blood samples were received from 91 families—49 nuclear test and 42 control—comprising veterans from the Army, Royal Air Force (RAF), and Royal Navy (RN).

Most veterans in the UK NTV cohort have no recorded dose as only a proportion were issued with film badges and no measurement for internal contamination took place. Accordingly, nuclear test veterans were assigned (blind to any results) to a simple three-point rank for the potential of internal/external exposure based on veterans' testimony and operation information drawn from the UK NTV cohort. Each case was *a priori* assumed to be in the lowest rank, and a higher rank allocated only if sufficient information was given to suggest a higher likelihood for radiation exposure e.g. a defined role in a contaminated or forward area (e.g. aircraft sample retrieval/cleaning) undertaken more than once. Geographical location of the test site was also considered relevant. For instance, the potential for a veteran working in a 'forward area' at Maralinga to be exposed to both external and internal radiation was assumed to be higher than a veteran who witnessed an atmospheric test in the safety zone (~40 km from the blast) on Christmas Island. Thus, although this "potential for exposure" ranking cannot be considered a substitute for recorded radiation dose, it was employed as a proxy from which sub-groups of the nuclear test cohort could be defined.

Among the nuclear test veterans, 19 (39%) were categorised as having medium or higher exposure potential, including 13 previously identified as part of special groups or recorded in Health Physics documents.

Cytogenetic markers of past and/or ongoing internal exposure

Ionising radiation is known to cause DNA double-strand breaks (DSBs), a key lesion leading to structural chromosomal aberrations. Fluorescence *in situ* hybridisation (FISH), a technique that "paints" individual chromosomes, enables the detection of structural changes such as reciprocal translocations, and is widely validated for assessing historical radiation exposure.

Reciprocal translocations are informative of radiation dose, as they are stable in cells over time and can persist in the body for decades following exposure. However, chromosomal translocations also accumulate naturally with age due to other factors. To provide a more comprehensive view, multiplex-FISH (M-FISH), which uniquely colours all chromosomes to identify more complex patterns of rearrangement, was employed. Complex chromosomal aberrations, involving three or more breaks across two or more chromosomes, are typically induced by low doses of high-linear energy transfer (LET) radiation such as alpha particles.

The frequency and type of chromosome aberrations observed by M-FISH are thus potentially informative of radiation exposure, dose and radiation type.

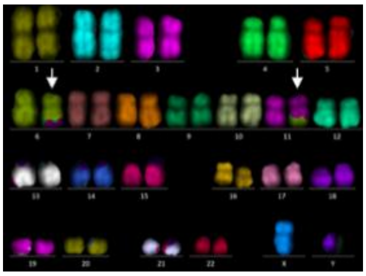

Figure 1: Representative M-FISH karyotype. Chromosomal abnormalities seen as colour changes.

This part of the study aimed to investigate whether there was any chromosomal evidence of past radiation exposure of nuclear test veterans. For this, blood samples from 91 veterans (48 nuclear test and 38 control) were analysed using M-FISH.

Both nuclear test and control veteran cohorts exhibited stable (e.g. reciprocal translocations) and unstable (e.g. dicentrics) simple and complex aberrations. Overall, we found no statistically significant differences in the frequency of any chromosome aberration type between the two cohorts. This suggests that—within the detection limits of this study—the sampled British nuclear test veterans did not experience radiation exposure sufficient to cause long-lasting chromosomal changes detectable by M-FISH. This finding provides reassurance to veterans and their families, as the chromosomal evidence does not support widespread significant radiation exposure among the nuclear cohort.

Higher average frequencies of complex chromosome aberrations were, however, seen in a small group of nuclear test veterans. For example, veterans at Maralinga (N=5) with a higher potential for radiation exposure exhibited a complex aberration frequency of 0.803±0.191 per 100 cells, which was higher than the nuclear test cohort overall (0.299±0.075 per 100 cells). An associated increase in unstable aberrations, including elevated dicentric equivalents (0.688±0.305 per 100 cells), was also seen in this subgroup. This is relevant because the presence of unstable chromosome aberrations of this type suggests their formation to be relatively recent events within the lifespan of the cell. A raised average frequency of complex and unstable aberrations was also seen in a small group of nuclear test veterans who were onboard ships (N=4; 3 out of the 4 personnel were on HMS Diana).

^{239}Plutonium, a long-lived alpha-emitter, is a known component of nuclear fallout. If inhaled, it accumulates in the liver and skeleton, with a small portion excreted in urine over time. ^{239}Plutonium is also encountered in industry; however, varying isotopic ratios of $^{240}Pu/^{239}Pu$ can be used to establish the potential source of Pu, as the isotope in weapons is primarily ^{239}Pu.

The potential for detecting $^{240}Pu/^{239}Pu$ in the urine of nuclear test veterans after this length of time (~60 years) was limited; however, a pilot study was undertaken to analyse urine samples from 20 veterans (nuclear test and control) using accelerator mass spectrometry. Initial analysis shows two veterans to show detectable levels of plutonium both with large uncertainties, one of which had an elevated complex aberration frequency and had reported working in the nuclear industry. No other participants had detectable plutonium levels (Jerome et al. in prep, personal communication).

Thus, we cannot corroborate from this urine analysis that the origin of the complex chromosome aberrations observed in the small group of nuclear test veterans present at Maralinga or on-board ships is associated with ongoing exposure to internalised radionuclide contamination. However, we can infer this is a likely explanation given what we understand about the mechanistic formation of complex aberrations from α-emitters [6, 7] and the potential for internalised radiation exposure in these subgroups.

Genetic anomalies in 1st generation descendants

Constitutional chromosomal abnormalities

Constitutional aberrations are defined as alterations in the number or structure of chromosomes present in all cells of an individual at birth and which are typically associated with a distinct set of clinical features. This part of the study aimed to investigate whether children born to nuclear test veterans displayed any constitutional chromosomal abnormalities.

We examined for but found no evidence of any constitutional chromosomal abnormalities in a sample of adult children born to nuclear test veterans. All individuals exhibited apparently normal karyotypes—46,XX or 46,XY—including those from families who self-reported adverse health effects.

Genomic instability in somatic cells

Genomic instability is defined as an increased tendency for the accumulation of diverse genomic alterations including DNA mutations, chromosomal aberrations, epigenetic changes and dysregulated gene expression. From a cytogenetic perspective, this may manifest as both stable and unstable chromosomal exchanges—such as reciprocal translocations or dicentrics—as well as chromosome breaks, fragments, chromatid-type (affecting just one DNA strand) and numerical aberrations.

Figure 2: Representative example of chromatid break.

Animal studies have demonstrated that radiation or chemical exposure to the germline can lead to increased frequencies of mutations and chromosomal aberrations in offspring, a phenomenon termed transgenerational genomic instability (TGGI). However, evidence for radiation-induced TGGI in humans remains inconclusive.

This part of the study aimed to investigate whether children born to nuclear test veterans displayed any cytogenetic evidence of genomic instability. For this, blood samples from 33 nuclear test and 26 control adult children were cultured to obtain first-division metaphase cells and Giemsa-stained for brightfield analysis.

No statistically significant differences in the overall frequencies of unstable structural chromosome aberrations (1.61±0.24 and 1.63±0.28 per 100 cells), chromatid aberrations (4.68±0.69 and 4.36±0.62 per 100 cells), or aneuploid cells (8.40±0.69 and 6.42±0.99 per 100 cells) were seen between nuclear test and control cohorts, respectively.

When the analysis was stratified by nuclear test veteran father subgroups, some differences were seen. Specifically, a small group (N=4) of adult children born to veterans who had served onboard ships during the tests (higher exposure rank) showed elevated chromatid aberrations—both in complete (7.8±4.01/100 cells) and aneuploid (1.75±1.18/100 cells) cells — which may reflect ongoing genomic instability. While these differences were statistically significant (p=0.02 logistic regression), they did not remain robust under sensitivity analyses. Accordingly, these observations should be interpreted with caution and warrant validation in larger cohorts.

Germline mutations

De novo mutations (DNMs) are genetic changes that appear for the first time in a child but are absent from the parents' genomes. Exposure to ionising radiation is known to increase the mutation burden, with evidence from animal studies showing increased DNMs following parental exposure to acute high doses of radiation. In humans, the data is mixed. Whole genome sequencing allows for comprehensive identification and analysis of DNMs across the entire genome.

This part of the study aimed to investigate whether there was any evidence of increased newly arising mutations (DNMs) in the germline of nuclear test veterans. For this, blood-derived DNA from 60 family trios (30 nuclear test and 30 control) was sequenced to a high depth (average >35x coverage) to ensure reliable detection of de novo single nucleotide variants (SNVs), insertions/deletions (INDELs) and structural variants (SVs). Variant calling was conducted using standard, validated bioinformatics pipelines. DNMs were identified by comparing the genomes of children with those of their biological parents, and all candidate mutations underwent strict quality control filtering to remove artefacts.

Overall, we found no significant differences in mutation burden between the nuclear test and control cohorts for any DNM type. These results align with other large-scale studies investigating potential heritable genomic effects of parental radiation exposure, such as those involving Chernobyl cleanup workers [8].

Single-base substitution (SBS) signatures, along with other mutational signatures, represent identifiable patterns of DNA changes that are increasingly recognised across various cancer types. In non-cancerous cells, such signatures are of interest because they reflect distinct patterns left in the DNA following damage and repair. Thus, mutation signatures can act as ‘fingerprints’ of the damaging exposure and/or the underlying mutational processes involved. The Catalogue of Somatic Mutations in Cancer (COSMIC) is a growing database of all identified mutational signatures [9].

To determine whether the germline SNVs identified in this study aligned with known mutational signatures, the total of 3,719 de novo SNVs detected in both control and nuclear test families were analysed using the COSMIC v3.2 database (March 2021). Several SBS signatures were found to differ significantly between the cohorts, with SBS16 showing the largest difference (control: 432; NT: 569; $p < 0.01$). A small group of families, hereon in termed as the high-SBS16 group (N=8; 2

control and 6 nuclear test), likely accounted for this overall significant difference in SBS16 (Figure 3).

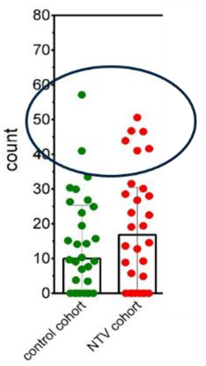

Figure 3: Total number of SNVs allocated to mutation signature SBS16. The high-SBS16 sub-group (N=8) was determined as those with >40 SNV mutations meaning the high-SBS16 subgroup comprised 2 control and 6 nuclear test families.

It cannot be ruled out with sufficient confidence that this small group represents a random finding. That said, the six nuclear test families with the highest SBS16 counts did not show any associations with known confounding variables, including child age at sampling, paternal age at conception, history of paternal occupational radiation or chemical exposure, medical imaging, alcohol or smoking. Further, four involved veterans classified as having the highest potential for radiation exposure ranking (includes two with a recorded dose of 0.4 and 1.4 mSv).

As discussed later, further study is needed to determine whether the SBS16 enrichment in these families is a meaningful biological finding or a statistical anomaly.

Examination for transgenerational Effects

This summary of the GCFT study thus far shows a series of comparisons between control families, nuclear test families, and subgroups within the nuclear test cohort, for either veteran or adult child.

To investigate potential transgenerational relationships of genetic burden within families, we matched veteran father–child datasets (in which both individuals had undergone analysis) to examine whether the father's chromosomal aberration burden was associated with the frequency of de novo germline mutations or somatic aberrations in their children.

Complex chromosome aberrations and mutation signature SBS16

We analysed families for which both M-FISH data from the veteran father and WGS germline data were available (30 nuclear test and 28 control families). When comparing the nuclear test and control cohorts, no significant associations were found between the father's total chromosomal damage or complex aberration burden and the number of germline DNA mutations in the child.

A different picture emerged when analysis focussed on families previously identified as the high-SBS16 group. We found a weak statistical association between the high-SBS16 group and increased average frequencies of complex chromosomal aberrations in the fathers, with p-values of 0.054 (Wilcoxon rank-sum test) and 0.032 (negative binomial regression).

These findings suggest a potential link between the presence of mutation signature SBS16 in the germline and complex chromosomal aberrations in veteran fathers, which as discussed earlier, may be indicative of long-lived internalised radionuclide exposure. This raises the possibility that SBS16 represents a molecular signature of radiation-induced DNA damage processing and, therefore, could serve as a candidate transgenerational biomarker of paternal radiation exposure. This is interpretation is complicated however by the presence of two control families within the high-SBS16 subgroup.

Genomic instability and mutation signature SBS16

We examined families for which both M-FISH data from the veteran father and Giemsa-stained chromosomal data from the adult child were available (33 nuclear test and 24 control families). The focus was on unstable chromosomal aberrations in veteran fathers—such as dicentric equivalents and all chromosome fragments. Chromatid aberrations were quantified from DAPI-stained metaphase spreads obtained from the M-FISH images.

When matched veteran father–adult child pairs were grouped by cohort (nuclear test or control), a non-significant upward trend was observed between paternal unstable aberration burden and the occurrence of both unstable chromosome- and chromatid-type aberrations in adult children from nuclear test families. No such trend was observed in control families.

Through modelling, we observed an association between increased unstable aberration burden in veteran fathers—including complex aberrations—and higher frequencies of chromatid aberrations in their adult children, which was stronger within the high-SBS16 subgroup. Thus, higher aberration frequencies in veteran fathers were linked with higher predicted frequencies in their children compared to the low-SBS16 group.

Although this observation may imply a relationship between cytogenetic markers of radiation exposure in the father (complex aberrations) and markers of effect (genomic instability) in their adult child, cautious interpretation is required. The many caveats already highlighted (small subgroups, presence of controls in subgroup, lack of radiation dosimetry), all downplay the confidence of this finding.

Self-reported health conditions

During the recruitment interview, both control and nuclear test veterans were asked whether they were aware of any birth defects, genetic disorders, inherited diseases, or cancers affecting their children or grandchildren. A significantly higher proportion of nuclear test families reported congenital abnormalities in their children or grandchildren compared to controls. This likely reflects heightened concern among nuclear test veterans, which may have influenced participation in the GCFT study.

Specifically, one-fifth of nuclear test veterans reported at least one child or grandchild with a congenital abnormality—including two stillbirths—compared to a much smaller number reported by control families (Fisher's Exact $p = 0.03$). No significant differences were found in reported cancer or non-cancer diseases among children (mean age: 53 years) between the nuclear test and control groups (Fisher's Exact $p=0.19$ and $p=0.6$, respectively). Moreover, significantly more health concerns were reported by veterans subsequently assigned to the higher potential for radiation exposure rank (across all geographic locations); controls (0.104; 5/48 families), lower and medium exposure potential (0.31; 11/35 families), and higher exposure potential (0.429; 6/14 families) ($p < 0.1$).

Of the families who reported at least one health condition, only one control and six nuclear test families provided blood samples from the affected child (the study protocol requested blood samples from the first child conceived after the father's last tour at a nuclear test site).

Among families reporting a health concern, we found no evidence of elevated chromosomal aberration burden in the veteran father. Furthermore, there was no statistically significant association between paternal unstable aberration burden and genomic instability markers—whether chromosome-type or chromatid-type—in the adult children of nuclear test veterans, even when grouped by specific health outcomes such as congenital disorders or cancer diagnoses.

Thus, in the broader context of health concerns reported by nuclear test families, we found no statistically significant relationship between paternal chromosomal aberration burden, germline mutation frequency, genomic instability, and self-reported adverse health outcomes in children or grandchildren.

GCFT study concluding remarks

In conclusion, this study found no chromosomal evidence of past radiation exposure in most nuclear test veterans sampled, offering reassurance that attendance at nuclear test sites was not associated with detectable levels of radiation exposure. However, a small number of veterans—categorised as having a higher risk of exposure—did show increased average levels of complex chromosomal aberrations. This may suggest internal contamination from radioactive fallout in a very small subset of veterans.

For adult children of nuclear test veterans, we found no evidence of constitutional chromosomal abnormalities or elevated genomic instability (when examined as a cohort), including among families that reported adverse health effects in one or more children or grandchildren. These findings should provide reassurance to concerned families, as no genetic effects or elevated chromosome aberration burdens in veteran fathers were observed that could be attributed to participation in nuclear tests.

A very small group of families (N=8; nuclear test and control) did show a weak association between complex chromosomal aberrations in veteran fathers and an enrichment of germline mutations associated with mutation signature SBS16. This SBS16 signature also appeared to be positively associated with cytogenetic features of genomic instability in adult children raising the possibility of a relationship between enrichment of mutation pattern SBS16, or an unidentified factor co-occurring in these families, and transgenerational genomic instability. It is worth highlighting that four of the eight families within the high-SBS16 subgroup include veterans classified in the highest exposure category, including two who had recorded doses of <1.5 mSv. Additionally, three of the eight nuclear test and control families in this subgroup self-reported a congenital condition within the family. While preliminary, these observations warrant further investigation in other human populations with known exposure to ionising radiation—especially those involving internal contamination with alpha-emitters—to both corroborate this finding and to explore the biological significance, if any, of SBS16.

Overall, despite ongoing concerns raised by nuclear test families regarding adverse health outcomes, our study found no statistically significant relationship between paternal chromosomal aberration burden, germline mutation frequency, genomic instability, and self-reported family health issues. Therefore, the congenital and other health concerns reported in these families are not explained by our findings. This suggests that if there is any effect of historical radiation exposure in families recruited within the GCFT study, it is either too small to be detected by current methods or unrelated to the outcomes observed.

Somatic mutational landscape in veterans

This work was carried out by Justin Dankwa as part of his Doctoral studies, supervised by Dr Cristina Sisu and Prof Rhona Anderson. For more detail, please see Dankwa et al. (in revision).

Somatic mutations are present in all human cells and accumulate throughout life. They can arise from normal cellular processes, exposure to damaging agents, and the cellular responses to such damage. The human mutational landscape is broadly classified into three categories: point mutations—including single-nucleotide variants (SNVs) and insertions/deletions (INDELs); structural variants; and copy number variations.

Ionising radiation is known to increase the mutational burden. It deposits energy in structured tracks, influencing the spatial distribution of initial DNA lesions and, consequently, the type and location of resulting mutations. INDELs and clustered variants—where multiple mutations occur in proximity—are considered characteristic of radiation exposure.

As introduced above, COSMIC is a growing database of mutational signatures that link specific mutation patterns to cancer types and, offer insight into the DNA damage and repair mechanisms that shape them.

This part of the programme examined the somatic mutational landscape in veterans using publicly available whole-genome sequencing data (Accession: PRJNA788492) generated as part of the GCFT study. Specifically, it aimed to compare genetic variation between control and nuclear test veterans and explore for any impact on gene function.

Overall, we found no increased occurrence of any mutation (variant) type, including those reported as radiation signatures, in nuclear test veterans compared to aged-matched control veterans. This lack of variation implies a shared genetic background and similar environmental, occupational, and lifestyle exposures across both cohorts. These findings are consistent with the cytogenetic data from the GCFT study which found no cohort level evidence of past radiation exposure in the nuclear test veterans.

Mutational signature analysis revealed SBS1 and SBS5 to be dominant across both veteran cohorts. These mutation signatures are strongly correlated with age, reinforcing ageing as the primary driver of genetic variation. SBS16, which as outlined above was identified as a dominant signature in the germline of a small group of families, was not seen to be enriched in veterans meaning we cannot corroborate SBS16 as a signature of molecular processing of radiation-induced DNA damage from this analysis. Further work is required as it is known that SBS16 may partially contaminate SBS5. Additionally, there are approximately 1000-fold more somatic mutations in veterans than there are de novo germline mutations, consistent with their accumulation with age, contributing to a large background noise level.

The functional impact on gene function and activity, if any, of the somatic mutations identified was assessed. This was carried out by exon variant analysis, which focuses on protein-coding genes, long non-coding RNAs (lncRNAs), and pseudogenes, as these regions are typically subject to stronger selective pressures. Our findings reflect previous results with no statistically significant differences in the distribution of SNVs and INDELs between nuclear test and control veteran samples in annotated exonic regions.

To gain an insight into cohort-specific characteristics, we identified the most shared variants within each cohort. In the control group, the LINC02098-ETS1 variant was present in 14 of 30 individuals. While LINC02098 remains poorly characterised, ETS1 is a known oncogene and transcription factor involved in immune regulation, alopecia, and arthritis—conditions frequently associated with ageing. Given the age-matched design of the study, similar mutations were expected in the nuclear test cohort. Although a single common variant was not as prevalent among nuclear test veterans, multiple mutations at this locus were observed.

The second most frequent variant in the control cohort was linked to RCL1, a gene involved in ribosomal function and protein synthesis. RCL1 has been associated with neuropsychiatric disorders, including depression—conditions relevant to ageing populations. Another gene with a high number of shared variants in controls was IGLV1-47, which plays a role in immune response and may reflect age-related mutational enrichment.

In the nuclear test cohort, CHODL variants were identified in 12 of 30 individuals (~40%) with several veterans sharing the same variant(s). CHODL encodes chondrolectin, a cell adhesion protein involved in tissue structure and cell signalling. CHODL also plays a role in maintaining the normal functioning of the nervous system, thus, variants in this gene could infer impact to muscle control and movement.

Another gene enriched in nuclear test veterans was BAZ1A, which encodes the chromatin remodelling factor ACF1. BAZ1A is involved in Wnt signalling and the regulation of genes critical to nervous system development. Its downregulation has been linked to cellular senescence, further supporting the role of ageing in shaping the observed variant landscape.

Summary of findings

Overall, no significant differences in somatic mutation burden were observed between control and nuclear test veterans. The distribution of SNVs, INDELs, and mutation clusters was consistent across cohorts and aligned with broader population data. Mutational signature analysis and dominant genes identified reinforce ageing as the primary driver of somatic variation.

Pre-conceptional radiation exposure and transgenerational health

This work was carried out by Jade Stephens as part of her Doctoral studies, supervised by Prof Rhona Anderson and Prof Joanna Bridger. For more detail, please see open access publications Stephens et al [10] and Amrenova et al [11].

The adverse consequences of radiation exposure during pregnancy are known but the heritable effects of parental radiation exposure pre-conception remain to be fully understood. The consensus within the radiation research community is that no epidemiological (health outcome) study has yet conclusively demonstrated a detrimental health effect in the offspring of radiation-exposed people. This is tempered by some evidence from cellular and animal studies that support the presence of detrimental outcomes.

This part of the programme focussed on systematically examining the published evidence on health outcomes in the offspring of individuals exposed to ionising radiation prior to conception. The overall aim was to evaluate the strength of the published evidence.

In the review by Stephens et al., data were extracted from 127 eligible peer-reviewed studies published between 1988 and 2018. Each study was assessed for potential sources of bias, including the timing of parental exposure—particularly instances where post-conceptional exposure (e.g. in utero or postnatal) could not be ruled out. Health outcomes were categorised into four main areas: pregnancy outcomes, genomic anomalies, solid and non-solid cancers, and other non-cancer diseases and mortality. Within each outcome category, studies were further grouped based on the nature of radiation exposure: occupational (e.g. nuclear workers), medical (non-cancer related), environmental, or atomic bomb related. The conclusions drawn for each group were based on the authors' interpretations of the individual studies being assessed and the overall direction of statistical findings within each group.

Across most health outcome categories, the evidence was found to be 'inadequate' to determine whether an association exists between parental preconception exposure to ionising radiation and adverse health effects in unexposed offspring. This was largely due to inconsistencies in study findings, a limited number of relevant studies per outcome group, and variation in method design.

One exception was noted in the category of congenital abnormalities in offspring of occupationally exposed individuals, where a possible association with parental radiation exposure was observed. However, the small number of studies in this grouping and other limitations reduced the strength of this finding.

Overall, the review concluded that the current body of evidence does not support a reliable assessment of adverse transgenerational effects of ionising radiation exposure in humans. The review emphasises the importance that this conclusion should not be interpreted as evidence that no effects occur, but rather that if such effects exist, they are likely to be small, difficult to detect, and not consistently measurable using current research methods.

Stephens et al. also emphasised the wide variability in study design, quality, and data reporting across the literature, which hampered the ability to draw consistent conclusions. The review highlighted the need for greater standardisation in study protocols and the importance of open access to primary datasets to facilitate future meta-analyses and improve evidence synthesis.

The follow-up review by Amrenova et al identified nine additional eligible studies published between 2018 and 2022. As with the earlier findings, this review did not uncover substantial evidence of transgenerational adverse health effects in the children of individuals exposed to radiation prior to conception.

Summary of findings

These reviews offer a comprehensive view of the available evidence on transgenerational effects of preconceptional ionising radiation exposure in humans. While they do not provide support for a causal relationship, they highlight the methodological challenges and limitations inherent in this area of research. Continued investigation—employing harmonised protocols, larger sample sizes, and data sharing—is essential to better understand the potential risks, however small, of radiation exposure across generations.

Ionising radiation and the human brain.

This work was carried out by Justin Dankwa as part of his Doctoral studies, supervised by Dr Cristina Sisu and Prof Rhona Anderson. Full details of this work will be prepared for publication.

The impact of exposure to ionising radiation on brain function and cognitive processes remains insufficiently understood. In recent years, evidence has emerged suggesting radiation as a possible risk factor for cognitive impairment, characterised by deficits in learning, memory, and information processing ability. While consequences of prenatal exposure have been more extensively studied, there is much more uncertainty about the effects when exposure occurs in adolescents and adults, particularly at low (<100 mGy) to moderate (100 mGy-1-2Gy) doses, relevant for medical diagnostic, occupational or nuclear disaster exposures.

The aim of this research was to investigate the relationship between radiation exposure and gene expression, with a focus on brain function and activity. All the work involved leveraging publicly available transcriptomic (gene expression) sequence data to:

i. establish baseline information on the transcriptional landscape of the brain in normal and diseased states
ii. evaluate the effects of radiation exposure on gene expression in human cells

Gene expression profiles for normal and diseased brains

This part of the study explored how gene activity differs between healthy and diseased brains using published transcriptomic datasets.

In the healthy brain, many genes were consistently expressed, reflecting their role in essential cellular functions and homeostasis. Gene expression patterns tightly regulate processes such as synaptic transmission, stress responses, and metabolism.

When analysing brain tumours—lower-grade glioma and glioblastoma—most genes retained expression like normal brain tissue, suggesting a tendency to preserve the transcriptional landscape. However, cancer samples also showed clear shifts: genes linked to cell growth and proliferation were upregulated, while those involved in neuronal signalling and synaptic transmission were downregulated.

Alzheimer's disease data revealed significant dysregulated genes associated with oxidative phosphorylation, DNA repair, neuroinflammation, immune modulation, and apoptosis—pathways previously linked to Alzheimer's disease pathology. Downregulated genes correlated with loss of neuronal integrity, another hallmark of disease progression.

Finally, transcriptomic profiles of major depressive disorder, bipolar disorder, and schizophrenia highlighted distinct molecular signatures, including a unique pattern for schizophrenia.

Overall, these findings provide insight into the complex transcriptional (gene expression) landscape of the brain, from normal to diseased states and provides a baseline for comparisons with radiation-exposed datasets.

Gene expression in radiation exposed human cell lines

This part of the study examined publicly available transcriptomic data from human cell lines which were exposed to radiation in culture.

In brief, results show the number of differentially expressed genes to increase roughly tenfold from low to high radiation doses. Critical pathways such as DNA repair, oxidative stress response, and inflammatory signalling consistently showed gene expression changes. At low doses, gene expression shifted toward downregulation, suggesting a protective response to stress. Candidate biomarkers for low, moderate, and high radiation exposure are being explored.

Exposure worry in British nuclear test veterans.

This work was carried out by George Collett as part of his Doctoral studies, supervised by Dr Wendy Martin, Prof Rhona Anderson, Dr Will Young and Professor Mary Gilhooly. For more detail, please see open access publications Collett et al., 2020 [12], 2021 [13], 2022 [14].

The context of ionising radiation exposure is inherently uncertain. Its ‘invisible’ nature—particularly in the absence of dosimetry—and the unpredictability of potential future adverse health effects for the exposed individual and their descendants contribute to significant psychological impact. Here, psychological impact refers to any thought process related to perceived or actual ionising radiation exposure. Among these processes, worry (and its associated affective experience, anxiety) appears especially relevant to uncertainty about possible exposure.

Worry has been defined as a chain of negative thoughts concerning events that might occur in the future. It is often considered a cognitive problem-solving mechanism aimed at preparing for uncertain outcomes, albeit outcomes that are perceived as negative.

Research on the psychological impact in radiation-exposed populations stems from studies of Japanese atomic bomb survivors, which highlighted anxiety about acute radiation effects and the transmission of adverse health effects to future generations. Following the Three Mile Island accident, elevated biomarkers of psychological stress were observed among residents living near the power plant. Similarly, the Chernobyl and Fukushima nuclear power plant accidents were marked by widespread psychological consequences, regardless of the dose received.

Themes describing anxieties about radiation-related health effects for United States (US) nuclear test veterans and their descendants have been reported. Interviews with US test veterans revealed changes in identity, worldview, and lifestyle, including loss of employment and social relationships.

Anxiety issues among British nuclear test veterans are shown, for example, by the Miles et al health needs audit [15]. They reported that 4% of participants were “extremely anxious or depressed,” while 31% were “moderately anxious or depressed.” Although these findings indicate mental health concerns among British veterans of the nuclear testing programme, it remains unclear whether these issues are specific to anxiety, depression, or both.

Aim of the Study

The aim of this component of the research programme was to examine the extent of exposure-related worry among British nuclear test veterans; to identify factors associated with such worry and explore the broader psychological impact of the British nuclear testing programme.

Psychological stress

The psychological consequences of low-dose and perceived radiation exposure—where the actual dose was no greater than background levels—were assessed in a comprehensive review of the literature. The research asked whether perceived radiation exposure can result in psychological stress, which in turn, negatively affects cognitive functioning.

Overall, the evidence showed prenatal exposure to low (<100 mGy) and moderate doses (100 mGy-1-2Gy) of ionising radiation can lead to problems with brain development and subsequent cognitive functioning, but the evidence for adolescent and adult low- and moderate-dose exposure resulting in similar problems remains uncertain.

The review showed that the persistent psychological stress from the worry of low-dose exposure in adulthood could pose a greater threat to cognitive functioning than the actual exposure itself. It also discussed the similarities in the ways ionising radiation and psychological stress can affect cognitive functioning. For instance, inflammation is relevant for both meaning the physical effects of worry and stress need to be considered when estimating the impact of low doses of ionising radiation.

Exposure worry

Using a validated tool to assess clinical anxiety in older adults, Collett et al 2021 examined the extent of exposure worry in 89 British nuclear test veterans. This was accompanied by follow-up in-depth interviews with 19 veterans to explore the broader psychological context of their experiences.

A higher prevalence of clinically relevant anxiety was found among nuclear test veterans (34%) compared to the general older population (~15%). This exceeds the prevalence of anxiety previously thought to exist in this population, although the potential for selection bias is acknowledged.

The emotional impacts of perceived exposure varied. While some veterans reported little or no psychological distress, others expressed deep concern—particularly for the health of their children and grandchildren rather than their own. This aligns with existing research on age-related patterns of worry, in which older adults often prioritise the wellbeing of loved ones over personal health concerns. For some, especially those with seriously ill family members, this worry was tied to feelings of guilt and responsibility.

Many veterans also reported feelings of betrayal and anger toward authorities, citing perceived negligence and lack of transparency.

Health perceptions

Collett et al 2022 extended this work by exploring health perceptions and the causal attributions of physical health conditions.

In interviews with 19 veterans, some expressed a sense of luck regarding their own health and that of their families. This perception often involved comparisons with peers and was shaped by personal beliefs about ageing, lifestyle, and family history. Others did not, expressing dissatisfaction when healthcare professionals attributed their conditions solely to getting older. This response was viewed by some as dismissive, especially given the unique historical context of their involvement in nuclear tests.

The medical uncertainty regarding the causes of health conditions complicates the experiences with healthcare providers, especially in the context of nuclear weapons testing. However, the research highlights that the healthcare experience may be improved by clinicians' understanding of the context and listening to veterans' beliefs or perceptions about their health conditions or symptoms.

Figure 4: Components of exposure worry

Summary of findings

This study has extended our understanding about the psychological impact of perceived ionising radiation exposure in this unique cohort. Identification of mechanisms to mitigate exposure worry is therefore essential for ensuring healthy ageing, including for their families and in similar groups affected by environmental exposures.

The study emphasised the value of clinicians having knowledge of veterans lived experiences and engaging with their beliefs about illness causality. Doing so may enhance trust, improve healthcare outcomes, and offer more holistic support to this population.

Complexities of identity, health and wellbeing, and the ageing process.

This work was carried out by Amy Prescott as part of her Doctoral studies, supervised by Professor Louise Mansfield and Dr. Alistair John.

Veterans of the British nuclear testing programme represent a population of ex-military personnel who could be considered as marginalised for two reasons; one, they belong to the oldest old category (85yrs+), and two, they were denied the opportunity to speak about their experiences for several decades due to the National Secrets Act. The National Secrets Act (now the Official Secrets Act) imposed strict confidentiality on individuals involved in sensitive government projects. British nuclear test veterans were bound by these legal restrictions, prohibiting them from discussing their experiences or the programme's details publicly. This extended to matters of health, safety, and exposure to radiation, effectively preventing them from seeking recognition or accountability. Violating the Act risked severe legal penalties, fostering a culture of secrecy. Only in recent decades have some veterans spoken out, advocating for justice and highlighting the long-term health impacts they believe they have suffered due to the tests.

Wellbeing, encompassing the concepts of happiness and quality of life, has become a significant focus in recent years across research, policy, and public health. Effective interventions aim to improve mental and physical health for the broader population rather than focusing on specific groups.

Among older adults, factors like a sense of purpose, physical activity, and social connections significantly impact wellbeing. Loneliness, especially among older adults, veterans, and widowed individuals, poses a major risk to wellbeing. Research links chronic loneliness to poor physical and mental health outcomes, including depression, dementia, and increased mortality.

Armed forces veterans, who often face isolation due to life transitions, bereavement, and health issues, are particularly vulnerable. Although digital tools offer social connectivity, they can also exacerbate feelings of exclusion for those unable to engage effectively. Improving wellbeing requires holistic, inclusive approaches that address physical health, mental resilience, and social inclusion, particularly for vulnerable groups.

Thus, the overall purpose of this part of the programme was to explore the life histories, lived experiences and lifelong impact of being a British nuclear test veteran.

41 life-history interviews (telephone and face-to-face) were conducted over two rounds of data collection with 29 members of the British nuclear test community (veterans, wives, and widows) between 2018 and 2019. For the first round, interviews were unstructured and used to understand their biography; broad topics were used and included armed forces history, nuclear testing experience, current health and wellbeing, politics of the British Nuclear Test Veterans Association (BNTVA), family life, and daily activities. The second round of interviews were more structured, with questions developed from the first round, including tailored questions for each person. The interview recordings were transcribed and analysed using narrative analysis. This technique explores the individual's story and draws comparisons with others within the cohort of participants.

The following key themes emerged:

Identity and Experience

Participants expressed a strong collective identity rooted in the unique experience of witnessing nuclear detonations. A shared narrative included vivid descriptions of the blasts, including the sensation of seeing "bones in their hands" during the flash—interpreted as a meaningful personal truth. Veterans often expressed a complex mix of emotions: pride in their service, fascination with the testing sites, and resentment toward the UK government for the lack of recognition and perceived exploitation. The BNTVA was identified as a vital source of community, offering emotional support, advocacy, and opportunities for reunion—though some veterans faced barriers to participation due to cost or geography.

Health and Wellbeing

Veterans reported age-related health issues such as heart disease, arthritis, and hearing loss. However, many associated additional conditions—such as skin and lung cancers, cataracts, migraines, and fertility issues—with radiation exposure, despite a lack of formal medical confirmation. Many of the veterans also expressed a long-held fear that their presence at the nuclear tests had genetic implications for their children and grandchildren.

In the event of their husbands' passing, the widows in this study all believed their deaths were a direct result of the testing, even if it was more likely to be due to lifestyle or age. For some, it appeared that believing their illnesses to be the responsibility of the UK government or MoD became a comfort to them; they blamed the radiation, witnessing the explosions, and the fallout from the blasts because that was easier than accepting their cancer was due to natural causes.

It has been shown previously [15] that many veterans did not access the health and social care provisions available, despite needing them. This was also the case within the present study. The veterans appeared to have a real reluctance to seek help, reflecting the idea of a British ‘stiff upper lip’ mentality arguably reinforced by a military identity. Older men, and particularly those who are veterans, tend to pride themselves on the mantra of ‘boys don’t cry’ as if it is a sign of weakness to show emotion. Such attitudes can act as a barrier for seeking support when needed later in life and was shown here by a reluctance to access health and social care services to avoid burdening the NHS and wasting health professionals time.

This attitude extended to their family members and children; with nearly all participants commenting on how busy their children were and did not want to add to their supposed hectic lives. The participants could be struggling with their mobility and ability to carry out domestic tasks but would insist this was not the case to family and close friends.

Loneliness and Isolation

Humans are innately social creatures with a strong yearning for social engagement – which, when unmet, can result in negative outcomes. Loneliness is a universal feeling (defined as “an unpleasant experience that occurs when a person’s network of social relations is deficient in some important way” either in number or quality) and is an experience that has accompanied humankind from the beginning of time. The key risk factors for feeling lonely include low income, poor physical and/or mental health, living alone and geographical isolation due to living in rural communities or deprived city communities.

Within this study, loneliness was a recurrent theme. The stories poignantly illustrated the emotional toll of isolation, with participants often sharing subtle yet powerful anecdotes of their struggles.

Another element of this loneliness, existential loneliness (a feeling stemming from a sense of fundamental separation from others and the world), which arises when one feels misunderstood by others. For the nuclear test veteran community, this arose when others were not aware of the nuclear tests, nor the sacrifices the veterans had made during this time.

Leisure and Community Activities

Physical activity offers many benefits yet physical inactivity remains a major risk factor for preventable deaths. Despite this, many still do not engage in regular forms of exercise. For older adults, staying active can help prevent conditions like osteoporosis, improve quality of life, enhance fitness and cardiovascular health, and reduce the risk of falls. Additionally, physical activity has positive effects on mental health, contributing to overall wellbeing as people age. For purposeful physical activity, some of the activities that were engaged with included: walking groups, gardening clubs, dance groups, yoga, and dog walking. The nuclear test participants emphasised the value of keeping active and moving the body. For those with a military past, older men tend to use a narrative that presents an active and independent appraisal of themselves, one that displays control of their lives and physical bodies.

Green spaces (such as parks, gardens, forests etc.) can provide physical, psychological, and social benefits for everyone – including older adults –

supporting overall wellbeing and quality of life. The nuclear test participants in this study made specific mention of the value and importance of having green spaces that they could access.

Many of the veterans and wives shared a keen interest in engaging in community-based activities. Most of the veterans discussed their pride in being able to give back to the local community through voluntary roles such as supporting local residential homes, belonging to the Freemasons, organising clubs/activities for the elderly, and gardening groups for their local village.

Being part of community groups also allows for identity construction, revisions, and reminiscence; this is especially important for nuclear test veterans regarding their own identity. During the interviews, the participants were asked whether their local community provides activities or clubs for older adults to join. We asked this to get a sense of whether they felt supported by either their housing authorities/local councils, local veteran groups or local charities. Some felt their local community did at least offer the chance to get involved with community-based activities. However, some felt that options within their local community were lacking for older members of the community. This meant that members of the nuclear test community often had to seek out their own opportunities to be active and engaged. For those who live alone, this can be an isolating experience – particularly if they have lost a spouse and do not have relatives who live nearby. This seemed to be more of an issue for those who lived in rural villages compared to those living in larger towns and cities.

While the focus of active ageing policies is on remaining active for the physical and mental health benefits it brings, some of the veterans made it explicitly clear that this was simply not possible. Their bodies were too frail to engage in regular physical activity, and they relied on walking aids or on a wheelchair. Therefore, an open mind as to what types of leisure activities can facilitate healthy ageing, not just those that require physical exertion, is necessary to avoid excluding those with chronic conditions and/or disabilities. For instance, engaging with puzzles, knitting, cooking, watching television, reading, or going for a drive.

Summary of findings

This research highlights the complex interplay between ageing, military identity, and wellbeing among British nuclear test veterans. While many continue to live active, socially engaged lives, others struggle with unresolved health concerns, loneliness, and limited access to supportive services. Understanding their lived experiences provides a platform for shaping inclusive public health, social care, and veteran support strategies, particularly for the oldest-old.

Three radio dramas based on the findings of this project have been produced and can be accessed here: https://chrc4veterans.uk/knowledge-hub/11656-2/ These audio dramas were scripted by Alex Perry, voiced by members from the Brunel Older Peoples Reference Group BORG, and were produced by Squeaky Pedal.

Evidence-based resources for education and information

Evidence-based information is principally shared through www.chrc4veterans.uk. The website is designed to promote and share information on CHRC research project outputs and to support understanding of key aspects relating to radiation and health.

The knowledge hub resource includes:

1**. Basic information education series** covering topics which are relevant to CHRC's research (Figure 5 and 6). Each edition is designed to act as a foundation for achieving a deeper scientific understanding of the key methods and processes involved in CHRC's research. All are available in either interactive or booklet formats online with hard copies available to order.

2. Catalogue of Lay Summaries aims to present published scientific research in an easy-to-read, accessible format for the non-scientist. The research question, the approach taken to address this and, the key findings are summarised to enable the reader to follow the scientific evidence and to draw their own understanding.

3. CHRC peer-reviewed publications. All outcomes of CHRC research are published in peer-reviewed Journals, which are accessible through open access links. All are accompanied by a lay summary of the manuscript and its key messages.

4. A glossary of terms provides an explanation of basic scientific information.

5. Catalogue of published references provides details of the articles sourced to create the knowledge hub resources.

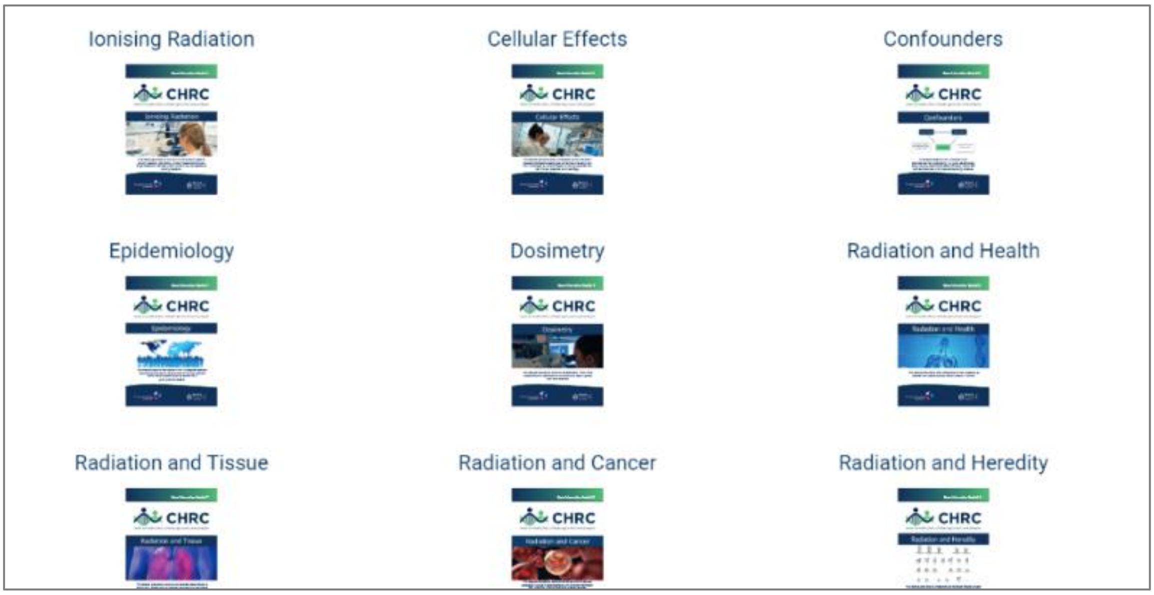

Figure 5: Basic information education series

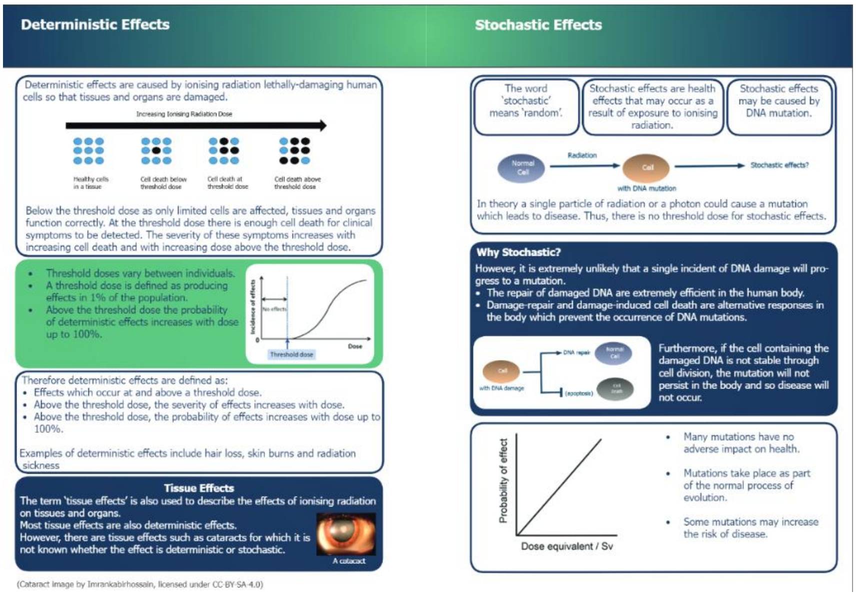

Figure 6: Basic information education series example content.

Resources for outreach initiatives have been developed e.g. the partnership with the Nuclear Community Charity Fund and Brunel STEM Centre delivered 'STEM Bioradiation' to secondary school students. This in-person learning experience included cross-disciplinary content; history, test veteran's stories, science of radiation & health effects and, sourcing peer-reviewed evidence.

Digital learning modules have also been developed (Figure 7) which use interactive animations and quizzes to teach students independently or in formal sessions e.g. STEM masterclass events. Resources for public engagement events include posters of research, interactive material/games e.g. chromosome challenge, reel of audio dramas, information leaflets & booklets.

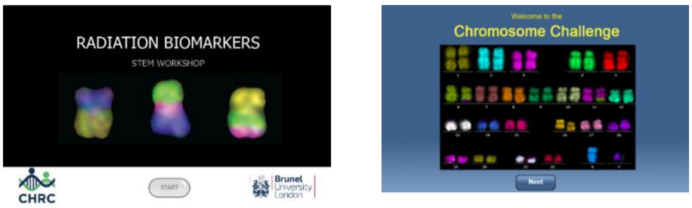

Figure 7: The Radiation Biomarkers module and Chromosome Challenge game for education & engagement events.

CHRC's research progress and findings are also shared through presentations at annual BNTVA/NCCF reunions, NCCF Trustee meetings, annual Brunel Research Festival, CHRC/NCCF stakeholder showcase events and other outreach events.

CHRC non-peer-reviewed publications

Evidence-based information is also shared directly to members of the nuclear community through publication of non-peer-reviewed articles and comments in community magazines *Campaign* (2016-2017) and *Exposure* (since 2018). Their purpose is to inform and educate on the science which underpins CHRCs research. *Exposure* is published by the Nuclear Community Charity Fund and is sent free of charge to ~700 households.

Links to these articles are available www.chrc4veterans.uk.

- *A summary of ICRP Task Group 121: Effects of ionising radiation exposure in offspring and next generations* (Winter 2024).
- *Human evidence for intergenerational effects of ionising radiation* (Autumn 2024).
- *Findings from the Veterans Chromosomal study* (Spring 2024).
- *Exploring for genetic variation in veterans* (Spring 2023).
- *Is that a coincidence: Exploring health perceptions and the causal attributions of physical health conditions in British nuclear test veterans* (Summer 2022).
- *Mortality and cancer incidence 1952–2017 in United Kingdom participants in the United Kingdom's atmospheric nuclear weapon tests and experimental programmes* (Spring 2022).
- *Lack of transgenerational effects of ionising radiation exposure from the Chernobyl accident* (Winter 2021).
- *Ionising Radiation and Cancer Part 2* (Spring 2021).
- *Ionising Radiation and Cancer Part 1* (Winter 2020).
- *Ionising Radiation and Tissue Effects Part 2* (Summer 2020).
  Ionising Radiation and Tissue Effects Part 1 (Spring 2020).
- *Radiation Exposed Populations* (Summer 2019).
- *Assessment of Risks from Combined Exposures to Radiation and Chemicals* (Spring 2019).
- *Investigating the DNA of British Nuclear Test Veterans and their Families* (Winter 2018).
- *Techniques to study de novo mutations* (Summer 2018).
- *Exposure Worry, Ageing, and Cognitive Functioning* (Summer 2018).
- *Why can't I volunteer for the genetic study?* (Spring 2018).
- *Genome Biology: Techniques to study chromosome aberrations* (Spring 2017).
- *Genome Biology: Chromosomes and their structural rearrangement* (Summer 2016).

CHRC peer-reviewed publications

Ofosu-Dankwa, J., Sisu, C. and Anderson, R. Somatic mutation profiles in aged military nuclear test veterans. *PLOS One* (Under review).

Stephens, J., Ermler, S., Rake, C., Sisu, C., Scholze, M and Anderson R. (2026). Limited evidence for intergenerational inheritance of chromosomal instability in families with elevated mutation pattern SBS16 in the germline. *International Journal of Radiation Biology*.

Anderson R. Complex chromosome aberrations as biomarkers of linear energy transfer: Applications in human biodosimetry. *In Low dose radiation risks: present research and future perspectives. NATO Science Series Book.* Ed Mothersill C. (Accepted).

Stephens, J., Moorhouse, A., Craenen, K., Schroeder, E., Drenos, F., & Anderson, R. (2024). A systematic review of human evidence for the intergenerational effects of exposure to ionising radiation. *International Journal of Radiation Biology*, 1-34.

Amrenova, A., Baudin, C., Ostroumova, E., Stephens, J., Anderson, R., & Laurier, D. (2024). Intergenerational effects of ionising radiation: review of recent studies from human data (2018-2021). *International Journal of Radiation Biology*.

Lawrence, K. J., Scholze, M., Seixo, J., Daley, F., Al-Haddad, E., Craenen, K., Gillham, C., Rake, C., Peto, J. and Anderson, R. (2024). M-FISH evaluation of chromosome aberrations to examine for historical exposure to ionising radiation due to participation at British nuclear test sites. *Journal of Radiological Protection*, 44(1)

Moorhouse, A., Scholze, M., Sylvius, N., Gilham, C., Rake, C., Peto, J., Anderson, R* and Dubrova, Y. (2022). No evidence of increased mutations in the germline of a group of British nuclear test veterans. *Scientific Reports*, 12, 1-8.

Collett, G., Martin, W., Young, W. R., & Anderson, R. M. (2022). "Is that a coincidence?": Exploring health perceptions and the causal attributions of physical health conditions in British nuclear test veterans. *SSM - Qualitative Research in Health*, 2, 1-26.

Rake, C., Gilham, C., Scholze, M., Bukasa, L., Stephens, J., Simpson, J., Peto, J. and Anderson, R. (2022). British nuclear test veteran family trios for the study of genetic risk. *Journal of Radiological Protection*, 42(2), 1-11.

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