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On radar and radio exposure and cancer in the military setting

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ABSTRACT

Introduction: In 2018, we reported a case series of 47 patients diagnosed with cancer following several years of exposure to high-intensity whole-body radiofrequency radiation (RFR) using the parameter of percentage frequency (PF). Consistent high and statistically significant PFs of hematolymphoid (HL) cancers were found in this group and in four previous reports on RFR-exposed groups in Belgium, Poland and Israel together with increased all-cancers rates. In this paper we report a new series of 46 young cancer patients who were exposed during military service to such radiation.

Materials and methods: The new group of patients comprises Israeli soldiers previously exposed to occupational RFR. The patients were self-selected to enroll in the research in cooperation with an NGO assisting patients with administrative counseling and legal and social services. The new group of patients was studied with respect to distribution (proportion) of cancer types using the method of PF. When possible, cancer risk ratios (RR) were estimated too. The results are compared to those of other occupational groups in three countries.

Results: Median age at diagnosis was 23 years; duration of exposure was between 1 and 3 years and the latencies were short, median 4.6 years. The PF of HL cancers was 41.3%, 95% CI (27%–57%), versus 22.7% expected in non-exposed subjects matched for age and gender profiles, $p = 0.003$; 19 out of the 46 patients had HL cancers. The PF of Hodgkin lymphoma cancers was 21.7%, 95%CI (11%–36%), versus 11.6% expected, $p = 0.033$. For a subgroup of 6 patients, the number of soldiers in the units was known, and we were able estimate approximately the overall cancer risk ratio (RR) after 8 years as being 8.0 with 95% CI (2.9, 17), $p < 0.002$, with only 0.75 cases expected from the Cancer Registry data. In this subgroup, there were 3 HL cancer cases and 3 non-HL cases. Sarcoma PF was higher than expected, 7 out of the 46 patients were diagnosed with sarcoma, PF = 15.2%, 95%CI (6.3%–28.9%), $p = 0.04$ versus the expected PF of 7%.

Conclusion: The HL PF was high and consistent with previous reports. Epidemiological studies on excess risk for HL and other cancers, brain tumors in cellphone users, and experimental studies on RFR and carcinogenicity strongly point to a cause-effect relationship. It is mandatory to reduce the RFR exposure of all personnel to that of the typical community levels, including the peak level of radar pulses. Radiation protection, safety instructions, cancer risk warnings and quantitative data on individual exposure together with regular medical monitoring must be instituted for all personnel exposed to such risks. The findings from our study add to the growing body of evidence underscoring the gross inadequacy of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) thermal standards. Based on our findings and on the previous accumulated research, we endorse the recommendations to reclassify RFR exposure as a human carcinogen, International Agency for Research on Cancer (IARC) group 1.

1. Introduction

This work is an update on radio frequency radiation (RFR) exposure and cancer in the military setting following the work Peleg et al. (2018), using the same methodologies developed therein. We present a new group of 46 cancer patients and compare them to groups in three countries reported previously.

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1.1. Brief summary of the relevant literature

RFR is used worldwide to provide cellular communication for smartphones and for other uses such as the Internet of Things. In the military setting, RFR is used for communications, radar, and electronic warfare. The frequency range of RFR is from around 100 kHz to around 300 GHz. This includes also microwaves and millimeter waves.

The International Agency for Research on Cancer (IARC) classified radio frequency radiation as a possible human carcinogen (IARC group 2 B) in 2011; see IARC 2013. The epidemiological basis was principally cancer in mobile phone users reviewed recently by Choi et al. (2020) Since then, research papers have identified RFR carcinogenicity and recommended RFR reclassification as a human carcinogen (IARC group 1), e.g., Hardell and Carlberg (2013) using the Hill viewpoints, Hardell and Carlberg (2019), Miller et al. (2018), Peleg et al. (2018) and the reviews by Clegg et al. (2020) and Hardell and Carlberg (2021).

Our work focuses on military and occupational settings where RFR exposure is typically high, involves the whole body and occurs mostly over a period of a few years per person, as investigated by e.g., Szmigielski (1996), Degrave et al. (2009), in our publications, Peleg (2009) and Peleg et al. (2018) and in the early review by Goldsmith (1997). These studies point to increased cancer risks in military settings with occupational exposure to RFR. The association of RFR with hematolymphoid cancers was reported by Szmigielski (1996), Tell-e-Lamberton (2010), Peleg et al. (2018) and others. Most of the findings in military settings are on radiation levels within the International Commission on Non-Ionizing Radiation Protection (ICNIRP) radiation standards as used by the military and industry, see ICNIRP 1998 and ICNIRP 2020. Whole-body exposure occurs also in communities near mobile base stations, as investigated by Wolf and Wolf (2004) and López et al. (2021) and the review by Balmori (2022).

RFR-related tumors have also been identified in large-scale animal model studies (see, for example, Chou et al. 1992; NTP on mice, 2018; NTP on rats, 2018; Falcioni et al, 2018).

Possible mechanisms for the interactions of RFR with living tissues have been presented, e.g. Friedman et al. (2007) reported changes in protein signaling pathways caused by RFR at sub-thermal levels of 5 $\mu W/cm^2$ and Pooam et al (2022) reported formation of Reactive Oxygen Species. Possible physical principles were reported e.g. Barnes and Greenebaum, 2014, Vistnes and Gjotterud (2001) **and** Peleg (2012).

The question of the carcinogenicity of RFR is still considered open, and it was not settled by the WHO, see IARC 2013 and the numerous references therein, some of which reported the carcinogenicity of RFR and some did not. Many studies show little or no relationship between RFR and health relevant outcomes, see for example the review within ICNIRP 2020. The recent work of Nordhagen and Flydal, 2022 discusses the tendency of ICNIRP 2020 to emphasize negative results and lists more review documents on the subject. We examine an in-depth investigation from the occupational military setting, showing little evidence of adverse health effects, Dabouis et al. (2016), and also Groves et al. (2002) which did report some adverse effects, see the discussion section of this paper.

1.2. Our previous report

In Peleg et al. 2018, we reported a group of 47 cancer patients who worked previously as radio and radar operators and developers and were exposed repeatedly to whole-body RFR at levels much higher than exposure from cellular base stations in the community, see Koppel et al. (2019) and Table 3, but still usually not exceeding the occupational ICNIRP limits. We found that the cancers in this group of patients had unusual characteristics. Most notably, there was a much higher proportion of hematolymphoid [1] (HL) cancers than expected for the appropriate age and sex profiles from the Israeli Cancer Registry (CR). Also, multiple primaries occurred significantly more frequently than expected. The data were analyzed by means of the percentage frequency (PF) of cancer types, that is, proportion of cancer types, see the Materials and methods section below.

Next, we found that this same characteristic of very high PF of HL cancers occurred together with elevated HL and other cancers risks in three other groups of cancer patients exposed to RFR in similar settings reported in Poland, Belgium and Israel during the last decades. Additionally, there is a fifth such group reported in Tables 2 and 3 of Richter et al. (2000).

1.3. The context of this paper

The 47 patients reported in 2018 were diagnosed mostly within the period from 1984 until 2007, none later than 2009. Starting from 2019 through 2021, we received new data on additional 46 cancer patients from similar military settings. These were diagnosed from 2002 until 2021 (median 2017), which is approximately 20 years later than the group reported in 2018.

This paper examines these new findings and their implications. We address the question of whether the same pattern of morbidity occurs now, 20 years after the diagnoses of the group reported in 2018.

2. Materials and methods

2.1. Cases: selection and diagnoses

All the patients served in the Israeli Defense Forces (IDF). They either operated radar and/or radio communications transmitters or performed duties nearby the facilities. They all contacted Zoar – a volunteer NGO whose mission is to assist cancer patients by providing administrative counseling and legal and social services. Zoar and the patients themselves suspected a high incidence of cancer cases among soldiers serving near RFR emitting equipment and started to record a list of patients. All medical and RFR exposure information was provided by the patients voluntarily through Zoar and all signed informed consent forms. The registration of patients continued up to October 2021.

The 25 male and 21 female patients participating in this study were those who considered causation of their cancer by RFR exposure during the military service as possible. Such patient self-selection tends to form a study group of young people, as they relate cancer to military service mostly if the time elapsed between their service and the cancer diagnosis was relatively short. The average age at diagnosis was 23.7 years. For the same reason, the latencies, calculated as the time from recruitment to cancer diagnosis, were brief - on average 5.4 years, see Table 1.

There were initially 54 patients in total. For 8 patients with tumors, essential information was unavailable on some of the following: definite diagnosis of the disease as cancer, exposure assessment or exposure

Table 1
Age at diagnosis and latency from recruitment to cancer diagnosis, years.

	minimum	median	mean	maximum
Age at diagnosis, years	19	23	23.7	33
Latency from recruitment to cancer diagnosis, years	0.85	4.6	5.4	15

[1] Tumors of the hematopoietic and lymphoid tissues, mainly leukemias, lymphomas and plasma cell tumors. Alternative term is hematopoietic malignancies.

statement and diagnosis of the type of cancer. Therefore, these 8 patients were excluded from the study, which analyzes data on the remaining 46 patients.

Diagnostic information based on medical documents in possession of the patients was provided initially by all the patients either in written form or during an interview. For 37 out of 46 patients, the diagnosis was then verified from their discharge summaries and other medical records. Medical documentation on the other 9 patients was not available.[2] In the 37 cases, the discharge summaries confirmed the diagnosis reported by the patients, except for a single case. Based on this, the remaining 9 patients' self-reported diagnoses are also expected to be reliable (see additional verification in the results section below). Fig. 1 presents the composition of the patients group studied.

As in Peleg et al. (2018), we have only very partial information on the "denominator", that is, on the occupational population the patients came from, such as the number of personnel exposed to RFR in the units. Additionally, the estimations of radiation exposure are less detailed than previously in Peleg et al. (2018), as we were not able to organize long personal interviews with all the patients after their initial interview by Zoar.

A subgroup of six out of the 46 patients was part of a group of 250 soldiers recruited in 2011 to serve in Iron Dome units; thus, for them, the "denominator" was available.

This paper analyzes mostly HL cancers, the data about HL patients are presented in Table 2. Data on all the patients are presented in the supporting material of this paper.

2.2. RFR exposure assessment

2.2.1. Standards of radiation levels

Military organizations reference the occupational ICNIRP 2020 recommendations on radiation levels as not to be exceeded in occupational settings. However, these recommendations were set mainly to avoid thermal effects despite the growing evidence on long-term effects of low level chronic sub-thermal exposures such as those reported by Friedman et al. (2007), Chou et al. (1992), NTP on mice (2018), NTP on rats (2018) and Falcioni et al (2018). The ICNIRP levels allow for much higher radiation exposures than are typical in the community, see Table 3.

2.2.2. Exposure overview

Each patient was asked to describe the sources of his/her RFR exposure to an extent permitted by security regulations. Such a description usually included an identification of the transmitter type, such as radar or communication transmitter, approximate distance of the soldiers from the transmitter and duration of exposure. The exposure was typically a few hours per day, most days in each year. Typical service period was one to three years. RFR measurements were not

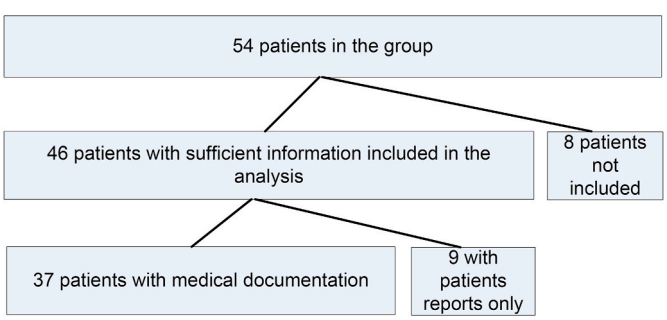

Fig. 1. The composition of the patient group.

Table 2
Diagnoses of the patients with hemolymphatic cancers.

Self-reported diagnosis	Diagnosis confirmed by documentation	Age at diagnosis	Gender	Latency from recruitment to diagnosis
Leukemia	Acute lymphoid leukemia	22	F	3.1
Non-Hodgkin's lymphoma	PMBCL - primary mediastinal large b-cell lymphoma - non-Hodgkin lymphoma	23	F	4.5
Hodgkin's lymphoma	Hodgkin's lymphoma	19	M	1.4
Hodgkin's lymphoma		20	F	2
Hodgkin's lymphoma	Hodgkin's lymphoma stage IIA	23	M	4.4
Hodgkin's lymphoma	Hodgkin's lymphoma	21	M	3
Hodgkin's lymphoma	Hodgkin's lymphoma	19	F	1.1
Hodgkin's lymphoma and thyroid cancer	Hodgkin's lymphoma + papillary thyroid carcinoma	28	M	7.7
Hodgkin's lymphoma		25	F	14.4
Hodgkin's lymphoma	Hodgkin's lymphoma	30	F	12.3
Lymphoma	Diffuse large b cell lymphoma	19	F	1.3
Leukemia + tumor between heart and lungs	Acute lymphoblastic leukemia T cell + mediastinal mass	28	M	9
Hodgkin's lymphoma		26	F	8.8
Leukemia		21	M	3
Leukemia	ALL - acute lymphocytic leukemia	27	F	8.3
Non-Hodgkin's lymphoma	Burkitt's lymphoma-non-Hodgkin's lymphoma	20	F	1
Chronic leukemia	Chronic myeloid leukemia	25	M	6.2
Hodgkin's lymphoma	Hodgkin's lymphoma	20	M	0.85
Chronic Leukemia		21	F	3

Table 3
Radiation levels for whole-body exposure in standards, in recommendations and in the community.

Radiation levels at frequency of 2 GHz	
The standard or scenario	Radiation level in microwatt/cm^2
Community exposure from base-stations, Koppel et al. (2019); Koppel and Hardell (2022)	0.1 to 10 (typical levels)
Swiss and Italian community radiation limits	4 to 10
Israeli community radiation limits for long-term exposure	100
ICNIRP recommendation for the general public, 6 min average.	1000
ICNIRP occupational recommendation, 6 min average.	5000
ICNIRP occupational recommendation, pulse peak level [a]	5 000 000

[a] As specified in ICNIRP 1998, is much higher in ICNIRP 2020.

[2] Each patient, in line with medical ethics, decided freely whether to provide personal medical documents. Patients who did not provide documents explained this by the possibility of loss of jobs, the possibility of reprisal by the authorities and a preference of soldiers and parents of the deceased to avoid traumatic memories.

available. The exposures included the whole body, not just the head as in mobile phone studies. The estimated power densities incident on the soldiers were much higher than those typical from cellular base stations in the community, up to the possible maximal levels listed in Table 3. The RFR incident levels were intended to be regulated by the ICNIRP occupational limits. The exposure included in most cases powerful radar pulses. The RFR radiation levels and other exposure characteristics, such as frequencies and modulations, varied considerably between the different units. The soldiers served in units operating the following systems: Iron Dome (20 patients), Arrow (4 patients), Hawk (1 patient), Patriot (4 patients), David Sling (1 patient), air force (11 patients), navy (4 patients) and other (2 patients). One patient served with two air defense systems. Altogether, 40 out of the 46 patients reported service near a transmitting radar. More detailed exposure estimates are presented in the next section.

2.2.3. Exposure in different military units

Note: This subsection includes web references which are listed separately below the regular reference list.

3.2.3.1. Iron Dome battery. Twenty soldiers served in Iron Dome batteries. A soldier typically serves in the unit for one to three years. The soldiers have different functions. The following applies to most of them. They spend more than half of their service in the vicinity of the battery radar, 5–100 m from it and usually not in the sector intended to be covered by the radar. This also includes sleeping near the radar with no radiation protection.

The radar, as obtained from the web references ELM 2084 MMR (2018), Globes (2020), Boguslavsky E., 2020, Orpaz (2012) and ELM-2084 (2020), is the ELM-2084; an active, solid state, phased-array radar. The antenna size, as seen in the same web references, is approximately 5 square meters. The radar transmit power is not readily available, and we present data from the tutorial by Sanders (2005), which, while not related to ELM-2084, may provide a rough estimate of a typical radar transmitter. Emissions are pulsed with typically 0.1% duty cycle, that is, short-duration powerful pulses with inactive intervals in between. Peak transmitter power levels can be 1 MW (1 million watts). Peak effective isotropic radiated power (EIRP) levels are of the order of 1 GW (one thousand million watts).

Such power incurs exposure of 790 000 μW/square centimeters at a distance of 100 m during the radar pulse on a soldier if he/she is located in the narrow antenna beam. The exposure is lower but still very high if the soldier is outside the antenna beam, as determined by the beam sidelobes and backlobes. The beam of phased-array radar can move quickly and over a wide range of directions. The exposure is whole-body since the radiation beam width is never smaller than the antenna array size as is well known from array antennas theory, see the Near and far field web reference for illustration.

The ICNIRP recommendations, which are typically used in the military, permit exposure of personnel to such peak radiation levels and higher, see Table 3. The explanation offered by ICNIRP is that because the pulse's duty cycle is low, that is, short pulses with long intervals between them, the temperature rise is within safe limits, and if there is no excessive temperature rise, then no adverse health effects occur. However, the peak power does have biological significance as reported by e.g., Kiel et al (2000) and Liu et al. (2000), and as possibly indicated by the rise in all-cancers risks in rats exposed to radar-like signals in Chou et al. (1992). We suggest that the peak power could well be the relevant parameter of risk for adverse biological effects.

The battery also includes communication equipment, as reported in the Orpaz (2012) web reference.

3.2.3.2. Hawk missiles. One soldier served in the Hawk missile unit. The exposure is of similar characteristics to the Iron Dome, using powerful radar. All the soldiers are in the vicinity of the radar 24 h a day. Radiation exposure is intense, see details in Degrave et al. (2009).

3.2.3.3. David's sling battery. One soldier served in a David's sling missile unit. The ELM 2084 MMR (2018) web reference states that this missile battery uses the same radar type as Iron Dome.

3.2.3.4. Arrow missile. Four soldiers served in an Arrow missile unit. According to the Green Pine Radar 2018 web reference, the Arrow missile uses a very powerful Green Pine radar.

3.2.3.5. Patriot battery. Four soldiers served in a Patriot battery. According to the web reference Sokol (2014), a Patriot battery uses advanced radar and communication equipment.

3.2.3.6. Other patients. The other patients served in various units of the IDF. All reported serving over months to years near transmitting antennas of communications and/or radar systems.

2.2.4. Other exposures

Data were not available on any other previous exposure, occupational or other. We cannot rule out the possibility of preexisting exposure serving as possible initiators or promotors. Personal cellphones, personal computers and other RFR exposures not related to the military service are ubiquitous. They are not likely to account for the unusual patterns of rather young age onset of cancers different from the general population.

2.3. Information from the patients

The patients were requested to fill out an online questionnaire providing additional information.

2.3.1. Radiation safety instruction

Only four soldiers out of 29 who answered our question were told by the Army that they belonged to the category of 'occupationally exposed' soldiers and needed to apply precautions. All the others reported that they had received no RFR safety instructions.

2.3.2. Other cancer patients in the same unit

Sixteen out of the thirty-one soldiers who answered this question were aware of additional cancer patients among soldiers in their same unit.

2.4. Cancer registry

We used the Israeli cancer registry (CR) (Israeli cancer database, as of November 2019 https://statistics.health.gov.il/views/_5/sheet2?%3Aembed=y) using tables derived from the Israeli Jewish populations in 2013, 2014, and 2015, summing up numbers of cases for each category (gender, cancer type, and age of diagnosis group) over the three years. The number of all patients with cancer was taken from the table denoted "all cancer types". For HL cancers, we summed leukemia, Hodgkin's and non-Hodgkin's lymphomas, multiple myeloma, and plasma cell tumors.

The data we used are plotted in Fig. 2, grouping the two genders for clarity. We plotted the number of cases which is the raw data from the CR and which is used directly in our analysis of HL PF presented in the next section rather than plotting processed data such as cancer rates per 100 000 persons.

For a wider perspective, we obtained incidence data on all cancers and on the most prevalent HL cancers from the IARC Global Cancer Observatory site Ferlay et al. (2020), see Table 4. The incidence rates in Israel are comparable to those in Europe. For all the HL PF evaluations of Israeli Soldiers below we use the Israeli CR data.

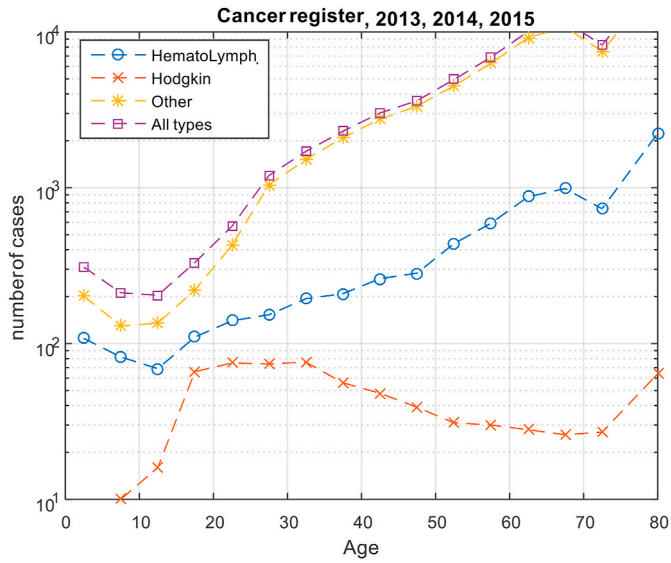

Fig. 2. Number of cases from the Israeli CR (Israeli cancer database, 2020). Years 2013–2015. Each point represents a 5-year range of ages at diagnosis. "Other" denotes non-hemolymphatic cancers. HematoLymph denotes all Hemolymphatic cancers.

Table 4
Age-standardized rates (world) per 100 000, 2020, ages 20–34, both sexes, (excl. non-melanoma skin cancers).

Age-standardized incidence rates per 100 000, 2020, ages 20–34, IARC site			
	World	Europe	Israel
All cancers	34.9	54.9	47.9
Leukemia	2.2	1.9	2.1
Lymphoma non-Hodgkin	1.7	2.6	3.1
Hodgkin lymphoma	1.2	3.8	4.5

2.5. Statistical methods

2.5.1. The percentage frequency method

We analyzed the percentage frequency (PF) of hematolymphoid (HL) cancers. This is the percentage of patients with HL cancers in a group of cancer patients. HL PF is a recognized epidemiological parameter explained by Boyle and Parkin (Boyle and Parkin, 1991). Furthermore, HL PF is available in cancer registries and can be statistically analyzed. The calculation of observed HL PF is performed by a straightforward division of the number of HL cases in a group of cancer patients by the number of all cancer patients in the group. The statistical method of analyzing the PF confidence interval and its p-value is detailed in Peleg et al. (2018). The young age profile of the group results from self-selection. This self-selection does not interfere with the PF analysis, which does account for age and gender, as presented in Peleg et al. (2018).

2.5.2. Subgroup of six cancer patients

The subgroup of six patients belongs to a group of 250 soldiers recruited in 2011. Given that the group size is known and the age at recruitment is 18 years, it is straightforward to calculate the expected number of cancer cases with no radiation exposure over the years from data available in the Israeli CR, Table 5. The proportions of males and females were estimated based on soldiers' reports. We used the rates of cases per 100 000 people per year for each age and gender category, specifically the categories "all tumors" and "Jews".

We calculated the expected and the observed cumulative number of cases, which is the total number of cases diagnosed from the time of recruitment up to each of the following eight years. The risk ratio (RR) and the 95%CI intervals were calculated.

Table 5
Reference data from the Israeli cancer registry, all cancers. 2015.

Expected cancer cases per 100 000 people per year, Israeli Cancer Registry.		
Age group	Male	Female
15–20	27.3	15.2
20–25	33.5	45.6
25–30	54.8	120.9

We evaluated the p-values conservatively, accounting for the fact that soldiers were recruited for Iron Dome over 11 years[3] while we have data on the number of soldiers drafted per year only for 2011. There may be an effect of multiple choices because we possibly let the year 2011 to be selected by available data out of 11 possible years. To address this issue, we first calculated the probability p_1 of six or more cancer cases in the 2011 group under the null hypothesis using the upper tail of the binomial distribution. Then we calculated the probability p_2 of an occurrence of at least 6 cancer cases (probability p_1) in at least one of the groups recruited each in one of the 11 years. The final p-value reported is p_2. As p_1 was small, the numerical result was near the Bonferroni correction, that is, $p_2 \cong 11 \times p_1$.

The RR and its confidence interval are valid for the group recruited in 2011; similar calculations for the 10 other groups recruited in the different years would require unavailable data on the number of soldiers recruited each year and on the number of all cancer cases, not only those who contacted Zoar.

3.6. P-value of sarcoma in rats

As reported by Chou et al. (1992), 3 out of 100 rats irradiated with RFR were diagnosed with a sarcoma versus zero in the same-size control group. We define the null hypothesis as an equal probability p_s of sarcoma in each rat regardless of exposure. We compute the p-value as the probability of zero sarcomas in the control group and at least 3 sarcomas in the RFR group. Since p_s is unknown, we conservatively choose p_s which maximizes the p-value.

4. Results

4.1. PF analysis results

The PF of HL cancers, of Hodgkin's lymphomas (subset of HL) and sarcomas was computed and analyzed, see Table 6.

4.1.1. Percentage frequency (PF) of hemolymphoid (HL) cancers

Out of 46 patients, 19 had HL cancers. The PF of HL cancer was high, 41.3%, 95% CI (27%–57%), p = 0.003, similar to Peleg et al. (2018) and Szmigielski S., 1996. The expected PF value for a group with this age and gender profile is 22.7%. Thus, the observed proportion of HL cases is nearly twice the expected number. The patient group was younger than that in our previous work.

Repeating the analysis only on the 37 patient's diagnoses verified by medical documentation yields a similar HL PF result with a higher but still significant p-value due to the smaller group, see Table 6.

4.1.2. PF of Hodgkin's lymphomas

The PF of Hodgkin's lymphomas is 21.7%, 95% CI (11%–36%), p = 0.033. This is almost double the expected PF value of 11.6%.

4.1.3. Sarcomas

Out of the 46 patients in the group, 7 were diagnosed with sarcoma,

[3] Iron Dome became active gradually in 2009, and soldiers drafted in 2019 and 2020 would not have sufficient observation periods.

Table 6
Percentage frequencies (PF) for Hemolymphatic (HL) and sarcoma cancer types. 95%CI denotes the 95% Confidence Interval.

Cancer type	Patients group	*PF* expected in the general population by the Cancer Registry according to the age and gender profile.	Group size *N*	Number of patients with cancer of this type in the group	Observed PF in the group (95% CI)	p-value of the observed PF
HL	all the 46 cases	22.7%	46	19	41.3% (27%–57%)	0.003
HL	only patients verified by medical documents.	23.3%	37	14	37.8% (22.5%–55%)	0.031
Hodgkin's lymphoma	all the 46 cases	11.6%	46	10	21.7% (11%–36%)	0.033
Sarcoma	all the 46 cases	7.0%	46	7	15.2% (6.3%–28.9%)	0.04

PF = 15.2%, 95%CI (6.3%–28.9%), p = 0.04, nearly twice the 7.0% PF expected for the group age and gender profile. All the sarcoma patients provided medical documentation. The reference data were retrieved from the large Surveillance, Epidemiology, and End Results (SEER) Program database[4] collected in the US, not in Israel where the cases occurred. The printouts of the SEER software are included in the supporting documents associated with this paper.

4.2. The subgroup of six cancer patients

The number of all cancer cases among the group of 250 soldiers recruited in 2011 was many-fold higher than expected from the CR. In 2014, three years after recruitment, the number of cancer cases reached 5 versus 0.22 cases expected by the CR, $p < 0.0001$. After eight years, up to 2019, the cumulative number of cases reached 6 versus the 0.75 cases expected by the CR, $p < 0.002$. Out of the six cases, three were HL cancers, and three were non-HL, see Fig. 3. The RR of all cancers after eight years, evaluated as the number of observed cases divided by the number of expected cases, is 8.0, 95%CI (2.9–17.0). The RR is estimated from the available data on the group recruited in 2011. Follow-up research using data on all the recruited soldiers and on all the cancer cases should be carried out.

Thus, with RR estimated as 8.0, the cancer risks are very high for both HL and non-HL cancers. The HL PF is high and similar to that of the whole group of 46 patients, and the latencies from recruitment to diagnosis are short, 2–8 years, median 3. The RR of all cancers is similar to that reported in Peleg (2009). The actual cancer risks may be even higher because there are possibly cancer cases among the 250 soldiers not reported to Zoar.

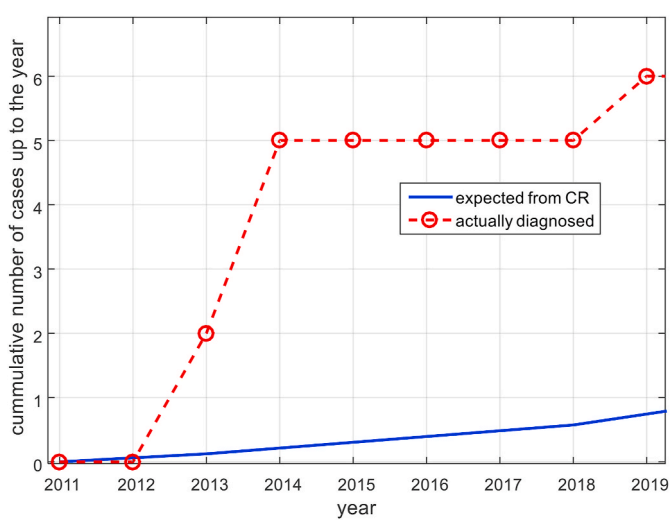

Fig. 3. *Cumulative all-cancers cases for the group of 250 recruited in 2011, actual cases* versus *cases expected from the Cancer Registry (CR).*

[4] Surveillance Research Program, National Cancer Institute SEER*Stat software www.seer.cancer.gov/seerstat version 8.3.9.2.; Stat Database: Incidence - SEER Research Data, 13 Registries, Nov 2020 Sub (1992–2018).

5. Discussion

5.1. Comparison with previous reports

Our main result on HL PF and on general cancer risks together with results from five other groups reported in previous publications are listed in Table 7. All those are studies of personnel in the defense sector with whole body occupational exposure to RFR in contrast to studies on brain cancers among cellphone users. We suggest that the shift from local exposure of the head among the mobile phones users to occupational whole-body exposure explain the additional types of cancers observed, mainly the HL cancers. The five previous groups of patients are 47 servicemen, engineers and technicians from the Israeli defense sector reported in Peleg et al. (2018); 5 engineers and technicians with cancer out of a workforce of about 30 people in an antenna ranges facility in Israel reported in Peleg (2009); 7 radar technicians with cancer out of a group of 25 workers at the site reported in Table 3 of Richter et al. (2000); approximately 66 patients from the defense sector in Poland reported in Szmigielski (1996); and servicemen in a Belgian air defense unit reported in a causes of death study analyzing 205 cancer-related deaths, Degrave et al. (2009).

The Observed/Expected (O/E) ratios of HL PF and the O/E of all cancers risks in the same six groups are plotted in Fig. 4. The O/E of HL PF is the observed PF divided by the PF expected from the CR data or from a comparison group.

The HL PF value of cancers reported in this work is much higher than that expected from the CR data and, importantly, it is consistent with the five other independent groups of patients exposed to whole-body RFR. The association of RFR with increased HL PF is evident and statistically significant in each group separately, the findings are robust. This is the main result of this work.

The RR of all cancers were identified as high in the first five groups with values ranging from 2 to 50 and median RR = 8 of the 5 groups. The RR in group 6, the causes of death study, is partially masked by cancers in older ages, it is still significant despite accounting for all cancers over lifetime. The estimates of the RR of all cancers in the first two groups are rough evaluations due to the missing or partial 'denominator'. The all-cancers RR in group 1 in Table 7 was estimated by analysis of a subgroup of 6 patients for which the size of the exposed population ('the denominator') was known and in group 2 by analysis of multiple primaries. The all-cancers RRs in groups 3,4,5 and 5 were calculated by the usual method based on known size of the exposed population.

Those six groups were studied using diverse research methods. The underlying pattern, that is, high HL PF and high all-cancers risks, were reported consistently in each group.

Increased HL cancer risks were reported also in the US navy during the Korean war by Groves et al. (2002) and Robinette et al. (1980), see

Table 7
Summary of parallel studies in three countries. Percentage Frequency (PF) of hemolymphatic (HL) cancers and general cancer risk ratios in this work and in previous publications. CR denotes Cancer Registry and CI is Confidence Interval.

Patient group	HL PF expected in the general population or in a non-exposed comparison group	Patient group size	Number of patients with HL cancer in the group	HL PF observed in the group and its 95% CI	p-value of the observed HL PF	All cancers risk ratio
1. This work, 46 cases from the Israeli Defense Forces	22.7% from CR	46	19	41.3% (27%–57%)	0.003	8, 95%CI (2.9–17) estimated from a small subgroup
2. Peleg et al. (2018), cases from the Israeli defense sector	23.4% from CR	47	19	40.0% (26%–56%)	0.0055	4.5, 95%CI (1.7–9) rough estimate from multiple primaries
3. Peleg (2009), Antenna ranges workers	17.5% from CR	5	3	60.0% (15%–95%)	0.0384	8.3, 95%CI (2–22.5) $p < 0.005$
4. Richter et al. (2000), radar technicians	22% from CR	7	5	71% HL RR = 250, $p < 0.001$	$p < 0.001$	50, $p < 0.001$
5. Szmigielski (1996), Polish military forces	12.0% comparison group	~66	~24	36.0% (24.9%–49%)	<0.001	2, $p < 0.05$
6. Degrave et al. (2009), Air defense radar in Belgium [a]	1.4% (comparison group)	133 Deaths from cancer, RFR group	11 Death from HL cancers, RFR group	8.3% [a]	HL RR = 7.2, 95% CI (1.09–47.9)	[a] 1.22 95%CI (1.03, 1.47)

[a] Degrave et al. (2009) is a study of causes of death over a lifetime; thus, HL PF is different from the other groups because causes of death also involve diseases of old age. Our analysis method is not applicable for computing the p-value and CI of the results in Degrave et al. (2009), as explained in Peleg et al. (2018). The rate ratio (RR) of HL cancers and its CI are copied from Table IV of Degrave et al. (2009).

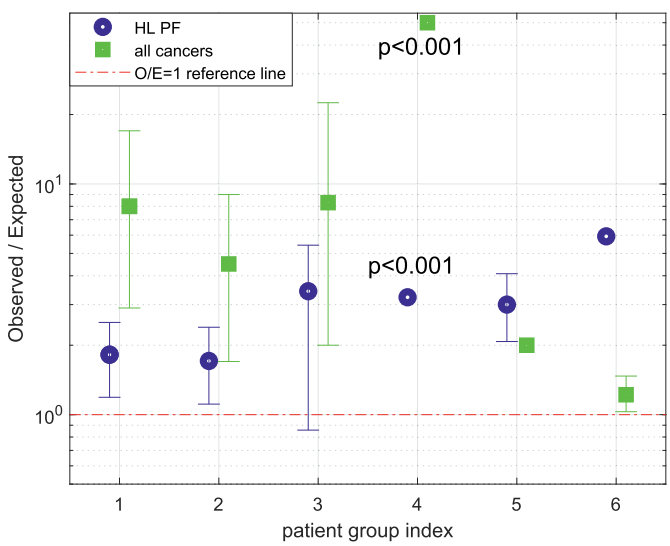

Fig. 4. *Summary of parallel studies in three countries. Observed/Expected (O/E) ratios of HL PF and of all cancers risks in the six groups in Table 7. The patient group indices are the same as in Table 7. 95% Confidence Intervals, when available, are plotted as short horizontal lines. HL PF denotes Hemolymphatic Percentage Frequencies.*

discussion below, and among US radio amateurs by Milham, 1988, and Milham (1985).

Increased HL cancer rates were found also in animal models. Increased lymphomas in pulsed-RFR-exposed transgenic mice were reported in Repacholi et al. (1997). Experimental study on rats exposed to radar-like pulsed RFR, Chou et al. (1992), Table 2, reported 32 HL cancers in a group of 100 rats exposed to RFR versus 19 HL cancers in a same-size unexposed comparison group.

5.2. Association and causation

The data presented in Table 7 and in Fig. 4 show high HL cancer risk and high all cancers risk in six independent groups of people exposed to RFR in the military/occupational setting. The risk is observed in all the six groups by a high HL PF and by an increased RR of all cancers.

We are not aware of any hidden bias or influence other than causation that could explain the association of RFR and of increased cancer risk in those six groups of patients. These groups were diagnosed in different locations spread over three countries, in different times spread over tens of years and operated different radiation-emitting equipment and different generations of equipment. We are not aware of any other hidden carcinogen, chemical, or physical radiation, in all the six groups. We are left with causation as the most plausible explanation of the association between RFR and cancer in the six independent groups.

5.3. On the possibility of bias

It is important to assess the impact of bias in a self-selected group of patients. The PF method is robust with respect to many possible sources of bias as discussed by Peleg et al. (2018). The only bias relevant to this work would be one that would cause a larger proportion of patients with HL cancers, as well as sarcomas, to join the research than patients with non-HL cancers. This is unlikely for the following reasons. The Zoar NGO assists thousands of cancer patients with difficult administrative, legal and social-services tasks and advertises itself as such. This help is needed by the patients and is not known to be related to cancer types. Some of the patients knew each other because of overlapping service in the same military unit but this occurred in some small groups of between one to three patients, the decisions to enroll were mainly individual. The NGO did not select the cases as the patients themselves initiated the connection. All patients who contacted the NGO and reported service near RFR transmitters enrolled in the research as can be seen from the admission criteria in Fig. 1. Moreover, the possibility that RFR raised the risk of HL cancers more than that for non-HL cancers was unbeknown to the participants. The minority of people who associate RFR with cancer consider only brain cancer from the wide-spread information in mass media regarding mobile phones. To examine the issue of bias further, we asked the patients if they had read, before contacting Zoar, the only newspaper article in Hebrew which reported the HL PF findings of Peleg et al. (2018). Out of 29 who answered this question only 8 gave a positive answer and only 3 out of those 8 suffered a HL cancer, a proportion similar to the HL PF results in Table 6. Only one out of the 8 answered that he was aware of a possible relation between a cancer type and RFR. Note that the earlier paper Peleg et al. (2018) contained no data on sarcomas.

However, this conclusion of non-bias will not apply to future

research. If the current work will be widely reported in the media, then the HL PF method of research will indeed become bias-prone, emphasizing the imperative, in future work, to collect full data, especially regarding the denominator.

5.4. Sarcomas

The PF of sarcomas in the group is about double the expected value and statistically significant. Unlike the PF of HL cancers which was analyzed following the high HL PF findings in previous research, the analysis of sarcomas here was triggered by its high PF in this same group of patients, so our sarcoma results by themselves are aposteriori findings requiring further confirmation. However, increased sarcoma incidence was reported in an animal model by Chou et al. (1992), Table 2. Three out of 100 rats irradiated with RFR were diagnosed with sarcoma versus zero in the same-size control group. Our calculation yields $p < 0.05$ ($p = 0.0437$). Chou et al. (1992) reported also a significant, more than two-fold, increase of all cancers, which he termed "provocative" in the report.

There are additional studies suggesting a possible association of sarcoma and RFR. Sulem and Rafnsson (2003) found an increase in soft tissue sarcomas in on-deck officers of Icelandic commercial, mostly fishing, ships, RR = 2.7, 95%CI (1.2–5.1). RFR is listed as one of the possible causes even though the intensity of RFR is not estimated. Nilsson (1998) is cited as reporting a similar finding among deck officers in Sweden. Tynes et al. (1992) reported increased soft tissue sarcomas, RR = 1.36, 95%CI (0.93–1.91) in Norwegian workers potentially exposed to electromagnetic fields. Most workers were exposed to low line-frequency electromagnetic fields and some to RFR. Pereira and Edwards (2000) reported a case of a benign pseudosarcomatous proliferative lesion of myofibrobroblasts in a heavy mobile phone user and Hardell et al. (1999) reported a case of angiosarcoma of the scalp in a heavy cordless phone user, in both cases the tumor site was on the head near the location of the mobile or cordless phone. Pearce et al. (2007) reported paternal occupational exposure to electro-magnetic fields as a risk factor for cancer in children and young adults, mainly leukemia and chondrosarcoma (OR 8.7, 95% CI 1.55–49.4). Sarcomas associated with RFR require additional research and the numerous reports state the case for precaution and prevention.

5.5. Non-HL cancer types

As explained in Peleg et al. (2018), if a carcinogen affects some cancer types more than others, the PF result will be higher than the general population value for some cancer types and lower for others, even if the cancer rates rise for all cancer types. Thus, PF is effective in detecting a carcinogen, but it cannot estimate the risk for all cancer types in a population. The analysis based on only HL PF does not indicate whether the other (non-HL) cancers in the group were associated with RFR; but there are compelling reasons for a positive answer:

1. The subgroup of soldiers recruited in 2011 in the current study suggests a severely elevated general cancer risk. There were three patients with non-HL cancers and three with HL cancers among these soldiers, whereas a total of 0.75 cases of cancer would be expected from the CR data and the subgroup size and ages.
2. 16 (51%) out of 31 patients who answered this question reported soldiers with cancer in the same unit, but we were unable to validate their claims. This high proportion is not to be expected among young people aged 18 to 23 and may indicate an excessive number of cancer cases.
3. High RRs of all cancers were reported in five other similar groups of cases, see Table 7 and Fig. 4. The approximate estimates of RRs in the first four groups are considerably higher than the rise in HL PF indicating increased all-cancers risk.
4. Numerous non-HL cancer types have been shown to be associated with exposure to RFR. See Szmigielski,1996, Hardell and Carlberg (2021), Miller et al. (2018), thyroid cancer in Luo et al. (2020) and Carlberg et al. (2020), breast cancer in Shih et al (2020), Tynes et al. (1996), West et al. (2013) and Kliukiene et al. (2003), pancreatic cancer in Zaret (1991) and the listing of additional cancer types in Peleg et al. (2018).
5. Animal studies strongly suggest that RFR is a universal carcinogen. The survey by Lin (2019) reported several cancer types in animal models exposed to RFR and consistent significantly increased total primary cancer rates or overall tumor rates in animals exposed to RF radiation.
6. The PF of sarcomas in the group of 46 patients reported here is high and supported by previous finding in humans and in rats.

5.6. The possible extent of the problem

The group of patients reported here is not a study of the whole military sector, as was accomplished by Szmigielski (1996), since it comprises only a self-selected group who came to us by the NGO Zoar. We hypothesize that most cancer cases of RFR-exposed soldiers have remained unreported in the scientific literature, as was proposed by Peleg (2009) in a study on defense military workers.

5.7. Latencies

The cancers latencies in most of our patients were short, 0.85–15 years, median 4.6, see Table 1. Hardell et al. (2013) presented findings consistent with the hypothesis that RFR plays a role both in the initiation and promotion stages of carcinogenesis while shorter latencies as reported in this work are more likely related to promotion and longer latencies to initiation.

5.8. The influence of age

The high cancer risk ratios (RRs) associated with RFR reported in this work, in Peleg et al. (2018), and in the references therein, occurred mostly among young men and women. The RR was higher than that reported in mobile phone settings. Apart from some possible age dependency of the RFR-induced cancer risks, there are two possible factors. The baseline cancer risks of young people are low (see Fig. 2); thus, additional RFR-induced cancers stand out. Furthermore, groups of people exposed to whole-body strong RFR over months and years occur mostly in military service and in advanced electronic industries, both involve a high proportion of young men and women. Indeed, Degrave et al. (2009) found that among radar operators the RR for cancer increased with decreasing age. Similarly, Szmigielski (1996), reported a rise in all RR of all cancers with decreasing age, see the exposed/non-exposed ratio for all cancers in his Table 3. An early similar finding from the mobile and cordless phone setting, Hardell et al. (2006), reported that RRs for RFR-related brain cancer were found to be highest in subjects at the young age groups who started to use such phones before reaching the age 20. Recently, Hardell and Carlberg (2021) reported an annual percentage change rise of incidence of brain tumors highest in the 20–39 age group and possibly linked to RFR.

5.9. Comparison to lifetime and causes of death studies

Our study focuses mainly on patients diagnosed within first 10 years after the first exposure, median 4.6 years, see Table 1 and Fig. 3. Dabouis et al. (2016) carried out a historical cohort mortality study on 57 000 military personal in the French Navy with measurement data and job exposure classification. They studied what happened to the exposed personnel over a longer period of up to 26 years in a causes of deaths research and found no health effects of exposure to radar RFR except for a rate ratio of 1.64, 95%CI(0.37–7.34) of deaths from tumors of the

lymphatic and hematopoietic tissue, see Table 6 there.

Previous large scale mortality studies on the US navy during the Korean war reported elevated HL and other cancers. Groves et al. (2002), see Table 4 there, reported Relative Risk for all leukemias of 1.48, 95%CI (1.01–2.17) and Relative Risk of 1.82, 95%CI (1.05–3.14) for nonlymphocytic leukemia. The study by Robinette et al. (1980), combining mortality and hospital admissions reported an increase in all and in HL cancers not reaching statistical significance, e.g. the Mortality Ratio (MR) of all cancers of 1.44 and of HL cancers of 1.64 in the highest exposed group, see Table 9 there. A focused analysis presented in Table 6 of Goldsmith (1997) shows significant increase of all cancers and of HL cancers among aviation technicians in the Robinette et al. (1980) report. The weak effects of RFR in the study by Dabouis et al., (2016) as compared to the very strong effects reported in this paper require discussion.

The Dabouis et al. 2016, Robinette et al. (1980), Groves et al. (2002) and our results are consistent with the following hypothesis: In the first years after the exposure the rate ratio of cancer diagnoses is very high. However, due to the low background risks for cancer at the young ages, most servicemen do not get cancer. This does not diminish the harsh consequences of RFR-caused cancers at young age of those who do. With modern healthcare most of the young patients are treated successfully and do not die from cancer and thus are not noticed in the causes of death studies. In later years the rising cancer rates of older ages, see Fig. 2, mask the cancers caused by the RFR exposure during the military service. Consequently, the two diverging lines in our Fig. 3, which shows striking cancer risks in the first years following the exposure, may eventually converge, that is, most RFR exposed personnel do not die from RFR-caused cancer.

There is a need to clarify two points concerning the important study by Dabouis et al (2016). It stated: "*Follow-up ended either on the date of death, …, or on the date of departure from the Navy for military personnel who had left the Navy.*" It is not clear how this research accounted for men diagnosed with cancer during service and leaving the service alive. Another point: there might be exposure to airborne carcinogens below the main deck producing bias, deaths from disease of the respiratory system are reported to be about 6 times more frequent in the comparison group serving below the deck indicating a possibility of very unhealthy environment. Dabouis et al (2016) reported: "*There was a statistically significant difference between the two groups for death from disease of the respiratory system, the number of which was lower in the radar group (RR = 0.17 95% CI: 0.03–0.92)."*

5.10. Implications of the exposure and it's assessment

Our exposure assessment is based on soldier reports and approximations of transmission power and distances. The information on exposure is limited also by security concerns. All 46 patients included in the study were exposed to RFR at estimated intensities much higher than the typical citizen exposure. Consider the influence of unknowingly including in the study group a small number of patients not exposed to intense RFR. Obviously, such mistaken inclusion would bias the HL PF toward the lower PF values expected from the CR data.

The exposure intensity and exposure characteristics of the 46 patients differed over a wide range according to the particular unit and to the role of each soldier in the unit. If all exposures were intense and identical, we would expect higher HL PF and higher cancer RR. Such a higher risk was indeed reported in small groups of engineers and technicians from the industry, see Peleg (2009) and Richter et al. (2000) in Table 7 above. These high RRs in small subgroups may be relevant to the six patients in this study recruited in 2011 to serve in the Iron Dome units, see Fig. 3.

5.11. Recommendations

5.11.1. Reduce human exposure to RFR

Considering the growing evidence of carcinogenicity, it is crucial to reduce human exposure to RFR while additional data accumulate. We suggest practical measures as follows:

Set an exposure threshold considering the reported biological effects of low level RFR and the RFR levels really needed for equipment function. Even in the military setting, this level should be the typical community RFR exposure, see Table 3. Possible suggestions:

$1\mu W/cm^2$ average level.
$5\mu W/cm^2$ peak pulse level.

The above average level is in the range of community levels reported in the literature. The higher recommended peak pulse level follows a rough estimate of typical peak to average power ratio (PAPR) of cellular communication using orthogonal frequency-division multiplexing (OFDM).

Increase the distance between personnel and transmitters.

Use antenna patterns with low sidelobes to reduce exposure.

If applicable, insert a high metal fence acting as a Faraday shield, between a powerful transmitter and the soldiers. The shielding is effective either near the source or near the personnel.

Create RFR-protected areas, for example, by covering buildings and tents with thin metal sheets functioning as Faraday shields or by incorporating such sheets in new relevant constructions.

Include exposure-reducing features in all new RFR equipment designs, such as automatically reducing transmit power to the minimal needed, automatic switch-off of not needed transmitters, transmitting antennas with low sidelobes, remote control to enable distancing the soldier from the transmitting equipment, and RFR-shielded operator stations.

Use RFR-protective clothing also including protection of the head and neck. Note that this is not a perfect protection since such clothing typically has openings. Protective clothing, while beneficial, is not a substitute for reducing the exposure at its source as described above.

Provide information to personnel about the carcinogenicity of RFR to motivate adherence to safety rules.

The obvious ultimate solution is a worldwide peace.

5.11.2. Medical support

For all personnel exposed to RFR at levels exceeding background community exposure, carry out periodical medical surveillance, including regular blood tests. Screen for cancer and for other RFR-related health effects. Include new tests sensitive to RFR exposure, aneuploidy in blood samples might be developed into such a test, Mazor et al. 2008. Continue with checkups at least 10 years after release from military service.

Military medical doctors need to be aware of the cancer risk from RFR and methods for monitoring, detection, and prevention. The diagnosis of many patients reported here occurred after many months of unacceptable delay; this should be corrected.

5.11.3. Documentation and research

Carry out epidemiological research on all RFR-exposed personnel, including the publication of results in peer-reviewed literature and in open databases, to enable closing the knowledge gap. Most carcinogens have non-carcinogenic effects as well, e.g., Belpomme et al. (2018); thus, research on health effects other than cancer is also needed, e.g. fertility problems in men and women.

Implement the obligation to inform and the right to know: Provide soldiers with data in real time on exposures and interpretation of the findings. Provide any soldier exposed more than typical community exposure with his/her personal exposure record to support research and to identify victims and provide them assistance.

6. Conclusion

This work reports a new group of cancer patients with previous RFR exposure in the occupational/military setting and reviews five similar groups in three countries reported formerly. The six groups of cancer patients with occupational and military RFR exposure are summarized in Table 7 and in Fig. 4. In all the six groups, there was a consistent, statistically significant, and well-documented atypically high HL PF, distinctly higher than expected in the community (Cancer Registry) or computed from unexposed comparison groups. In each group, except one[5] (Degrave et al. 2009), there was also an indication of highly elevated risk ratios (RRs) for all cancers. Those groups are generally characterized by whole body exposures of several years, young ages at diagnosis, and brief latencies from the beginning of exposure to diagnosis.

The above findings of increased all-cancers risks and increased HL PF in the six RFR exposed groups in the occupational setting, together with the previous works on brain tumors of cell-phone users, animal model studies, laboratory results and theories of possible physical mechanisms, indicate with a high degree of confidence, that high intensity and long-term whole-body exposure to RFR causes an increase in cancer risk in groups of occupationally exposed young people. The median risk ratio for all cancers in the five groups reported here is RR = 8. We suggest that the high peak power of radar pulses may be a contributing factor. The HL PF and all-cancers risks findings reported here add to the large body of evidence which justifies recommending reclassification of RFR by IARC as a human carcinogen, IARC group 1.

The high PF of sarcomas reported here and the previous sarcoma findings suggest the case for carcinogenicity.

The RFR exposure of the current group and of some of the other groups was regulated to be within the occupational ICNIRP recommendations, indicating that those recommendations are not protective or rigorous. The group of young patients reported here demonstrates that the problem is current and ongoing. There is a strong case for preventive measures to protect personnel and bystanders from whole body exposure to RFR with attention to high peak power pulses.

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Human research approval

The manuscript reports questionary-based non-interventional retrospective research on human subjects. The compliance of the research to the Helsinki rules was reviewed and approved by the accredited ethics (Helsinki) committee of the Hadassah university hospital, Jerusalem, Israel, under research number HMO-0804-21.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M.P. is employed by a company producing RFR transmitting equipement. M.D. is a foundder and the CEO of Zoar. E.R. : The Unit of Occupational and Environmental Medicine in the Hebrew University-Hadassah School of Public Health and Community Medicine provided medical opinions to previous cancer patients. The fees went directly into the Unit research budget in the University.

[5] Degrave et al., (2009) is a cause of death study with a mean follow up of 26 years, thus cancer risks at young ages are partially masked by cancers at older ages although they are still significant.

Data availability

Patients data table and SEER printouts are included in the supporting material uploaded to the Journal site.

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This paper presents the findings, analysis, and interpretation of the authors, and does not imply endorsement or responsibility by the authors institutions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.114610.

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