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PAPER

Resilience after a nuclear accident: readiness in using mobile phone applications to measure radiation and health indicators in various groups (SHAMISEN SINGS project)

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Keywords: post-accidental recovery, nuclear accidents, mobile apps, ionizing radiation dose measurements, stakeholders, health

Abstract

An anonymous web-based survey was developed to check different aspects (SHAMISEN SINGS project): stakeholder awareness and perceptions of available mobile applications (apps) for measuring ionising radiation doses and health/well-being indicators; whether they would be ready to use them in the post-accidental recovery; and what are their preferred methodologies to acquire information etc. The results show that participation of the citizens would be most beneficial during post-accident recovery, providing individual measurements of external ionizing dose and health/well-being parameters, with possible follow-up. Also, participants indicated different preferences for sources to gain knowledge on ionising radiation and for the functions that an ideal app should have. The level of awareness and readiness to use apps to measure ionising radiation dose depended on two main aspects: individual differences (age & gender) and whether people were from countries affected by the previous major accidents. We concluded that stakeholders could have benefits from the data management plan: (1) it potentiates resilience at individual and community level; (2) citizens' measurements contribute to environmental monitoring and public health screening; (3) linkages between different types of data (environmental exposure, individual behavioural diaries, and measurements of health indicators) allow to perform more rigorous epidemiological studies.

1. Introduction

SHAMISEN SINGS is the inverse acronym for 'Nuclear Emergency Situations: Improvement of dosimetric, Medical And Health Surveillance—Stakeholder INvolvement in Generating Science' and it was an EU-funded project. Its overall goal was to study how to enhance citizen participation in the aftermath of

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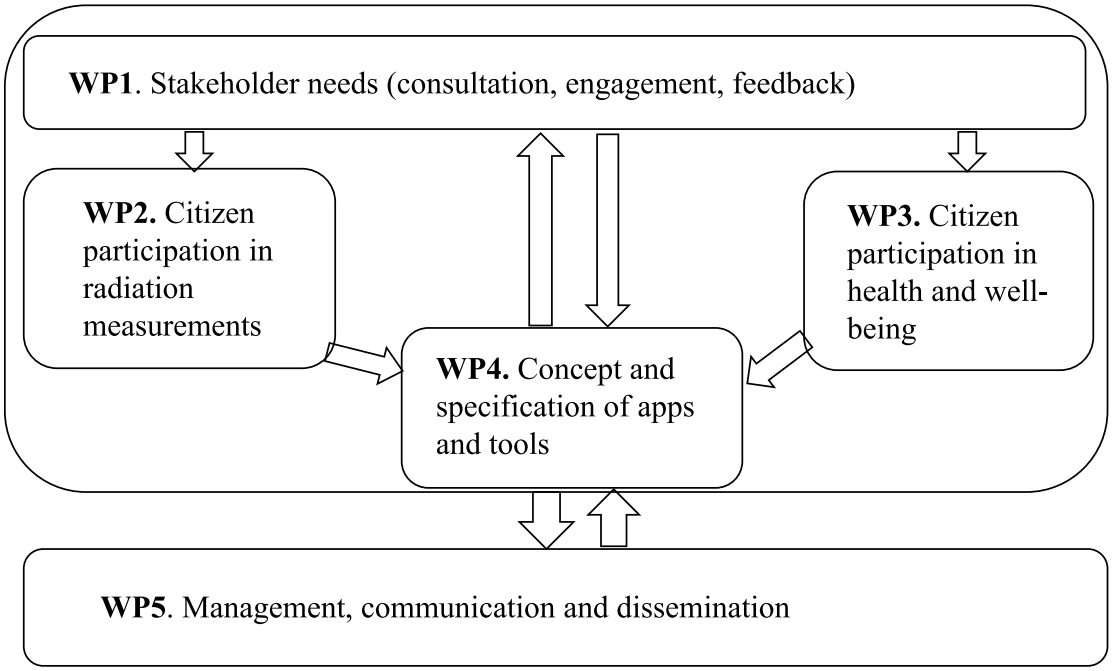

Figure 1. SHAMISEN SINGS project structure. Adapted from [2]. CC BY 4.0.

radiation/nuclear accidents to collect data on ionizing radiation (IR) dose and health indicators through mobile apps, with the support of professional stakeholders where needed.

More specific objectives of the SHAMISEN SINGS project were the following: (1) interact with interested stakeholders; (2) review existing apps for citizen-based measurements of IR dose, and for post-accident health monitoring (including social and psychological consequences of radiation/nuclear accidents); and (3) assess ethical challenges and implications of both the apps and the citizen science activities through a joint reflection by natural and social scientists, public, authorities, and stakeholders [1] (figure 1).

The summary of the project together with its dissemination material are available on the website of the project: https://radiation.isglobal.org/shamisen-sings/. There, you can find the following final products of the project:

(1) infographics for the general public 'How to measure radiation with your mobile phone' (available in English, French, Spanish, Italian, Japanese, Russian, and Ukrainian; for the English version, see Annex I);
(2) video-tutorials that accompany the infographics (available in English, French, Spanish, Japanese, and Russian);
(3) booklet 'Mobile apps for monitoring radiation doses, health and welfare in the context of a nuclear or radiological accident: Guidelines and recommendations for users, developers and public authorities' (available in English, French, Spanish, Italian, Japanese, Russian, and Ukrainian).

All this material was elaborated by a team of professionals in different areas (public health, dosimetry, radiation protection, epidemiology, social sciences and humanities, psychology, ethics, and communication) with consultation of the general public. This material represents a good basis to involve the general public (including citizen scientists), and professional stakeholders. It will enhance the protection of health and well-being of the populations affected by a radiological or nuclear accident, and increase their resilience.

1.1. Citizens science and involvement of the general public after radiological or nuclear accidents

Nowadays, involvement of the general public in research and decision-making processes is not only accepted, but is encouraged and widely demanded on the basis of international standards and recommendations. It helps citizens to gain scientific knowledge and skills, increases their awareness of environmental issues, and contributes to their mental and social well-being with little or no additional cost [3]. A great example is the transformation of citizen behaviour because of climate change policies [4].

Citizen science has bloomed in the past decades with the involvement of the general public at different levels [5]. Nevertheless, in radiation research, such participation is still scarce (around 0.02% of publications in comparison to other areas (biodiversity, climate, etc.) [6]. Since nuclear accidents are rare, the general

population is not motivated to know about IR and preparedness to radiological or nuclear accidents; even stakeholders that are involved in emergency response sometimes do not know each other [7]. However, protection from radiation remains an important issue for the general population because of the increasing IR exposures from natural and artificial (e.g. medical) sources [8].

By definition, 'citizen scientists' do not perform science as their main job [9]. Two main incentives for the participation of citizens as scientists in the research are their own motivation to obtain knowledge or skills, and their concerns for environmental conditions [10]. For instance, after the Fukushima accident, women were motivated to measure IR because they were living in the areas affected by a nuclear accident; and had a protective role in families [11]. As mentioned by Ando, a non-governmental organisation (NGO) in the Fukushima prefecture, it is critical to regain the trust lost after the unclear messages from governmental sources and media in situations of emergency [12]. Finally, the involvement of the general public and citizen scientists in the post-accidental recovery could have several beneficial effects: it could help to reduce anxiety caused by uncertainties and lack of knowledge on radiation and radiation protection; and it may reduce the impact of false or biased sources of information, especially mass and social media [13–16].

Nowadays, modern advanced technologies and the widespread use of mobile phones make it easy for the general public to participate in different projects. Such projects include the creation of citizen scientists' networks, 'in situ' observations, and immediate sharing of results [17, 18]. One of the main advantages is low-cost of environmental monitoring by citizens [19], including free and accessible education to anyone interested [20]. Previous studies showed no significant difference in the individual use of mobile apps for health/well-being across ethnicities and people with different demographic characteristics; however, young stroke survivors had a significantly higher preference for using these apps, in comparison to the general population [21]. Moreover, overall, several population groups are more inclined to use mobile health apps: women, younger people, and participants with a high educational level [22]. During the management of past disasters, stakeholders searched for the most relevant and up to date information, and they found it useful to employ data from mobile apps [23].

Unlike mobile apps to measure IR dose, mobile apps to assess health and well-being are widely known to be useful, and their use is exponentially increasing [24]. In 2012, there were more than 40 000 apps for healthcare professionals and consumers, including 80 just for diabetes [25]. Currently, e-health apps are widely used for patient self-assessment, as well as for several other purposes, such as: self-diagnosis; self-monitoring (blood glucose recording, medication logs, insulin calculators, etc.); management of chronic diseases and life-style; and remote access to the therapist and to personal health information [25]. Additionally, mobile apps can be used to prevent affective disorders, significantly decreasing their incidence [26]. Systematic reviews, meta-analyses and individual studies show that mobile apps can also be used for psychological interventions, as they may reduce anxiety and depression and could generally improve personal well-being [18, 27, 28].

Thus, current mobile technology, together with sensor devices and artificial intelligence, empowers and facilitates data gathering and analysis by predictive models in healthcare and personalised treatment [29]. However, despite these advantages, there is limited information on using mobile apps to measure IR dose, and we aimed to fill this gap.

With respect to nuclear emergencies and post-accidental recovery (that may last for many decades), all the stakeholder groups may play a mediating role to provide information, motivation, and support to the affected population. In the case of the Fukushima accident, people mostly trusted local doctors and teachers [7] and followed their advice in daily life.

After the Fukushima nuclear accident (2011), examples of successful use of professional mobile devices to measure IR dose by different citizen scientists' groups include the following: SAFECAST [30] and the D-shuttle projects [13], and the most recent projects conducted by Open-Radiation® [31]. Later on, in the Belarus area affected by the Chornobyl accident (1986), a citizen science group implemented a successful dosimetry system previously developed under the D-shuttle project [32].

Professional stakeholders should consider and accept citizen scientists' data as complementary measurements to obtain a greater contribution from and for society. Such measurements might cover regions that are not under the state monitoring system; therefore, once data from different users are integrated, they could serve for modelling and prediction of environmental exposure [33]. Finally, it is generally acknowledged that measurements of radiation with smartphone CMOS (complementary metal-oxide semiconductor) camera sensors reach adequate levels of reliability if irradiation and measurements are performed under controlled laboratory conditions [34, 35].

In SHAMISEN SINGS [1, 36], we also analysed the impact of environmental parameters (e.g. temperature and light) and human factors (e.g. mistakes in the use of the technology, and errors in the device positioning) on the reliability of radiation measurement. The outcomes of such tests are described elsewhere [37] and preliminary results show that un-trained users can use mobile apps utilising the video camera

sensors only under certain conditions. Issues related to data gathering and their further use were also discussed during the workshop on ethical issues, organised by the SHAMISEN-SINGS partner NMBU (Norwegian University of life sciences). The results are summarised in the booklet 'Mobile apps for monitoring radiation doses, health and well-being in the context of a nuclear or radiological accident: Guidelines and recommendations for users, developers and public authorities' [2, 38] and infographics for general public (figure A1 in appendix A).

Professional stakeholders' groups (e.g., teachers and medical workers, especially local doctors and nurses) might contribute to the development of citizen science by playing a supportive role for radiation protection agencies and institutions. They can either perform a mediating role or be involved as 'core' citizen scientists.

1.2. Aims of the current study

The main goals of the current study were to assess the following aspects:

- The awareness of apps measuring dose rates in comparison to the awareness of apps evaluating health indicators, in different stakeholder groups, including the general public. At the same time, we checked the level of knowledge on IR among the participants; the sources from which this knowledge was acquired; and the sources of information they would prefer to refer to in a post-accidental period.
- The desire and readiness to use the apps in the case of accidents.
- The perceptions on dose measurements. We wanted to see the perceptions (neutral, reassuring, useless, or stressful) for the whole group, and split by participants from countries directly affected by the previous major nuclear accidents (DAA) of Chornobyl and Fukushima (Belarus, Ukraine, and Japan) and those from least/non-affected countries (Rest).
- The choice of parameters for ideal apps (for the measurement of IR doses and health indicators) in the post-accidental period.

Moreover, we suggested a data management plan (DMP) on how the data gathered by citizen scientists and the general public, with the help and support of professional stakeholders, can better contribute to the resilience of affected communities.

2. Materials and methods

The data for this project were collected through an anonymous on-line survey: 'Needs on Apps (mobile applications) for dose measurements & health/well-being related to radiation exposure'. The survey was performed in seven languages—English, Russian, Ukrainian, Japanese, Spanish, French, and Italian—to gather opinions of the stakeholders (including the general public). The questionnaire was developed by partners and experts from Spain, Italy, Norway, France, Ukraine, Belarus, and Japan. The opportunistic snowballing technique was used to disseminate the survey, inviting people to participate through different means: (1) email; (2) an announcement on the website of the project; (3) a special blog publication at ISGlobal website (bilingual—Spanish and English); and (4) the distribution of leaflets (figure A2 in appendix B) to universities (medical, ecology, and biology degree courses), conferences, and associations (environmental protection or patients' associations). The average time to complete the survey was about 10–15 min.

2.1. The questionnaire's scope and structure

The questionnaire was divided into four main blocks. The first one concerned general data on the survey participants: age, gender, professional status, area of work or study, country and province/region of residence, level of education, and information about the family nucleus (living with children or not, living alone, etc.).

The second block was dedicated to self-assessment of knowledge and concerns about IR and sources. Participants were also asked whether they lived near a nuclear power plant.

The third block referred to the potential interest of participants in using mobile apps to measure radiation dose, assess health, and obtain information and advice. Here, we also evaluated the acceptability to share data with stakeholders (local authorities, doctors, etc.).

The fourth block was optional and only targeted people who had already experienced a radiological or nuclear emergency. We asked questions on the access to information during the emergency and on the application of measures for radiation protection in daily life after the accident. This paper does not cover this part.

2.2. Ethics and participants' inclusion rules

This survey targeted stakeholders, including the general public, aged >18 years, except in Japan, where only researchers were recruited because of special restrictions on ethical procedures, requirements, and approval

from the FMU (Fukushima Medical University) ethics committee (General no. 30077). Additionally, the local laws in Japan require a minimum age of 20 years for participants, instead of the minimum of 18 years required in Europe.

2.3. Data collection, analysis, and discussion with stakeholders

Data were collected from March to November 2018, with differences of up to 3 months for the start dates of the various linguistic versions of the survey. Descriptive, paired *t*-test, and ANOVA analyses were performed using Excel and STATA software. In the discussion section, we include opinions from group discussions of stakeholders during four international and two Spanish workshops [6, 7, 27].

3. Results

In total, 401 participants from 28 countries participated in the survey. Most participants were from Belarus, Spain, Japan, Ukraine, France, Italy, Norway, and the UK (figure 2). 68% of the participants were women. The age distribution of participants was the following: <30 year olds, 36%; 30 to 60 year olds, 53%; and >60 year olds, 11%. 51% of the participants were from DAA countries, see figure 2. For descriptive statistics of DAA participants in comparison to the rest, see table A1 in appendix C.

11% self-reported that they did not know what IR means (100% response rate): 8% were from DAA countries, in comparison to 14% from the Rest countries ($p = .079$) (table A1 in appendix C).

The sample consisted of the following stakeholders (including the general public) (table 1): (1) radiation protection specialists (13% of participants; not all working in scientific research); (2) teachers (12%); (3) medical workers (including nurses, pharmacists, and under-graduate students) (11%); (4) researchers in health, epidemiology, and other (42%, including undergraduate students mainly in the areas of biology, physics, ecology, geography, and psychology); (5) administrative workers (10%); (6) IT personnel, economists, engineers, and other industrial workers (not nuclear, 7%), and (7) other stakeholders like first responders (firemen, security guards, etc.), people having their own business, journalists, musicians, representatives from the government, and patient associations (6%). Globally, people with occupations not related to research or radiation protection accounted for 55% of the participants, representing the general public or potential citizen scientists. However, some professionals such as teachers and medical workers may also be considered as 'intermediate' stakeholder groups who may play a role of 'leading' citizen scientists. They may help to involve the general population in the contribution to radiation research (including preparedness to emergencies and recovery after radiological or nuclear accidents). The participants' professional areas are shown in table 1.

Most participants were undergraduate students and professionals with higher education (74%); PhD and Masters students (8%); people with a professional education (8%); and people with secondary education (10%). As per professional status, 70% of participants were employed; 22% students (mainly from areas of medicine, biology, ecology, and psychology, and mostly included in the 2nd and 4th categories in table 1), 6% retired, and 2% of unemployed.

All participants replied to the question about the possible sources to acquire knowledge on IR: 'Where/from which sources do you usually learn about ionizing radiation? (multiple choice answers)'. The results are presented in table 2 as frequencies of 'Yes' for each multiple-choice option. Results are presented for all participants ('All'), and split into groups of 'DAA', and 'Rest'. The three highest frequencies in each group are highlighted in bold: for all participants as follows—1) School/university courses; 2) Scientific journals/conferences/books and 3) Information released by Official Institutes/Government. For DAA group participants the ranking of the first three priorities on sources are the same; whereas for Rest group participants, the first is the same, but on the 2nd and 3rd place they mention—2) Media (Discovery Channel, Natural Geographic Channel, etc.) and 3) Internet and social media (Facebook/Twitter, etc.) (table 2). These differences (also for the National News channels category) are statistically significant ($p < .001$) (table 2).

65% of participants replied to the question 'Should a radiological or nuclear accident occur near you, which sources would you most likely consult to learn about radiation exposure/radioactive contamination?'. It was a multiple-choice question, and the results are shown in table 3.

Table 4 shows the results of the participants' opinions on the functions of the ideal app for dose measurements for all the participants, and the DAA and Rest groups (87% response rate). There were no statistically significant differences between preferences in DAA and rest groups and the priorities lists were the same (table 4).

32% of participants replied to the question on the preferences on the functions of the ideal app for the measurement of health indicators. Results are shown in table 5.

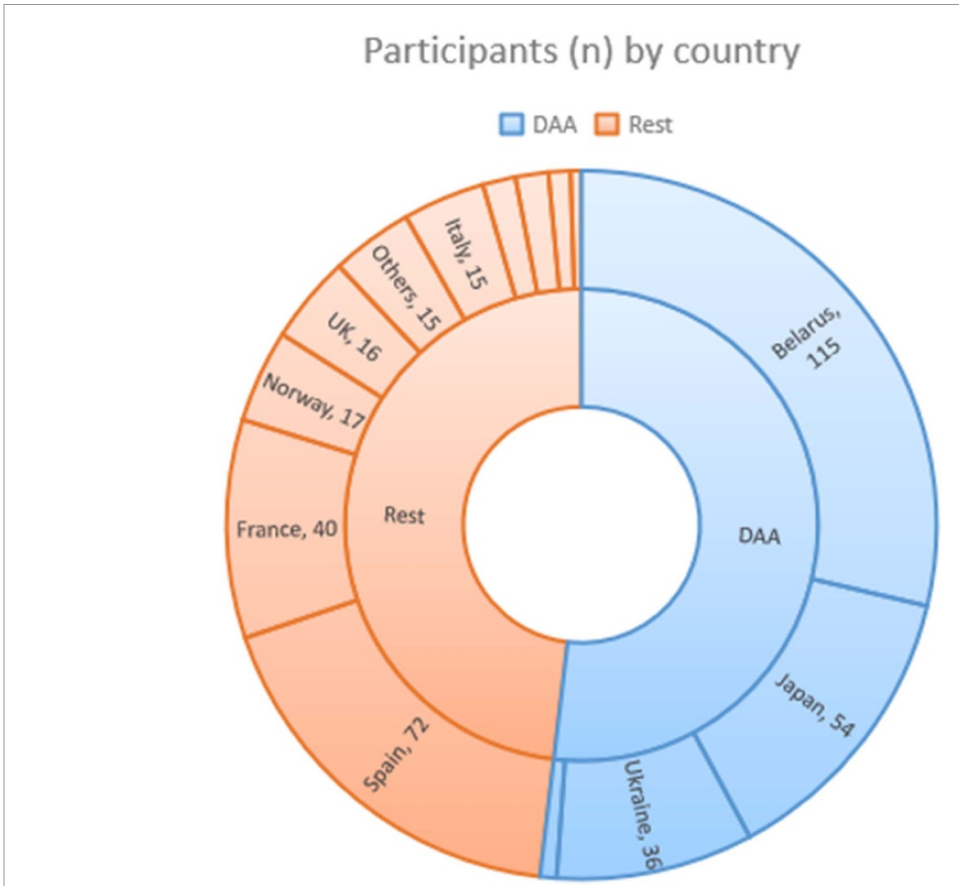

Figure 2. Participants by country and group: (1) DAA—directly affected by the Chornobyl or Fukushima accidents. Rest—not/less affected. On the graph the countries with >15 participants are only presented with numbers.

Table 1. Participants' professional area.

	Professional area of participants	N	(%)
1	Radiation-related (researchers, university students; radiation protection professionals, nuclear engineers and industry workers).	43	13
2	Medical (nurses, pharmacists, and students from medical universities).	36	11
3	Education.	38	12
4	Scientific research in health, epidemiology, and other fields (undergraduate students and researchers in the mentioned fields plus biology, physics, ecology, geography, psychology, and others).	140	42
5	Administration.	32	10
6	IT, innovative technologies, computer scientists, economists, engineers, personnel from oil/gas industry, etc.	22	7
7	Others, such as first responders (firemen, security guards, etc.); government delegates; journalists; musicians; patients/research representatives; and people with their own business.	21	6

Legend: the overall response rate for this question was 83% ($N = 332$).

We also studied individual differences that influence awareness of and willingness to use mobile apps to measure radiation doses among the participants in this study. We looked for differences on the basis of the following parameters:

(1) *Age*. We found statistically significant differences ($p = .001$) in the awareness of mobile apps between three age groups: 18 (20 in Japan) to 30 years; 30–60 years; and >60 years. Specifically, greater awareness is positively correlated to increasing age ($r = .25$, $p > .001$).

We observed a similar positive age trend for the willingness to use the apps: 18 (20 in Japan)- to 30 year olds—11%; 30- to 60-year-olds—25%, >60 year olds—38% and with correlation between variables of $r = .21$ ($p < .001$).

Table 2. Sources that the participants used to acquire knowledge on IR (self-assessment).

Source of IR knowledge (multiple choices were allowed)	Yes (%)			*p*-values
	Total	DAA	Rest	
School/university courses	**62**	**64**	**60**	.378
Scientific journals/conferences/books	**42**	**46**	38	.111
Information released by Official Institutes/Government	**32**	**32**	32	.987
Media (Discovery Channel, Natural Geographic Channel, etc.)	30	18	**42**	<.001
Internet and social media (Facebook/Twitter, etc.)	30	20	**40**	<.001
Interpersonal communication with family members/friends/colleagues	25	26	25	.794
National news channels	18	11	24	<.001

Legend: DAA—directly affected (or most affected) by the previous major accidents (Chornobyl & Fukushima)—participants from Belarus, Ukraine, and Japan (51%); Rest—not affected or slightly affected by the previous major accidents (49%). In bold are the three highest frequencies reported in each group. The sources of IR knowledge (first column) which differ between DAA and Rest groups at a statistically significant level ($p < .05$) are highlighted in bold and cursive.

Table 3. Preferences in the sources where to consult information about radioactive contamination in case of a radiological or nuclear accident.

Preferred sources	Total	YES (%)		*p*-value
		DAA	Rest	
Official (government) sources	**79**	**76**	**81**	.401
Research institute/expert sources	**69**	22	**68**	.613
Foreign (International Organizations like IAEA, ICRP, etc.)	**45**	18	42	.196
Local/National/TV/Newspapers	44	10	48	.022
Medical Institutions (doctors/nurses)	44	21	**51**	<.001
Internet (Facebook, Twitter, etc.)	28	**52**	28	.718
Non-governmental organization (NGO) sources	21	**71**	15	<.001
Foreign TV/Newspapers	15	32	14	.448
Friends/neighbours/Family	13	9	14	.323

Legend: in bold are the three highest frequencies reported in each group. The answers with statistically significant differences ($p < 0.05$) between the DAA and Rest groups are highlighted in bold cursive.

Table 4. Participants' preferences on the functions of the ideal app on dose measurements (multiple choice) with significance level for DAA vs. Rest groups differences.

Ideal APP should:	% YES			*p*-value
	Total	DAA	Rest	
Measure environmental doses	**86**	**85**	**88**	.378
Measure radiation in food and other consumption products	**66**	**68**	**64**	.461
Provide real-time information on the situation (official channels only)	**61**	**60**	**62**	.693
Provide general information on the effect of radiation on health and protection measures	55	54	55	.901
Provide specific instructions related to my personal situation and status	51	52	49	.587
Provide real-time information on the current situation (non-government channels)	39	37	42	.293
Provide some degree of interactivity (questions/answers/live chat)	34	33	36	.578

Legend: in bold are the three highest frequencies reported in each group. The categories (1st column) on which answers) between the DAA and Rest groups differed with statistically significant differences ($p < .05$) are highlighted in bold cursive.

(2) *Gender*. There was a quite similar percentage of awareness of the mobile apps among participants of both genders: 31% in women and 38% in men. However, men were more willing to use such apps (32% of men vs. 19% of women, $p < .05$).

(3) *Family (or living with) status*. 61% of participants living alone were not aware of existing mobile apps on dose measurements, in comparison to 66 and 70% of participants living with children and with other household members correspondingly; though these differences did not reach statistically significant level ($p = .308$). The family status did not seem to influence the willingness to use the apps for measuring

Table 5. Participants' preferences on the functions of the ideal health app for post-accidental management (multiple choice) with significance level for DAA vs. Rest groups differences.

Ideal APP should:	Total	DAA	Rest	*p*-value
Measure health parameters	**105 (88%)**	**46 (94%)**	**59 (83%)**	.079
Provide general information on the effect of radiation on health and protection measures	**93 (85%)**	**37 (88%)**	**56 (84%)**	.517
Provide specific advice and instructions related to your personal situation and health status and/or wellbeing	**92 (84%)**	**38 (95%)**	**54 (78%)**	.020
Collect physical activity data	66 (62%)	31 (84%)	35 (51%)	.001
Provide some degree of interactivity (questions/answers/live chat)	58 (60%)	19 (70%)	39 (56%)	.187
Collect information on your mental health/well-being through a questionnaire	47 (52%)	23 (85%)	24 (38%)	<.001

Legend: in bold are the three highest frequencies reported in each group. The answers with statistically significant differences ($p < .05$) between the DAA and Rest groups are highlighted in bold cursive.

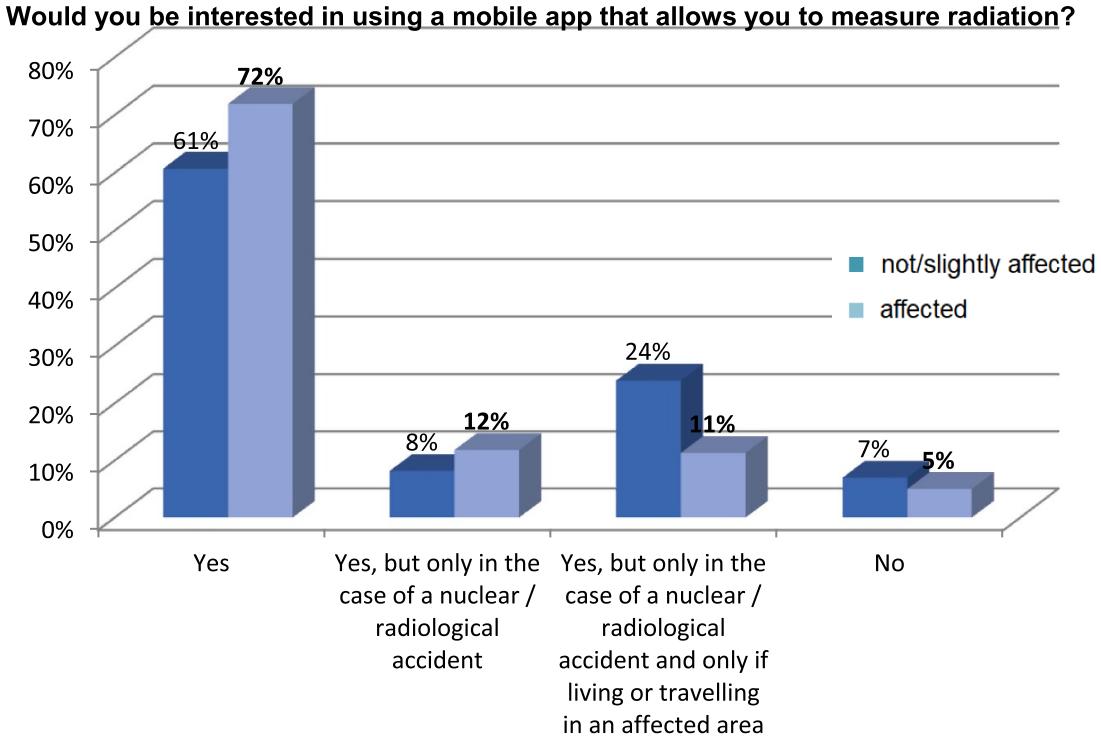

Figure 3. Interest expressed in measuring radiation through mobile apps. Different results were reported for the 'rest' group and the DAA group.

radiation dose: 27% of people with children vs. 22% and 25% of people participants living alone and with other household members correspondingly were ready to use them ($p = .108$).

In general, the study participants were more aware of apps for measuring health parameters (45%), than of apps for measuring radiation dose (33%).

In DAA countries, there was a higher interest in using mobile apps to measure radiation: 72% of the people from these countries were willing to use the apps, in comparison to 61% of participants from rest of countries. Significant differences in frequencies were observed between the two groups for replies on willingness to use mobile apps for dose measurements, such as 'yes' (61% vs. 72%) and 'yes, but only in the case of nuclear/radiological accident and only if living or travelling in an affected area' (24% vs. 11%) ($p < .05$). There were no significant differences between the two groups for other replies, such as: 'only in case of a nuclear/radiological accident', and 'no' (figure 3). About 10% of the participants replied that these measurements would be beneficial under specific conditions, such as professional support, or trainings for measurements and interpretation of the data.

People from DAA countries may have implicit knowledge of radiation and radiation protection because of their own needs and more information and formation provided in these regions. Therefore, we compared

Table 6. Individual differences in the perception of using mobile apps to measure radiation dose.

Emotions:	Total	DAA	Rest
Reassuring	59 (49%)	32 (39%)	27 (71%)
Neutral	37 (31%)	33 (40%)	4 (11%)
Useless	9 (7%)	6 (7%)	3 (8%)
Stressful	4 (3%)	3 (4%)	1 (3%)
Other	12 (10%)	9 (11%)	3 (8%)

them with the Rest. We detected differences in the sources used to acquire knowledge on IR: 42% of the people from the Rest countries used Media (Discovery Channel, Natural Geographic, etc.), in comparison to 18% from DAA countries; also, 24% of people from the Rest countries used national news channels, in comparison to 11% from DAA countries; and 40% of people from the Rest countries used internet and social media, in comparison to 20% from DAA countries.

Only 25% of participants replied to the question on the aims to share the data if gathered by a citizen science approach. Their preferences were distributed as follows: (1) to create real-time radiation maps—79.4%; (2) to inform and possibly contribute to decision-making (government/local authorities)—78.4%; and (3) to perform citizen science projects (in which local citizens work with scientists to answer scientific questions on health and environment for example)—77.5%.

Replies to the question about how the respondents perceived being able to measure doses with mobile apps (reassuring, neutral, useless, or stressful, 70% response rate) with the distribution of replies for the whole group and subgroups (DAA & Rest) are shown in table 6. The most commonly chosen response category for the whole group was Reassuring (49%) followed by Neutral (31%); however, responses to this question significantly differed in DAA and Rest groups ($\chi 2 = 13.25$, $p = .01$). The numbers of respondents who selected Useless and Stressful as a response to this question were low in both subgroups (table 6). The majority of those who replied Other referred to dose measurement as being 'interesting' or 'useful but with more information to be provided on it', 'useful with support of professional stakeholders to measure correctly', etc.

4. General discussion

Projects investigating IR dose are quite scarce, and this exploratory study is pioneering in the field. IR understanding is difficult for the general public, and it should be carefully supported by relevant stakeholders with adequate knowledge of radiation and radiation protection [13, 30, 31]. As the Fukushima experience showed, the general public mostly trusted the local stakeholders, particularly professionals, such as doctors, nurses, psychologists, and teachers [39]. It was crucial to work jointly on radiation protection and health-related issues. In this context, our study targeted the opinions of the above-mentioned stakeholder groups.

Fifty five percent of our sample consisted of participants with occupations not related to research or radiation protection, and they represent the general public or potential citizen scientists. However, some professionals, like teachers and medical workers, may be also considered as 'intermediate' stakeholders. They may play the role of 'leading' citizen scientists by involving or giving examples to other representatives from the general population on how to contribute to radiation research (including preparedness for emergencies and recovery after radiological or nuclear accidents).

Information sources that study participants used to acquire knowledge on IR differed between the two groups (DAA—directly affected by previous nuclear accidents vs. Rest). A higher proportion of the participants of Rest group used Media (Discovery Channel, Natural Geographic, etc.) (42% vs. 18% for DAA). Similarly, participants of Rest group reported higher use of national news channels (34% vs. 20% for DAA) and internet and social media (40% vs. 20% for DAA), which might partially reflect the implicit experience they had with the different information sources. These differences might be attributed to the fact the participants from countries affected by the previous accidents were less confident with national news, internet and social media sources due to their own experience [12]. The fact of trusting less to national news channels also reflects this as a 'gained' experience or possible specific socio-historic and cultural differences in trust in government or not local news [12, 40]. However, the first preference, as a main source of obtaining information on IR, was shown the same for both groups—schools and university courses which highlight the importance of these institutions in formation and education of people on IR and radiation protection.

In general, all participants chose an official governmental source as their preferred source of information in case a nuclear accident was to occur. People from Rest countries indicated research institutes or information provided by experts as their 2nd choice, and medical institutions as 3rd. Participants from DAA

countries indicated NGO sources as 2nd choice, and the internet (Facebook, Twitter, etc.) as 3rd choice. They did not seem to trust local/national/TV/newspapers, showing a statistically significant difference in their information consumption as compared to participants from the Rest countries (10% in comparison to 48%). These data either show that trust was not regained after the accidents of Chornobyl and Fukushima, or they reflect a general attitude to local media.

As to the ideal app for dose rate measurements, both the DAA and Rest groups expressed similar preferences on its functions with few exceptions. First, participants from the DAA countries tended to value the possibility of measuring contamination of food products higher than participants from the Rest countries. Second, participants from the Rest group valued more the fact that the app should 'provide general information on the effect of radiation on health and protection measures', in comparison to DAA participants. The first point reflects real needs in the post-accidental period—to measure food contamination before consumption [41] and DAA people were more conscious of them. The second point reflects the fact that people from the Rest group have less knowledge of radiation's effects on health and need more support to overcome their uncertainties. Indeed, it would be beneficial to develop apps providing information on radiation-related health effects and supportive interaction functions between professional stakeholders and final users.

In our study, a high proportion of participants were highly educated, and we found that results on awareness and willingness to use mobile apps, especially for dose measurements, were strongly correlated with age. This might be because, with age, people become more concerned about their health and the environmental problems affecting it, especially radiation. We found also that a high proportion of stakeholders (including the general public) were open to using mobile apps to measure IR dose. A low percentage of them replied 'No' to the question about whether they would like to measure radiation: 5% of respondents from DAA countries, and 7% of respondents from the rest of the countries.

Mobile apps for measuring IR dose rates have some limitations and are far from being a substitute for professional instruments. Nevertheless, the results of this survey suggest that they are perceived as a complementary source of information by citizens. This is especially evident in geographical areas that are not covered by governmental network stations for monitoring radiation. This conclusion is in line with the experience acquired after the Fukushima accident. On that occasion, the use of self-measurements favoured the reduction in anxiety caused by uncertainty in mapping radiation dose in areas where people resided, worked, or conducted leisure activities [41]. The information gained from apps could lead to greater self-confidence and better management of daily routines. Indeed, people may avoid staying long in places with higher contamination, and this helps to control the situation and prevent health issues. Moreover, authorities should prepare themselves to inform and train citizens in the correct use of mobile phones for radiation detection in case of a radiation emergency [2, 37].

If these data were linked to health follow-up, they could provide a very useful basis for future epidemiological studies on the effects of low doses of IR. The results might guide health surveillance policies and population behaviours, with the aim of protecting public health and improving mental health (see an example of DMP in [2]). Such developments would likely raise ethical and legal issues. This was highlighted by a parallel study, which addressed the ethical issues linked to the use of apps, such as the privacy of data during collection and their further use; autonomy and dignity of populations involved in measurements; and data collection, sharing and use [38].

Overall, this study is an important contribution in the area of IR and radiation protection, with respect to the possible involvement of citizen scientists and stakeholders in research on post-accident management. It shows differences (mainly depending on origin—from countries most or least affected by the previous nuclear major accidents- but also on age, gender, and family status) in different aspects, such as knowledge of IR; sources of information used; readiness in using mobile apps to measure dose and health indicators; pre-disposition to share the collected data; perception on usefulness of the apps; and suggestions on the functions of the ideal app. Finally, the suggested plan for data management shows how data from citizens can be integrated for their further exploitation, supporting environmental and health monitoring. These data may contribute to public health screening and other decision-making processes at the local and international levels.

4.1. Limitations

The main limitation of this study is the difficulty we had in attracting volunteers from the general public to reply to the survey. This might be due to a low 'attractiveness' to gain more knowledge about IR and radiological/nuclear accidents. Excellent or professional knowledge was reported in 28% of participants, 13% of whom were professional stakeholders who worked or had worked in areas related to radiation and/or radiation protection. The remaining 15% of participants with an excellent knowledge of IR were professionals in other fields (nuclear power industry workers and engineers, and medical workers who

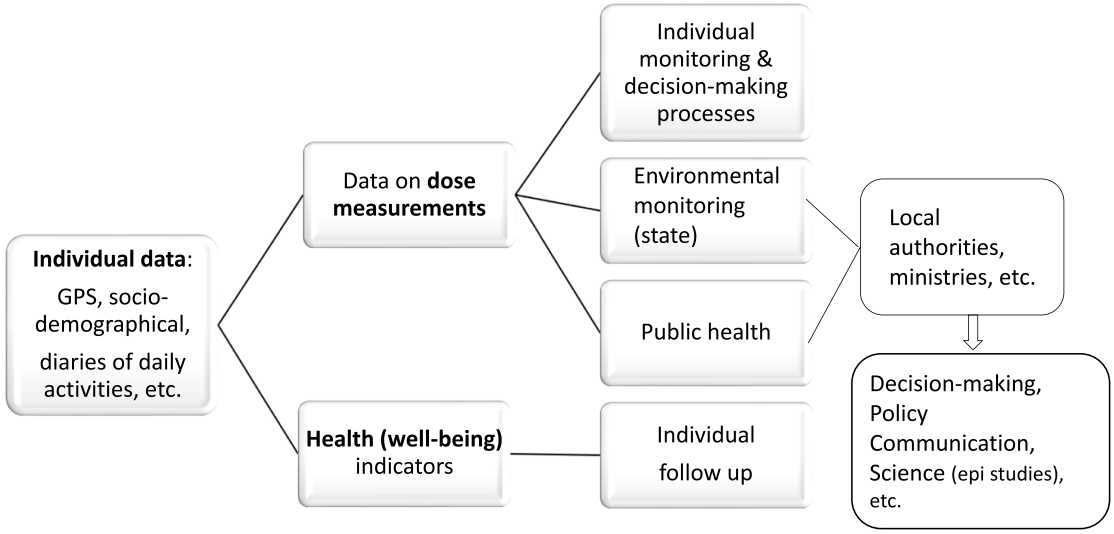

Figure 4. An example of a general plan for the use of data at the individual and societal levels (SHAMISEN SINGS project, source: [19]).

worked with radiation, but not in research), or scientists involved in IR research. Finally, the low participation of citizens with low knowledge of IR reflects the difficulties we met in involving citizen scientists in radiation and radiation protection research, especially if they had no risks and were living in Rest countries. More education on IR should be provided in schools to increase awareness among the general public, and more effort should be put in the communication with affected populations in emergencies and in post-accidental period. In particular, medical workers, nurses, and teachers could play an important role in establishing trustful contacts with the general population, especially at the local level, as previously pointed out by Maître *et al* [39].

Another limitation of the study consists in the opportunistic sampling, without a huge campaign (that requires more economic support and time). This resulted in a different distribution of participants from various countries, and in the impossibility of performing an analysis based on countries. Therefore, all countries were grouped into two categories: DAA (51%) and Rest (49%). Even in such an aggregation, results should be cautiously interpreted with a possible bias deriving from a younger population in DAA countries (table A1, appendix C). However, this grouping facilitated the analysis and allowed more homogeneous sampling by gender and other socio-demographic parameters in both groups.

4.2. DMP

Data collected by citizen scientists could be used at the individual level, where only users are involved; or at a community level, including professional stakeholders, for societal benefits. Medical and/or radiation protection professionals could help to interpret the feedback automatically obtained from the apps for screening and identifying the possible public health risks for the community. Also, local authorities and environmental monitoring and public health officers could share data at the international level. This can also contribute to decision-making processes, public communication, and policy regulation (figure 4).

The DMP will necessarily be a living document that is regularly updated on the basis of population, legislation, and technological advancements.

Below, we report four specific aspects for managing data from apps and for their use in the aftermath of a nuclear/radiation accident.

1. *Need for advice and assistance for the app users*. Studies to date have shown the importance of sharing concerns to obtain advice and assistance at both individual and community levels. This requires appropriate permissions and channels for the secure transmission of concerns and health issues. First, it would be necessary to identify the specific entities (e.g. medical institutions, local administration) to which to transmit the data. Second, it would be essential to create the best channels for sharing data exclusively with these entities. This can either be done in a specific framework, or in the context of a global DMP. The latter would include different uses and links with other stakeholders and resources; therefore, specific levels of access, permissions, and security would need to be defined.

2. *Need to exchange information in the community or family*. This may require the possibility to share data with specific individuals chosen by the user through the app, without access to an overarching data management platform.
3. *Citizen science*. The general principle of citizen science is to make the data created by citizens open and FAIR (Findable, Accessible, Interoperable, and Reusable). The objective is to promote citizen-driven data governance, with citizens having control of the data collected in the study. This requires providing them with the knowledge and tools to make decisions about what data are used and published, and under which conditions. To this end, it is important that citizen scientists attend workshops and debates about the risks and benefits of data sharing in research. It will also be important to involve participants in designing licenses and conditions that allow citizens to easily grant researchers and third parties permission to use their data. Finally, participants will be invited to assign licenses that best match their preferences for the use of personal data, and data about their living environment, health, and well-being.
4. *Monitoring health and wellbeing following a nuclear/radiological incident*. This includes studies of trends in different parameters over time, between regions, or in relation to dose, accident circumstances, and remediation. These studies can be conducted at an aggregated level, with surveillance of disease patterns over time by level of exposure, for example. They can also be conducted at an individual level, with more detailed epidemiologic data. This disentangles the relationship between the accident, remediation activities, and doses, with important health factors and psychosocial and well-being outcomes, in individuals in the aftermath of an accident. These studies require, either at the population or individual level, a linkage to 1) data on doses obtained either from individuals through the dose measurement apps, or from temporal and spatial maps of dose rates generated by local, regional, and national authorities; 2) population diseases and vital status registries; and 3) hospital registries to obtain more specific information (figure 4). In specific circumstances, such as in studies conducted in Europe, where both people and radiation may cross the boundaries of countries, it might be also required to link data from different countries. All these aspects need careful consideration, appropriate ethics approval, and security settings for information exchange. In the case of a radiation accident, it is necessary to obtain legal agreements between different authorities on the conditions of information exchange. Whatever the level of sharing, strict security procedures must be in place.

Data collection, storage, and further use require careful considerations of ethical issues to ensure that they follow the general data protection regulation and address the broader societal consequences of citizen science projects [38].

5. Conclusions

The study findings suggest that people are aware of and use mobile apps for health (well-being) and radiation dose measurements, but with a preference for health-related ones. The willingness to use dose measurement apps increases with age, and men were more likely to use them than women, despite there being no statistically significant gender differences in awareness of the apps. It is important to consider these individual differences, and not to recommend self-measurements for all people, but only to those who feel that it could be beneficial for their emotional state, and/or who wish to volunteer as citizen scientists. In conclusion, citizen science participation in radiation research might be difficult because of the lack of knowledge and motivation. But, especially in the case of DAA countries, measuring IR environmental doses and health indicators may not only benefit at an individual level, but also contribute to environmental and public health monitoring.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

Conceptualization, L L and E C; methodology, L L, E C, P F, L D, T S, D O, K T; software, P F, S D; formal analysis, L L; investigation, all; resources, E C; data curation, L L; writing—original draft preparation, L L; writing—review and editing, all.; visualization, all.; supervision, E C; project administration, L L and E C; funding acquisition, E C All authors have read and agreed to the published version of the manuscript.

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Informed consent statement

Informed consent was obtained from all subjects involved in the study by clicking on 'Agree and Sing it' before filling the online Survey.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Appendix A

The Infographics on How to measure radiation doses with the use of a mobile app:

Figure A1. The SHAMISEN SINGS infographics.

Appendix B

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Figure A2. A leaflet with QR code for recruiting participants.

Appendix C

Table A1. Descriptive statistics and differences between participants' subgroups for each category (1–4) specified in the columns.

		Total	DAA	Rest	p-value
1. **Sex**	**M**	128 (32%)	57 (28%)	71 (36%)	.112
	F	273 (68%)	148 (72%)	125 (64%)	
2. **Age group**	**18–29**	145 (36%)	113 (55%)	32 (16%)	<.001
	30–60	211 (53%)	83 (41%)	128 (65%)	
	>60	45 (11%)	9 (4%)	36 (19%)	
3. **IR knowledge**	**No**	44 (11%)	17 (8%)	27 (14%)	.079
	Yes	357 (89%)	188 (92%)	169 (86%)	
4. **Family/living with**	**1**	166 (41%)	96 (47%)	70 (36%)	.057
	2	97 (24%)	48 (23%)	49 (25%)	
	3	138 (35%)	61 (30%)	77 (39%)	

Legend: family/living with: 1- with partner or other adults; 2- alone; 3- with children.

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