ANSES Opinion
Request No 2016-SA-0176

The Director General

Maisons-Alfort, 24 October 2025

OPINION
of the French Agency for Food, Environmental and Occupational Health & Safety

on the "radiofrequencies and cancer" expert appraisal

ANSES undertakes independent and pluralistic scientific expert assessments.
ANSES's public health mission involves ensuring environmental, occupational and food safety as well as assessing the potential health risks they may entail.
It also contributes to the protection of the health and welfare of animals, the protection of plant health, the evaluation of the nutritional characteristics of food and the protection of the environment by assessing the impact of regulated products.
It provides the competent authorities with all necessary information concerning these risks as well as the requisite expertise and scientific and technical support for drafting legislative and statutory provisions and implementing risk management strategies (Article L.1313-1 of the French Public Health Code).
Its opinions are published on its website. This opinion is a translation of the original French version. In the event of any discrepancy or ambiguity the French language text dated 24 October 2025 shall prevail.

On 2 August 2016, the French Directorate General for Health made a formal request to ANSES to analyse the preliminary results of the US National Toxicology Program study on the carcinogenicity of radiofrequencies in rodents and then, considering the final results of this study, to assess whether these results were likely to change the classification of radiofrequencies as "possibly carcinogenic to humans" (Group 2B), established by the International Agency for Research on Cancer (IARC) in 2011. The formal request (see Annex 1) was registered under No 2016-SA-0176.

In 2019, in anticipation of the availability of new scientific knowledge published since ANSES's previous expert appraisal on the health effects of radiofrequencies in 2013, ANSES began the process of updating its expert appraisal on the carcinogenicity of exposure to radiofrequencies.

1. BACKGROUND AND PURPOSE OF THE REQUEST

1.1. General scientific background

When radio waves (or "radiofrequencies"[1]) encounter biological structures, any radiation not reflected by the surface of the skin penetrates them. Energy is then transferred from the wave to the surrounding tissue. The mechanism by which electromagnetic energy is converted into thermal energy is well documented in the scientific literature (Foster et Schwan, 1986). The type and heterogeneity of tissues determine how the heat produced is distributed among the surrounding tissues, by conduction and diffusion (Foster et Glaser, 2007). As long as the amount of energy converted is low in relation to the body's ability to adapt (thermoregulation), no local or systemic macroscopic heating effect is observed. With localised exposure, if the heat produced cannot be evacuated, the temperature of the affected tissues increases. In certain therapeutic applications, this is the desired effect (Dewey *et al.* 2009). When the whole body is exposed, its thermoregulatory capacity is potentially exceeded by the increase in energy input, leading to the physiological effects of excessive body temperature. Beyond a threshold increase in body temperature, behavioural changes can be observed, which have been precisely characterised in animals (D'Andrea *et al.* 2003). The exposure limits currently in force[2] were established to prevent this type of effect.

Apart from this direct heating effect, could exposure to radiofrequencies cause health effects in the longer or shorter term? In the short and medium term, for example, this is the question asked by individuals who declare themselves to be electrohypersensitive (Anses, 2018). Regarding the long term, a great deal of research has been carried out over the last 20 years or more in an attempt to identify health effects and biological mechanisms of action that are not directly linked to the heating of tissues. These include studies carried out on humans through clinical and epidemiological research, but also on animals, cell cultures and even plants. Since 2009, when ANSES published its first report on the effects of radiofrequencies on health (Afsset, 2009), the rate of publication of scientific articles on the effects of radiofrequencies, or on the search for possible mechanisms of action, has shown no signs of slowing down, despite an end to funding for major national research programmes on this topic, particularly in Europe. France is an exception in this respect, with the continuation of a system for funding research into the health effects of radiofrequencies, provided for in the 2011 Finance Act.

The possibility of radiofrequencies inducing cancer is a major public health issue. Regarding the mechanisms potentially involved in these diseases, in its 2013 opinion on the effects of radiofrequencies on health (Anses, 2013), ANSES noted that the possibility could not be excluded that under certain conditions, exposure to radiofrequencies could promote DNA damage (oxidation of bases, strand breaks). However, there was no evidence of any lasting effect on the loss of DNA integrity. The damage sometimes observed seemed to be quickly

[1] In the remainder of this document, the term "radiofrequencies" will be used to refer to radio waves in the range 3 kHz–3000 GHz. While the International Telecommunication Union (ITU) defines radiofrequencies from 3 kHz (see Radio Regulations (Volume 1, Chapter I, Article 2, Section I): https://www.itu.int/en/publications/ITU-R/Pages/publications.aspx?parent=R-REG-RR-2024&media=electronic), the European Electronic Communications Committee has set the lower limit of the lowest allocated band at 8.3 kHz (see https://docdb.cept.org/download/4316).

[2] https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999H0519&from=EN, https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000226401&categorieLien=id.

repaired. The other biological data did not reveal any mechanism supporting the hypothesis of a carcinogenic effect.

Since then, much has been said about published studies simulating long-term exposure in animals. For example, Falcioni *et al.* (2018) reported observing tumours of the heart in rats following exposure to radiofrequencies. Then in late 2018, the US National Toxicology Program (NTP) published its final reports on a very large-scale study conducted over nearly 10 years on the potential carcinogenicity of radiofrequency exposure in laboratory rats and mice (National Toxicology Program (NTP) 2018a; 2018b). The authors concluded that there was an "equivocal" level of evidence[3] that exposure to radiofrequencies causes the development of brain tumours (gliomas) in rats. They also attributed a "clear" level of evidence[4] to the link between exposure of rats to radiofrequencies and the development of tumours of the heart (malignant schwannomas). These conclusions were valid for male rats, for both GSM and for CDMA signals used in 3G.

Alongside these studies on the biological effects of exposure to radiofrequency electromagnetic fields, numerous epidemiological studies have examined the links between mobile phone use and the associated risk of brain tumours. Since the primary use of mobile phones involves contact with the head, it was logical for research to focus on brain tumours. In 2011, IARC concluded that there was a possible link between exposure to radiofrequencies and an increased risk of glioma, mainly on the basis of studies examining the link between exposure via mobile phones and brain tumours, particularly the international Interphone study (*The Interphone Study Group*, 2010). In 2013, in its assessment of the health risks associated with radiofrequencies, ANSES had also concluded that there was a possible carcinogenic effect of exposure to electromagnetic fields for "intensive"[5] users of mobile phones. ANSES thus stated that an increase in the risk of rare glial tumours (less than a 20% increase in incidence) could not be ruled out for this sub-group of users, for periods of use greater than 15 years (no data were available beyond that).

Between 2013 and 2023, numerous publications continued to analyse and interpret the results of the Interphone study ((Turner *et al.* (2016); Momoli *et al.* (2017); Vila *et al.* (2018)). In addition, new very large-scale epidemiological studies involving several thousand people were carried out, examining the association between mobile phone use and the occurrence of tumours. For example, the results of a study from The Million Women Study cohort were published in 2013 (Benson *et al.* 2013) and updated in 2022 (Schüz *et al*. 2022), while the first results of the Cosmos cohort study (Feychting *et al.* 2024) and those of a study based on the UK Biobank cohort (Zhang *et al.* 2024) were published in 2023 and 2024. In addition to these studies conducted in adults, the results of epidemiological studies in children ((Hauri *et al.* 2014) and MOBI-Kids (Castaño-Vinyals *et al.* 2022)) have been published.

Knowledge of the *hazard* potentially posed by exposure to radiofrequency electromagnetic fields has increased significantly in recent years, in terms of both assessing the possible link with different types of cancer, via epidemiological studies, and studying the biological

[3] "equivocal evidence of carcinogenic activity" (NTP, 2018a).
[4] "clear evidence of carcinogenic activity" (NTP, 2018a).
[5] i.e. those who have accumulated more than 1640 hours of exposure in their lifetime. This duration corresponded to the share of the population in which an excess risk was found in the Interphone study (The Interphone Study Group, 2010).

mechanisms involved in carcinogenesis. To assess the *risk*[6] potentially posed to health by the use of mobile phones, particularly regarding the development of cancer, the above-mentioned knowledge of the *hazards* needs to be combined with data representing the exposure of populations or individuals to electromagnetic fields.

Although our electromagnetic environment has been changed by the deployment of mobile networks, and in particular the installation of base stations, simulations and observations of this exposure currently show that apart from in localised areas (atypical points)[7], there has been a relatively limited increase in the average level (temporal and spatial) of exposure. However, the growth of the mobile Internet could significantly increase the average level of electromagnetic field intensity in the environment, along with the acute exposure of users under specific conditions (5G). Moreover, the entire population is exposed to these electromagnetic fields to varying degrees, with the exception of anyone a very long way away[8] from base stations and radio and television broadcast towers, i.e. in places with poor or no coverage by audiovisual broadcasting and mobile networks. However, there is only a small variation in exposure in the environment in relation to these "distant" sources, which makes it difficult to set up population studies to assess the incidence of disease as a function of the level of exposure.

On the other hand, the case of the mobile phone is unique. Of all the sources of electromagnetic fields close to the body in our everyday environment, this is the one that generates the greatest exposure (in terms of intensity, duration and number of people affected). Moreover, this source of radiation is still often carried close to the head, and therefore the brain. Exposure is not permanent as in the case of base stations, but it is much higher. Exposure from mobile phones carried close to the ear is around 100 to 1000 times higher than environmental exposure from distant sources (audiovisual broadcasting relays, mobile phone base stations, Wi-Fi boxes, etc.). Lastly, the number of users, some of whom are very young, is extremely high, and mobile telephone technology is now extensively used. It is therefore logical that the potential effects of exposure to the radiation emitted by mobile phones have been investigated for many years now, and continue to raise questions.

1.2. Purpose of the expert appraisal

In 2016, the French Directorate General for Health (DGS) made a formal request to ANSES, firstly to provide an analysis note on the preliminary results published by the National Toxicology Program on the carcinogenic effects of exposure of rats to radiofrequency electromagnetic fields[9] and secondly, once the final results of this study had been published, to indicate whether they were likely to change the classification of radiofrequencies as Group 2B, i.e. possibly carcinogenic to humans, established by IARC in 2011 (IARC, 2013).

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[6] *Risk* is defined here as the product of the intrinsic *hazard* of an agent and the *exposure* to that agent. For example, one very real and well-known *hazard* of electromagnetic fields is the heating of body tissue. The health *risk* associated with this heating process depends on the level of exposure.

[7] Every year, the ANFR publishes a report describing exposure to electromagnetic waves in the environment, based on measurements carried out under the national monitoring scheme: https://www.anfr.fr/rapports-etudes.

[8] Several kilometres or even tens of kilometres.

[9] The analysis note on the "preliminary" NTP results published in 2016 was sent by ANSES to the DGS. An opinion on the "interim" NTP reports released in 2018 was subsequently published by the Agency (https://www.anses.fr/fr/system/files/AP2016SA0176.pdf). At the same time, the Agency released a document containing *answers to the questions raised by the preliminary results of the study by the US National Toxicology Program (NTP) on the potential health effects of radiofrequency radiation emitted by mobile phones on rats and mice* (https://www.anses.fr/fr/system/files/AP2016SA0176-Anx1.pdf).

Before undertaking an assessment of the level of evidence of the carcinogenicity of exposure to radiofrequency electromagnetic fields, ANSES believed it necessary to wait for new scientific knowledge, i.e. published since ANSES's previous assessment in 2013, to become available. Following publication of the studies carried out by the NTP, and the expected publication of the results of the MOBI-Kids study on children (Castano-Vinyals *et al.* 2022), in 2019 ANSES began the process of updating its expert appraisal on the carcinogenicity of exposure to radiofrequencies.

2. ORGANISATION OF THE EXPERT APPRAISAL

The expert appraisal was carried out in accordance with French standard NF X 50-110 "Quality in Expert Appraisals – General Requirements of Competence for Expert Appraisals (January 2024)".

This expert appraisal fell within the sphere of competence of the Expert Committee (CES) on "Physical agents and new technologies". ANSES entrusted the expert appraisal to the Working Group (WG) on "Radiofrequencies and cancer" set up in February 2020. The methodological and scientific aspects of the work were presented to the CES between May 2020 and May 2025. This work was adopted by the CES on "Physical agents and new technologies" at its meeting on 13 May 2025.

The expert appraisal was coordinated by the Unit for Assessment of Risks Related to Physical Agents (part of ANSES's Risk Assessment Department).

ANSES analyses interests declared by experts before they are appointed and throughout their work, in order to prevent risks of conflicts of interest in relation to the points addressed in expert appraisals.

The experts' declarations of interests are made public via the website: https://dpi.sante.gouv.fr/.

2.1. The Working Group

The Working Group was formed following a public call for applications. The experts in this group were recruited for their scientific and technical skills in the areas of electromagnetic fields, biology and epidemiology. Set up in February 2020, the Working Group held 45 plenary sessions between February 2020 and September 2024. An interim report on the work carried out was drawn up at the end of these meetings.

This interim report was published on 30 September 2024, and called on interested parties to comment on the work as part of a public consultation (see Sections 2.3 and 2.4).

The Working Group then met again nine times between September 2024 and May 2025, to prepare the public consultation, then analyse and respond to the comments received, particularly during a day of discussions on 31 January 2025, and update the expert appraisal report with regard to all the information deemed relevant (see Section 2.3).

2.2. Expert appraisal method

Drawing on the Agency's previous expert appraisals, particularly those in the field of radiofrequencies, the Working Group decided to adapt the method used by IARC to assess the carcinogenicity of agents and substances (IARC, 2019) (see Section 3.1 for details).

The expert appraisal work first sought to assess the carcinogenicity of radiofrequencies for each organ or physiological system, before providing an overall assessment of carcinogenicity in humans.

To support its determination of the level of evidence of the carcinogenicity of radiofrequencies, the Working Group carried out a systematic review of the scientific literature in this field for the period 2013–2021, extended to July 2024 for epidemiological studies. In particular, this enabled the US National Toxicology Program study to be viewed in the context of studies focusing on carcinogenic effects. In order to take account of knowledge acquired before 2013, the expert appraisals carried out by ANSES in this field ("Radiofrequencies and health", ANSES, 2013; "Radiofrequencies and children", ANSES, 2016) formed a large part of the scientific foundation on which this expert appraisal was based.

The frequency band considered for the expert appraisal was between 3 kHz and 300 GHz[10], in line with the Agency's previous expert appraisals in the field of radiofrequencies.

As well as studies examining the carcinogenic effect of radiofrequencies on humans and those carried out on mammalian models, the Working Group analysed all the studies on plants and animals other than mammals identified by the literature search. The studies devoted to non-mammalian models were not used to establish the level of evidence of carcinogenicity, but they did contribute to general knowledge of the interactions of radiofrequencies with living organisms.

The expert appraisal work was regularly submitted to the CES on "Physical agents and new technologies", leading to numerous exchanges with the Working Group. The report produced by the Working Group takes account of the observations and additional information discussed with the CES members. The results were therefore produced by a group of experts with complementary skills.

2.3. Public consultation

The Agency carried out a consultation on its draft expert appraisal report, mainly for members of the scientific community and interested stakeholders, from 30 September to 25 November 2024. The aim of this public consultation was to gather additional data to those already taken into account, as well as scientific comments. ANSES specified how to submit comments on a dedicated web page. This consultation was prompted by society's interest in the topic as well as the chance for the Agency to consider additional more recent data.

All comments complying with the submission conditions were analysed by the WG on "Radiofrequencies and cancer". It took account of the scientific arguments and literature references submitted, mainly in the form of additions or clarifications to the expert appraisal report that were validated by the group's experts. Of these comments, those submitted directly in PDF format were compiled in a single document. Those submitted via the web form for general comments were also grouped together. These two documents are available in the form of annexes that can be downloaded from the ANSES website. Comments that did not comply with the conditions for responding to the consultation are not included in these annexes. A quantified review of the comments received during the public consultation is available in the expert appraisal report (see § 1.4.4), along with a summary of the day of discussions held on 31 January 2025 to respond to the questions raised during this consultation (see below).

[10] See note 1.

Following the public consultation, many sections of the expert appraisal report were amended to take account of the comments made. For example, the expert appraisal method was better explained throughout the text. Similarly, the descriptions of the results of certain epidemiological studies were clarified. The report was also supplemented by a paragraph on the health impact of technological developments in mobile communications, and a section devoted to recommendations intended for the public authorities, the general public and research.

Lastly, the careful and detailed review carried out by the contributors raised important cross-cutting questions that led the Agency to clarify its methodological choices, detailing their implications and thus reinforcing the robustness of its expert appraisal.

2.4. Day of discussions

At the start of the public consultation, ANSES had announced that a day of discussions would be held, open to anyone who had commented on the expert appraisal report and indicated their intention to take part, as well as to members of its dialogue committee on "Radiofrequencies and health"[11]. This day, organised to enable direct exchanges and a better understanding of the work carried out by the Working Group, took place on 31 January 2025 at the Agency's headquarters in Maisons-Alfort. It was attended by 36 people, including nine of the 12 members of the WG on "Radiofrequencies and cancer".

As a preamble to the day's discussions, a review of the public consultation was presented, along with the procedures for taking account of the comments and literature references received.

In view of the numerous comments on the expert appraisal method, the methodological foundations used for expert appraisals in the field of radiofrequencies were presented, followed by an initial discussion. This provided an opportunity to address the literature search, the criteria for assessing study quality, the assessment of the level of evidence and how personal interests are managed. For this part, in line with an internationally shared scientific approach, ANSES called on IARC[12] to present the main methodological principles for assessing the carcinogenicity of physical, biological and chemical agents.

In addition to comments on the document's form and requests for clarification or for scientific publications to be taken into account, which led directly to amendments to the expert appraisal report, many of the comments received provided a basis for discussions with the members of the Working Group. These comments gave rise to questions, some that were highly specific – including questions about studies with differing interpretations – and others of a more general methodological, scientific or epistemological nature.

Several sessions were therefore organised, grouping the numerous scientific questions raised during the public consultation according to theme:

- Expert appraisal method and scientific data. This session provided answers to several questions raised in comments and on the web form, mainly concerning the approach to assessing levels of evidence (overall versus organ-by-organ), the differences between studies on adults and on children, the interpretation of cohorts and the impact on the expert appraisal of the lack of biological data for humans.

[11] https://www.anses.fr/en/content/dialogue-committee-radiofrequencies-and-health.

[12] Presentation by Mary Schubauer-Berigan, Head of the "Evidence Synthesis and Classification" Branch.

- Biological mechanisms of action and role in carcinogenesis. Discussions focused mainly on the integration of biological mechanisms in the assessment of the level of evidence, the role of oxidative stress and the question of a possible adaptive effect of exposure to radiofrequencies.
- Experimentation. The debates focused on the use of controlled versus real signals, the differences between continuous and modulated signals, and the impact of different telecommunications technologies on risk assessment.
- Consideration of population data. The members of the Working Group presented the different epidemiological approaches (meta-analyses, cohorts, case-controls), providing the insights requested on interpretation of the results and on the relevance of bio-epidemiological studies.
- Specific studies. Discussions focused on the analysis of the results of the NTP studies on male rats, the co-exposure studies (Tillmann *et al.* 2010 and Lerchl *et al.* 2015) and the study based on the UK Biobank cohort (Zhang *et al.* 2024).

This was the first time the Agency had organised a day of discussions for a non-finalised expert appraisal. This initiative formed part of ANSES's efforts to promote openness to society[13] and experiment with new ways of linking dialogue and expert appraisal[14]. The discussions raised a number of questions about the nature of the scientific data available, the interpretation of study results, and the uncertainties and gaps associated with research into the potential effects of radiofrequencies on living organisms.

While this day of discussions did not necessarily aim to achieve a convergence of points of view, the talks did identify some common ground on possible avenues for further research. Lastly, these discussions served as a reminder of the importance of preparing to receive the expert appraisal's conclusions, and of paying close attention to how ideas are organised and formulated throughout the report.

The discussions between contributors to the public consultation and members of the Working Group, which were productive in both intellectual and human terms, also testified to the importance of allowing enough time for direct discussion when dealing with complex scientific concepts. Despite it being a difficult exercise, contributors and experts alike praised the organisation of the day and the commitment of all the participants.

3. ANALYSIS, CONCLUSIONS AND RECOMMENDATIONS OF THE WG AND THE CES

3.1. Expert appraisal method

3.1.1. General method

To answer the question of whether or not radiofrequencies are carcinogenic under specific conditions of exposure, the Working Group initially adopted a method based on the analysis

[13] This is a long-standing commitment, since it was enshrined in ANSES's founding values when the Agency was created in 2010. ANSES also signed the charter on openness to society in 2011 and reaffirmed the importance of dialogue with society in its most recent goals and performance contract (COP 2023–2027, ANSES's new 2023-2027 goals and performance contract | Anses - Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail travail).

[14] See the report on *ANSES's relations with its stakeholders from civil society*: How are we doing as regards openness to society? | Anses - Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail.

of evidence by organ or by group of organs representing particular physiological systems. To do this, it examined the scientific literature relating to each of these organs or physiological systems (endocrine, reproductive, immune, etc.). In a second phase, these data were considered as a whole in order to produce an overall assessment for the entire body.

Several arguments justify the methodological choice of an initial analysis by organ or physiological system. Firstly, a physical or chemical agent's classification as carcinogenic is always based on evidence of specific types of cancer in target organs (e.g. lung for tobacco, skin for the sun, etc.). Secondly, this approach increases the likelihood of identifying specific carcinogenic effects in certain sensitive locations. Lastly, it reflects current practice in scientific production, where each study often focuses on a limited number of organs or physiological systems. Once the data had been collected and analysed for each organ, they were integrated into an overall assessment that established a level of evidence for the carcinogenic effect of radiofrequencies on humans.

A particular characteristic of this approach was the determination of a level of evidence of carcinogenicity based on data that were complementary. Mechanistic studies were therefore included in the analysis, in addition to epidemiological data and data from animal studies on tumour development. This approach was mainly inspired by that of IARC, which, in its preamble to the monographs published in 2019 (IARC, 2019), strengthened the role of mechanistic data in assessing an agent's carcinogenicity.

3.1.2. Literature search, selection and analysis of study quality

The literature review brought together a body of articles (corpus) that was as comprehensive and relevant as possible, on the effects of radiofrequencies on the occurrence of cancer. All articles in French or English published in a peer-reviewed journal and addressing the possible biological or health effects of exposure to radiofrequencies were included in the corpus.

The literature search was based on queries of several databases with complementary specificities. Scopus provides access to a broad range of multidisciplinary scientific journals, PubMed focuses on biology and medicine, while EMF Portal directly targets publications on electromagnetic fields and their health effects. This corpus was supplemented by references provided by members of the Working Group and of the dialogue committee on "Radiofrequencies and health", as well as contributors to the public consultation. The initial inclusion period was defined as running from 1 January 2013 to 21 September 2021. It was then extended to July 2024 for epidemiology. It should be noted that the publications already analysed during ANSES's expert appraisals published in 2013 and 2016 (Anses, 2013; Anses, 2016) contributed to establishing the levels of evidence.

The search algorithm was built around three categories of keywords: terms relating to radiofrequencies in order to capture all forms of exposure, keywords relating to cancer that sought to identify studies on the aetiology or mechanisms linked to carcinogenesis, and lastly exclusion keywords to rule out publications concerning therapeutic or diagnostic applications that did not look at the carcinogenic effect.

Following this process, the corpus of articles obtained underwent two successive sorting phases to select relevant publications of adequate quality. Initially, the titles and abstracts were reviewed to exclude studies that did not meet the inclusion criteria. Secondly, the full texts of the selected articles were analysed in depth to assess the quality of the studies. This analysis was first carried out by the physicists, in order to assess the quality of the exposure system (animal and *in vitro* studies) or exposure conditions (epidemiological studies), and then by two

experts in biology and/or epidemiology with complementary skills. This method guaranteed a rigorous and independent analysis of each publication (in the sense that each disciplinary field was represented within the Working Group), while avoiding influencing the views of the other experts. Once the analyses had been pooled, any disagreements over the quality level assigned to each article were discussed in the plenary session. Only articles deemed by these assessors to be of high quality according to the predefined criteria (see § 4.2.4.2 of the expert appraisal report), or presenting only minor methodological limitations, were selected to establish the lines and levels of evidence enabling a conclusion to be drawn as to whether or not there is an association between exposure to radiofrequencies and the occurrence of cancer.

3.1.3. Establishment of the level of evidence

The level of evidence of the carcinogenicity of radiofrequencies was determined by taking the following evidence into account: epidemiological data in humans, data on the development of tumours in animals and mechanistic studies. Each of these three types of study made a specific contribution to the assessment of the hazard of radiofrequencies. The significance of epidemiological studies in assigning a level of evidence stems from the fact that they alone enable the risk of cancer to be compared between exposed and unexposed populations. Animal studies analyse tumour induction in models under controlled conditions. Although they cannot be directly extrapolated to humans, when used as whole body models, these studies are a key element in assessing the level of evidence. Mechanistic studies aim to determine whether radiofrequencies induce biological mechanisms that could be involved in carcinogenesis. They are carried out both *in vivo* (in exposed humans or animals) and *in vitro* (using primary cell cultures or cell lines). The phenomena being investigated include genotoxicity, oxidative stress, inflammation, cell proliferation and immunosuppression. Although it is difficult to deduce a level of evidence of the risk of tumours developing in the human body from these *in vitro* models, they nevertheless provide a wealth of information on the diversity and intensity of cellular responses to radiofrequencies and an in-depth understanding of the mechanisms and processes involved.

For each organ or physiological system, the evidence was then grouped together to form lines of evidence specific to these three types of study (see § 4.1 of the expert appraisal report). Each line of evidence was classified according to categories reflecting the quality and quantity of the data: sufficient evidence, limited evidence, inconclusive evidence or no data. This classification was intended to reflect the level of certainty as to the existence of a carcinogenic effect of radiofrequencies.

Once the different lines of evidence had been established, they were combined to define a level of evidence for each organ or physiological system. The hierarchical combination of these lines, considering the relative weights assigned to epidemiological studies in humans, animal studies and mechanistic studies, then enabled an overall level of evidence to be defined. This level of evidence was broken down into four degrees (see Figure 1 and Annex 2): "the carcinogenic effect of radiofrequencies is proven for humans", "the carcinogenic effect of radiofrequencies is probable in humans", "the carcinogenic effect of radiofrequencies is possible in humans" and "it is not possible to conclude whether or not radiofrequencies have a carcinogenic effect on humans".

Line of evidence in human epidemiology: evidence linked to the development of a tumour or cancer	Line of evidence in animals: evidence linked to the development of a tumour or cancer from *in vivo* data	Line of evidence of induction of biological mechanisms linked to cancer from a combination of biological mechanisms	Level of evidence
Sufficient	*Does not affect the classification*	*Does not affect the classification*	Proven effect for humans
Limited	Sufficient	Strong suggestion of induction in humans *in vivo*	Proven effect for humans
		Other levels of mechanistic evidence	Probable effect on humans
	Limited or inconclusive	Strong suggestion of induction in humans *in vivo*	Probable effect on humans
		Other levels of mechanistic evidence	Possible effect on humans
Inconclusive	Sufficient	Strong suggestion of induction in humans *in vivo*	Proven effect for humans
		Strong suggestion of induction in human models (primary cells and organs)	Probable effect on humans
		Strong suggestion of induction in human lines and animal models	Possible effect on humans
		Other levels of mechanistic evidence	No conclusion possible
	Limited or inconclusive	Strong suggestion of induction in humans *in vivo*	Possible effect on humans
		Other levels of mechanistic evidence	No conclusion possible
No data	Sufficient	Strong suggestion of induction in humans *in vivo*	Probable effect on humans
		Strong suggestion of induction in human models (primary cells and organs)	Possible effect on humans
		Strong suggestion of induction in human lines and animal models	Possible effect on humans
		Other levels of mechanistic evidence	No conclusion possible
	Limited or inconclusive	*All levels of mechanistic evidence*	No conclusion possible

Figure 1: Hierarchical version of the table for defining levels of evidence based on lines of evidence (epidemiological, tumours in animals and mechanistic)

It is important to note that the Working Group did not wish to conclude that there was no effect when the data were insufficient. A level of evidence can only be established on the basis of the information available at a given time. The possibility cannot be excluded that future developments in techniques or experimental models will lead to the emergence of new results.

3.2. Key points of knowledge

3.2.1. Carcinogenesis

3.2.1.1. Terminology

The term "cancer" refers to a group of diseases characterised by the abnormal and uncontrolled growth of cells in the body that can invade and destroy surrounding tissues, and spread to other parts of the body via the blood and lymphatic systems, forming metastases.

The term "tumour" refers to a mass of tissue formed by an accumulation of abnormal cells. Tumours can be "benign" or "malignant", without this prejudging the prognosis of the disease.

Benign tumours: these tumours are not cancerous and do not invade surrounding tissue or spread to other parts of the body. Benign tumours can sometimes develop into malignant ones.

Malignant tumours: these are cancer tumours that can invade surrounding tissue and metastasise to other organs.

Therefore, not all tumours are cancerous. A tumour is a cellular mass that may be benign or malignant, whereas cancer refers specifically to a malignant tumour.

3.2.1.2. Carcinogenesis process

In adults, the development of cancer tumours is a long process that takes place over several years, or even decades. This length of time is explained by the numerous events and successive steps that characterise carcinogenesis.

The process begins with the "initiation" phase, during which DNA undergoes irreversible changes under the effect of genotoxic agents, whether chemical, physical or biological. When these alterations – or mutations – affect the genes that regulate cell division, they give cells an increased ability to proliferate. This partly random phenomenon involves the transformation of proto-oncogenes into oncogenes[15] and the inactivation of tumour suppressor genes. At the end of this initiation phase, a population of so-called initiated or pre-tumour cells acquires a selective advantage that promotes its expansion.

This is followed by the "promotion" phase, which encourages the proliferation of altered cells and the formation of small pre-cancerous lesions that are still undetectable. This process, which is independent of new mutations, can be promoted by chemical or physical agents, or by physiological conditions that stimulate cell growth. This step is stimulated by extracellular signals, such as increased production of growth factors, increased cell survival, reduced effectiveness of the immune system and disruption of cell signalling. This phase explains how certain agents can be carcinogenic without being genotoxic or mutagenic.

"Progression" is the final phase, during which the tumour acquires invasive and metastatic properties. Tumour growth is initially limited by restricted access to nutrients. Angiogenesis then becomes a key factor, promoting the supply of oxygen and nutrients and accelerating tumour expansion. At this stage, tumours reach a detectable size, enabling them to be diagnosed and treatment to begin. Genetic instability intensifies, leading to an accumulation of mutations that give cancer cells new properties, such as metabolic changes, exploitation of their microenvironment and increased proliferation. A major characteristic of this phase is the acquisition of an invasive and metastatic capability: certain cells leave their tissue of origin to enter the bloodstream or lymphatic system and form secondary tumours in other organs. In general, cancer cells have certain fundamental capabilities, known as the hallmarks of cancer (see Figure 1 in the expert appraisal report).

3.2.1.3. Biological mechanisms involved in carcinogenesis

Based on the classic presentation of tumour development in three phases (initiation – promotion – progression), a list of the key mechanisms involved in cancer can be drawn up. Figure 2 below shows the steps to which each of these mechanisms can be linked. Clearly, many other important parameters are also involved, such as cancer stem cells, hypoxia, the microenvironment, etc. The new IARC preamble, published in 2019 (IARC 2019), refers to 10 major biological mechanisms that can lead to cancer. These mechanisms are genotoxicity, modulation of the response to DNA damage, epigenetic alterations, induction of oxidative stress, induction of inflammation, immunosuppression, modulation of metabolism, modulation of receptor-mediated effects, alteration of cell proliferation, cell death or nutrient supply and cell immortalisation.

[15] An oncogene is a gene whose expression promotes the occurrence of cancer. It results from the modification or overexpression of a normal gene, therefore known as a proto-oncogene, involved in the control of cell division.

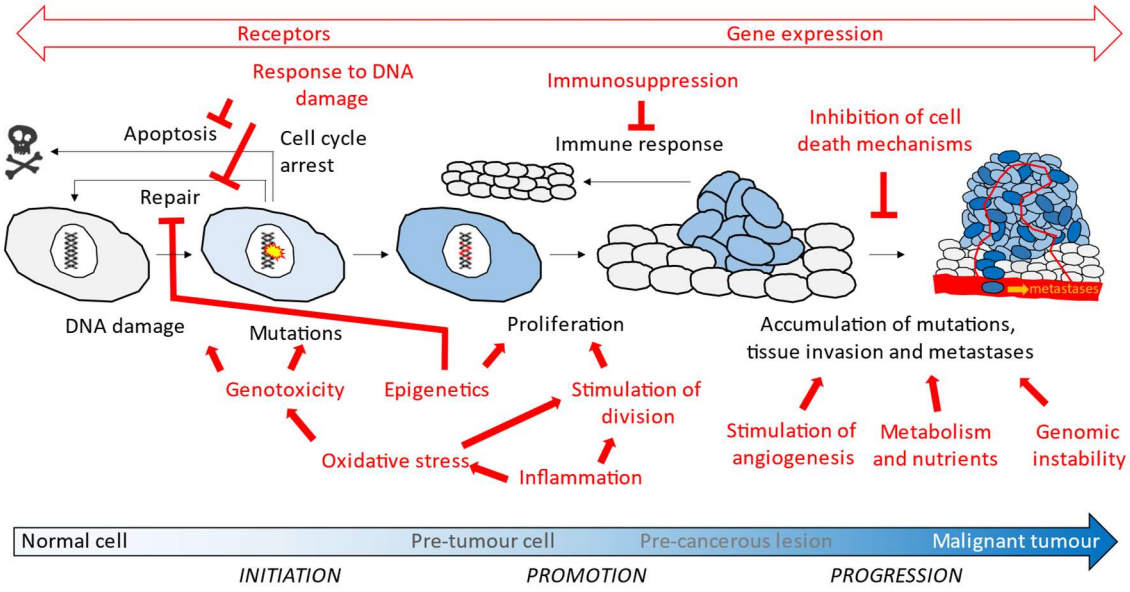

Figure 2: Main biological mechanisms linked to the development of cancer. The graphical elements in red represent responses that, if stimulated (→) or repressed (⊣), could contribute to cancer.

Identifying carcinogens requires two essential precautions. Firstly, it is crucial to distinguish biological effects from health effects, since a cellular response observed in the laboratory is not in itself sufficient to predict an effect on human health. Secondly, an agent cannot be classified as a carcinogen solely on the basis of an isolated biological effect. Because tumour development is a complex process involving several steps, assessing an agent's carcinogenicity should systematically take account of the combination of multiple mechanisms (IARC, 2019).

3.2.2. Changes in exposure to radiofrequencies

Telecommunications systems have evolved considerably over the last 25 years, with the introduction of Wi-Fi networks and the massive spread of mobile telephone technology.

Wi-Fi is a wireless network technology whose radiated power via "access points" is limited to 100 mW, 200 mW and 1 W in the 2.4 GHz, 5.25 GHz and 5.6 GHz bands, respectively. With the most recent systems using several communication antennas (MIMO[16]), as well as different channels and frequency bands simultaneously, assessing exposure becomes highly complex.

The technological development of mobile networks is ongoing, with a new generation being deployed every 10 years or so. In 2020, 4G was succeeded (but not replaced) by "5G". Although mobile operators plan to stop using 2G and 3G in the next few years, for the time being these technologies still coexist. One of the most significant recent developments has been the introduction of the MIMO technique, which arrived with 4G. This enables parallel channels to be set up on which different types of information can be transmitted, using a network of antennas on the base stations and at least two antennas on the mobile phone. This spatial diversity also enables the volume of communications to be increased. The 5G network, which was initially based on the existing 4G infrastructure, is expected to use two new frequency

[16] Multiple-input multiple-output, a technique used to increase network reach and bandwidth.

bands, one around 3.6 GHz and the other, eventually, around 26 GHz. Another expected development for 5G concerns the ability of antennas to focus radiation on the user, rather than emitting it uniformly over a wide area, as is currently the case. The aim of this approach is to increase bandwidth, but it could also lead to an overall reduction in radiated power and exposure levels (depending on the number of communications). On the other hand, the constant increase in traffic on mobile networks, particularly data exchanges, is inevitably leading to an increase in the level of exposure. However, estimating the respective influence of these two mechanisms on the exposure levels in our environment requires the development of characterisation techniques tailored to these complex radiation sources and signals, as well as measurement campaigns.

Moreover, mobile phone features have evolved considerably since the first handsets appeared in the early 1990s. Using the Internet, viewing videos and accessing social media while on the move have become the norm, and communication methods have diversified (text messages, voice messages, etc.). Initially mimicking landline telephones held against the ear, mobile phones can now be used via wired or wireless headsets and earpieces, held in front of the mouth or horizontally against the ear, etc. All these changes in usage, and technological developments in terms of electromagnetic field emissions from devices, have a tangible impact on user exposure. The transition from GSM technology to subsequent generations (starting with 3G), for example, has helped to reduce exposure during a telephone call. On the other hand, the extreme diversity in the ways and length of time they are used makes it very complicated to assess changes in people's exposure to mobile phones.

The rapid and ongoing development of technologies and uses is creating a gap between the state of knowledge and the reality of exposure, since it generally takes several years for research work to be completed and published. However, the data produced over several decades in the field of wave interactions with living organisms are accumulating, to constantly update and enhance knowledge. Until now, the frequency ranges and powers used have generally remained of the same order of magnitude, particularly for frequencies below 6 GHz. However, the predicted increase in the frequency of certain telecommunications signals, above several GHz, will make it necessary to update the methods for characterising and monitoring individual exposure, which above around 10 GHz is concentrated in the superficial tissues of the body (skin and cornea, in particular).

3.3. Results of the expert appraisal

In this expert appraisal on the carcinogenicity of radiofrequencies, a level of evidence was established for each organ or group of organs representing particular physiological systems (groups of organs performing the same function, such as the endocrine, reproductive and immune systems, etc.). All the data collected for each location were also analysed in their entirety, in the conclusion, to define an overall level of evidence of the carcinogenicity of radiofrequencies in humans.

3.3.1. Assessment of the level of evidence by organ or physiological system

The amount of information available differs greatly from one organ or physiological system to another. Below are the locations for which there were the most data, or which gave rise to limited or conclusive lines of evidence (see Chapter 5 of the expert appraisal report).

3.3.1.1. Brain and central nervous system

It was not possible to conclude from all the available data whether or not radiofrequencies have an effect on the development of tumours[17] of the brain or central nervous system. This was based on the following lines of evidence.

- Epidemiology: it was not possible to conclude from the epidemiological data whether or not radiofrequencies have a carcinogenic effect on the development of tumours of the brain or central nervous system. Some case-control studies[18] have suggested an effect on the development of gliomas in certain population sub-groups with the highest exposure. However, their results were not very consistent. Moreover, cohort studies showed no effect. It was therefore not possible to conclude whether or not there is a major association between exposure to radiofrequencies and the risk of brain tumours and cancers. Furthermore, the change in the incidence[19] of brain tumours does not support the existence of an effect;
- Tumours in animals (rodents): studies on the induction of tumours in animals involve long periods of exposure (1 to 2 years, the lifetime of rodents, depending on the publications). Large-scale studies by the Ramazzini Institute and the US National Toxicology Program concluded that there was a possible link between exposure to radiofrequencies and the development of brain tumours in animals, although their respective data show no statistically significant difference between the animals in control groups and those in exposed groups. Regarding these conclusions as questionable and noting that the other studies selected in the corpus of articles did not report any induction of brain tumours, the Working Group and the CES considered that it was not possible to conclude from the evidence whether or not radiofrequencies have an effect on the induction of brain cancers in animals.
- Mechanistic: no high-quality mechanistic data (see Section *3.1.2*) on *in vivo* human exposure were available, and only one high-quality article was identified for *in vitro* human models. In contrast, many data on animal models were available. These studies, carried out *in vivo*, showed that radiofrequencies induced a large number of mechanisms linked to cancer: genotoxicity, oxidative stress, cell death, inflammation, immunosuppression and autophagy[20]. However, these observations were not confirmed by the *in vitro* studies, whose results were contradictory. There is therefore limited evidence available for reaching a conclusion about the induction of mechanisms linked to brain cancer in human cell lines and animal models.

One of the Working Group's experts expressed two dissenting positions regarding brain tumours. One concerned the epidemiological data, which in his view provided limited evidence (rather than being inconclusive) for reaching a conclusion about whether radiofrequencies have an effect on the development of brain cancers. In addition, he considered that the mechanistic data in human cell lines and animal models suggested the induction of mechanisms linked to brain cancer (see Annex 4 of the expert appraisal report). He did not dispute the lines of evidence on tumours in animals or the mechanisms in humans *in vivo* or the human models. In his view, these lines of evidence led to an overall level of evidence that

[17] The term tumour is used here to refer to both benign and malignant (cancer) tumours.
[18] For definitions of the types of epidemiological studies, see Section 4.2.3.1.
[19] See the expert appraisal report, § 4.2.3.1 (definition) and § 4.2.4.2.2 (contribution to establishment of the epidemiological line of evidence).
[20] For definitions of the mechanisms, refer to Section 2.1.4 of the expert appraisal report.

the carcinogenic effect of radiofrequencies on the brain and central nervous system is possible in humans.

The positions expressed and justified by this expert did not lead the Working Group, after discussion, to change its finding – namely that it was not possible to conclude from the available data whether or not radiofrequencies have an effect on the development of tumours of the brain and central nervous system.

3.3.1.2. Blood and plasma

It was not possible to conclude from the available data whether or not radiofrequencies have an effect on the development of haematological cancers. This was based on the following three lines of evidence:

- Epidemiology: it was not possible to conclude from the epidemiological data whether or not radiofrequencies have an effect on the development of haematological cancers. The seven studies with high-quality individual data on which this analysis was based did not reveal any association between exposure to radiofrequencies and haematological cancers.
- Tumours in animals (rodents): there is limited evidence for reaching a conclusion about whether radiofrequencies have an effect on the induction of haematological cancers. This was based on the results of the US National Toxicology Program study, which was carried out on female mice only, using two types of radiofrequency signals and several levels of specific absorption rate (SAR). None of the other studies considered observed a similar effect.
- Mechanistic: no high-quality mechanistic data on *in vivo* exposure were available for humans. In human models, it was not possible to conclude from the available mechanistic data that radiofrequencies induced mechanisms linked to cancer. Some studies even showed an adaptive protective effect of exposure to radiofrequencies against other toxic physical or chemical agents. In non-human models, there were limited mechanistic data for reaching any conclusion about the induction of mechanisms linked to cancer. This was based on studies of oxidative stress and inflammation *in vivo*. It is consistent with the "limited" evidence of cancer induction in animals.

3.3.1.3. Immune system

It was not possible to conclude from the available data whether or not radiofrequencies have an effect on the development of cancers of the immune system. This was based on the following lines of evidence:

- Epidemiology: no epidemiological studies on immune system organs were available. It was therefore not possible to conclude whether or not radiofrequencies have a carcinogenic effect in the aetiology of these cancers. It should be noted that lymphoma and leukaemia, which also affect cells involved in the immune system, were addressed in the section on "Blood and plasma" and that no effects had been revealed in the epidemiological studies, despite the existence of a number of high-quality studies.
- Tumours in animals (rodents): it was not possible to conclude from the studies whether or not radiofrequencies have an effect on tumour induction in the different organs of the immune system.

- Mechanistic: the mechanistic articles available show the induction of oxidative stress, inflammation and immunosuppression. These data provide limited evidence on the ability of radiofrequencies to induce a range of mechanisms linked to cancer in the immune system.

3.3.1.4. Cardiovascular system

It was not possible to conclude from the available data whether or not radiofrequencies have an effect on the development of cancers of the heart or cardiovascular system. This was based on the following lines of evidence:

- Epidemiology: no epidemiological data were available to conclude whether or not there is a link between exposure to radiofrequencies and cancers of the heart or cardiovascular system. It should be remembered that cancers of the heart are rare, often metastasising from tumours in other organs.
- Tumours in animals (rodents): no aortic tumours have been observed in animals exposed to radiofrequencies, but cardiac schwannomas were detected, with a low incidence, in a study in rats. In conclusion, the data show a limited effect of radiofrequencies in inducing tumours of the heart in animals. This conclusion recalls the results of the US National Toxicology Program, which were not selected by the Working Group to establish the level of evidence, due to the high mortality rate in control male rats.
- Mechanistic: there are few mechanistic data. The results of *in vivo* studies between rats and mice were not consistent. It was therefore not possible to conclude whether radiofrequencies induce a set of mechanisms linked to the formation of tumours in the cardiovascular system.

3.3.1.5. Liver

It was not possible to conclude from the available data whether or not radiofrequencies have an effect on the development of liver cancers. This was based on the following lines of evidence:

- Epidemiology: only one – inconclusive – epidemiological study was available on the link between exposure to radiofrequencies and liver cancers. It was therefore not possible to conclude whether or not radiofrequencies have an effect on the aetiology of liver cancers. It should be noted that there are a great many causes of liver cancers, all of which are confounding factors that would make it difficult to identify a specific effect of radiofrequencies.
- Tumours in animals (rodents): the work by the US National Toxicology Program showed the statistically significant induction of hepatocellular adenomas (which are benign tumours) and hepatoblastomas in male mice. These results were not found in all the studies, nor in female mice or in rats. These data therefore provided limited evidence for reaching a conclusion about the ability of radiofrequencies to induce liver tumours in animals.
- Mechanistic: few mechanisms have been established in the liver or its cell models. *In vivo* studies show oxidative stress, while *in vitro* studies show a reduction in cell proliferation. Genotoxicity was not induced *in vivo* and no other mechanism has been documented *in vitro*. It was therefore not possible to reach any conclusion about the induction of a set of mechanisms linked to cancer.

3.3.1.6. Reproductive system

It was not possible to conclude from the available data whether or not radiofrequencies have an effect on the development of cancers of the reproductive system. This was based on the following lines of evidence:

- Epidemiology: It was not possible to conclude from the two available studies whether or not radiofrequencies have a carcinogenic effect in the aetiology of cancers of the reproductive system in women. In men, only one study, which was exploratory in nature and did not take account of the important factor of screening, was available on the prostate. As a result, it was not possible to conclude from the available data whether or not radiofrequencies have an effect on the occurrence of prostate cancer.
- Tumours in animals (rodents): animal studies have not reported any tumour induction, and it was therefore not possible to conclude from these studies whether or not radiofrequencies have an effect on the induction of tumours in the organs of the reproductive system in males or females.
- Mechanistic: with regard to mechanistic studies, the data show some effects on the female reproductive system. However, there are too few of them to reach any conclusion about the induction of a set of mechanisms linked to cancer.
  Conversely, numerous *in vivo* and *in vitro* studies report the induction of various mechanisms in the male reproductive system. One *in vivo* human study reported an effect on DNA. *In vitro* studies on human and animal sperm show that this cell type is highly sensitive to radiofrequencies. Moreover, many animal studies report the induction of numerous mechanisms in the testicles (genotoxicity, oxidative stress, apoptosis, impact on proliferation, reduced hormone production, etc.). These data suggest that exposure to radiofrequencies induces, in human cell lines and non-human models, a combination of mechanisms involved in carcinogenesis in the organs of the male reproductive system.

3.3.1.7. Other organs and physiological systems

The data available for certain organs or physiological systems were too limited to establish solid lines of evidence. They concerned the following locations: head and neck, endocrine system, pulmonary system, digestive system, breast and mammary glands, kidneys, urinary system, skin, bones, muscles and nerves excluding the central nervous system. In addition, mechanistic data were analysed to study the impact of radiofrequencies on *in utero* and post-natal development (rodents) and on non-mammalian biological organisms (fish, nematodes, insects, plants), without any level of evidence being established.

3.3.2. Assessment of the overall level of evidence for the whole body

Epidemiological data on the carcinogenic effect of radiofrequencies are numerous for the brain and blood, but rare for other organs. It was not possible to conclude from the studies on the brain whether or not there is a carcinogenic effect. Some case-control studies did suggest a risk for highly exposed sub-groups, but their results were inconsistent and subject to bias. In the case of blood, no relationship was found with leukaemia or lymphoma. It was not possible to reach any conclusion from two exploratory studies on other organs, despite some isolated

associations. Overall therefore, it was not possible to conclude from current data whether or not radiofrequencies have a carcinogenic effect on humans[21].

Fewer than 10 high-quality studies have examined the induction of tumours by radiofrequencies in animals, with long follow-up and large groups of animals. The studies by the US National Toxicology Program provided detailed analyses, showing overall that radiofrequencies had no effect on the development of tumours, except for an increase in the number of benign tumours in male mice exposed to a GSM signal at 5 W/kg[22]. A few isolated cases of tumour induction were observed (lymphomas, schwannomas, liver tumours), but it was not possible to establish any links between the results (location, species, sex). There is therefore limited evidence for reaching a conclusion about whether radiofrequencies have a carcinogenic effect on animals.

The analysis of the literature showed that radiofrequencies can induce certain mechanisms linked to cancer in different organs or physiological systems. In the brain, genotoxicity was induced by short periods of exposure (less than 3 months). Induction of oxidative stress was observed in the majority of studies, despite some contradictory results (no induction or even a reduction). Only a limited number of studies documented cell death, inflammation and autophagy. As with the brain, there were abundant data on blood tissue. In general, the results of *in vivo* mechanistic studies in animals were fairly consistent. Evidence of genotoxic effects was rarely reported, but the induction of oxidative stress has been clearly established. Several studies showed that radiofrequencies have a protective effect against other physical or chemical agents. Conversely, the results of *in vitro* studies often contradicted each other and the results of *in vivo* studies. The mechanistic data for the other organs were less numerous and only focused on a limited number of mechanisms. One exception was the male reproductive system, where a large number of mechanisms were observed concomitantly in studies. However, these biological responses did not lead to the induction of tumours, either in humans or in animals. In conclusion, there is limited evidence so far to suggest that exposure to radiofrequencies induces a range of mechanisms involved in carcinogenesis.

Thus, after analysing the scientific literature according to the method of assessment of the levels of evidence described in Section 3.1, incorporating epidemiological data, animal studies and mechanistic data, the Working Group finds overall that regardless of the organs or physiological systems analysed in this report, it is not possible to conclude from the available data whether or not exposure to radiofrequencies has a carcinogenic effect on humans.

3.4. Conclusion of the CES

The Working Group applied a method for assessing the level of evidence tailored to the issue of carcinogenesis, based on a literature analysis that was as exhaustive as possible. The CES stresses that this approach revealed the fact that the epidemiological studies do not provide conclusive evidence of cancer induction in humans. However, in some organs or physiological systems, limited evidence of tumour development in animals or induction of mechanisms was observed. Strong evidence of induction of mechanisms was also observed in the male reproductive system. The two lines of evidence concerning firstly, the development of tumours in animals and secondly, the mechanisms of carcinogenesis, were inconclusive for the other

[21] See the dissenting position of one of the Working Group's experts expressed in the expert appraisal report's conclusion (see Chapter 6) and Annex 4.
[22] Level of exposure above regulatory exposure limits.

organs or physiological systems. Based on the combination of these different types of data, it was impossible to conclude, for each organ or physiological system, whether or not radiofrequencies have a carcinogenic effect on humans. The assessment of an overall level of evidence for the whole body, based on the combined consideration of all the data collected, came to the same conclusion[23].

It is important to note that this level of evidence is different to the one presented in ANSES's 2013 report, which classified the occurrence of glioma as "possible" for the highest levels of exposure to radiofrequencies. This level of evidence also differs from that proposed by IARC in 2011, which classified radiofrequencies in Group 2B (possibly carcinogenic to humans). Since then, numerous data have been published, including epidemiological results from cohort studies. Consideration of these data led the Working Group and the CES to revise the level of evidence of the carcinogenicity of radiofrequencies.

3.5. Recommendations of the CES

In light of the Working Group's analysis of the impact of radiofrequencies on cancer, the CES on "Physical agents and new technologies" presents the following ideas and recommendations.

The CES believes that questions need to be asked about the development of technologies using radiofrequencies. The transition from 4G to 5G and the move towards 6G are often presented as "logical", "natural" and even inevitable. However, the CES questions these constant developments in terms of frequencies used, coverage and bandwidth. In a socio-economic context that is driving the development of these mobile communication technologies (which are responsible for most exposure to radiofrequencies) and not knowing how future developments will impact human health, the CES questions the systematic implementation of new technologies in the absence of prior risk assessment and public debate.

The CES stresses that, in addition to exposure to radiofrequencies, digital technologies can have other health effects associated with their use.

It also mentions that these digital technologies have consequences for the climate, biodiversity, energy consumption, water and mining resources (including the environmental impact of their exploitation). There are close, interdependent links between the health of humans, animals and ecosystems, as stated by the "One Health"[24] concept.

Moreover, since the effect of radiofrequencies on human health is an issue of both public health and occupational health, the CES stresses the importance of conducting high-quality research to help monitor the possible health consequences that could arise from developments in wireless communications technologies.

3.5.1. Public health

Recommendations for public health managers

The CES reiterates the Working Group's observation on the risk of cancer: in this regard, based on current knowledge, there are no arguments that justify changing the current exposure limits

[23] One of the Working Group's experts considered that, overall, radiofrequencies have a possible effect on carcinogenesis in humans (see Section 3.3.1.1).

[24] https://www.who.int/news/item/29-04-2022-quadripartite-memorandum-of-understanding-(mou)-signed-for-a-new-era-of-one-health-collaboration.

and recommendations on the use of communicating devices (see section below on "Recommendations for the general public").

The CES endorses the recommendations of the Working Group in that it advises:

- continuing to issue recommendations on the use of existing wireless communication devices to the general public;
- monitoring technological developments and the possible health impact of exposure to radiofrequencies. Because the finding that it is impossible to conclude whether or not radiofrequencies are carcinogenic was based on past and current levels of exposure and technologies, this assessment will need to be updated in line with future developments;
- securing and even expanding epidemiological surveillance of cancer using cancer registries in particular;
- supporting research into the impact of radiofrequencies on male fertility, given the results of the available mechanistic studies, and on female fertility, given the lack of data.

In addition to the effects of radiofrequencies on cancer, and more generally on health, the CES recommends considering other impacts of the development of digital technologies on:

- the environment: carbon footprint, energy consumption, mining resources, equipment lifecycle, water and biodiversity;
- new uses and practices, and their consequences for mental health in particular;
- repercussions on workers' health, employment, working conditions and quality of life.

Recommendations for the general public

The CES would like to emphasise the point made by the Working Group: mobile phones are currently the predominant source of exposure to radiofrequencies in terms of intensity, compared with other sources (microwaves, Wi-Fi, base stations, etc.).

The recommendations on using mobile phones should be reiterated: reasonable use, choose areas with good reception, use earpieces or hands-free kits, limit use by children, in particular.

3.5.2. Research

The CES endorses the Working Group's observations and recommendations in terms of research, to ensure that future studies can overcome the limitations encountered to date and take better account of the variety of exposure patterns, technologies and populations concerned.

Limitations observed

Together with the Working Group, the CES notes the methodological limitations of many studies:

- incomplete descriptions of the methods used, making it difficult for other laboratories to replicate these studies;
- exposures to radiofrequencies that are not sufficiently realistic in experimental *in vivo* and *in vitro* studies;
- imprecise estimates of past and current exposure in epidemiological studies;

- the inadequate length of longitudinal follow-up in existing epidemiological studies for diseases such as cancer.

Recommendations

Consequently, and in view of the diversity of exposure patterns, the constant development of technologies and the variety of populations exposed, the CES recommends that studies incorporate exposure parameters that are more in line with the reality of exposure, enabling a better understanding of the effects in biological models and on the human population.

The Working Group sought to make proposals for various fields of research in order to improve the quality of studies and, consequently, the results obtained. The CES sets these proposals out below.

For biological effects:

- significantly improve the quality of biological studies in humans (recruitment of participants, consideration of confounding factors, choice of biological parameters, exposure assessment, etc.);
- search for links between physical parameters (frequencies, specific absorption rate (SAR), power density, continuous, modulated or pulse signal, exposure time, chronicity, etc.) and biological responses in experimental studies;
- improve experimental approaches in *in vitro* studies, through:
    - new biological models (organoids, etc.);
    - combinations of methods ("omics", imaging, biochemistry, etc.);
    - new forms of data processing (modelling, bioinformatics, etc.).

For epidemiology:

- pay particular attention to qualifying and quantifying exposure, in particular by exploring the possibility of using data from mobile phone operators;
- continue to monitor cohorts over a period compatible with the time taken for cancers to develop;
- document and monitor digital usage in the population over time (e.g. use of the phone under the chin, wireless headphones, tablets, etc.);
- take better account of socio-economic and behavioural variables (in particular, level of education, family context, living conditions);
- set up cohorts of workers particularly exposed to radiofrequencies.

For the physical characterisation of exposure in the laboratory:

- ensure the validity of the associated exposure and measurement systems (bandwidth, field homogeneity, temperature measurement, etc.);

- use suitably documented means (digital simulation or experimental measurements) to determine the distribution of the electromagnetic field within the exposure device and its temporal and spatial variations;
- systematically monitor and quantify, above 100 MHz, the real-time measurement of the incident electric field at the location of the *in vitro* test samples, in order to be able to compare exposures to electromagnetic waves;
- use numerical and biological models that take account of the scale factors between animals and humans, in order to extrapolate observations to humans;
- define new exposure systems above 6 GHz, to take account of developments in mobile telephone frequencies, in particular, and carry out dosimetry measurements.

For the characterisation of the electromagnetic environment:

- continue to develop measuring equipment, simulation methods and exposure mapping, and improve the characterisation of exposure to new signals and new uses in different environments;
- quantify the exposure of tissues (skin, eyes) targeted by the higher frequencies of new, less penetrating signals;
- study the impact of the growing number of base stations and the change in characteristics of the transmitted signals;
- study in greater detail the exposure to radiofrequencies of organs identified as sensitive in animals, such as the heart, liver and testicles.

4. AGENCY CONCLUSIONS AND RECOMMENDATIONS

According to the latest digital barometer[25] published by ARCEP in March 2025, the share of the population aged 12 years and over using the internet exclusively via a mobile connection rose from 3% to 9% between 2015 and 2024, while fixed connections fell from 30% to 4%. These figures illustrate just how important the use of mobile networks has become, as part of the digital transformation of society, even when alternatives are available.

However, while the number of mobile phone base stations has risen sharply over the same period (221,619 transmitting sites as of 1 May 2025[26]), it is very difficult to assess changes in the resulting exposure to electromagnetic fields, whether individually or for the population. The sources of electromagnetic waves found in our environment (mobile telephone technology, audiovisual broadcasting, connected objects, etc.) make up a heterogeneous whole that fluctuates over time and uses multiple frequencies, located at varying distances from people and delivering radiation in a wide range of intensities.

These developments in the electromagnetic environment raise legitimate questions about their possible effects on health. Scientific research has a fundamental role to play in generating

[25] https://www.arcep.fr/uploads/tx_gspublication/barometre-du-numerique_edition_2025_RAPPORT_mars2025.pdf.
[26] https://www.anfr.fr/fileadmin/mediatheque/documents/Observatoire/0525/Observatoire_mobile_Metropole010525.pdf.

knowledge and reducing the uncertainties that make risk assessment (and therefore management) particularly complex. These questions about the health effects of exposure to electromagnetic fields have fuelled a vast number of research projects since the 1990s, supported in Europe and particularly in France by a series of specific funding programmes dedicated to radiofrequencies. In 2020, a scientometric analysis carried out by the Interdisciplinary Laboratory in Social Sciences and Innovation (LISIS), at the request of ANSES[27], estimated that around 26,000 scientific publications on the health effects of radiofrequencies were published between 1996 and mid-2019. Six years on, for the period from 1996 to mid-2025, this number is close to 46,000. In addition to the quantitative aspect in terms of the number of publications, ANSES points out that, in qualitative terms, the new knowledge also includes the results of large-scale epidemiological studies for different populations, as well as a series of major toxicological studies by the US National Toxicology Program.

Drawing on this continuous output of scientific data, ANSES periodically updates its assessments of the risks associated with electromagnetic fields. These expert appraisals are systematically carried out in accordance with its guiding principles of collective assessment, multidisciplinary scientific skills and adversarial debate[28].

In 2013, ANSES updated its previous expert appraisal on the health risks associated with exposure to radiofrequencies[29], focusing mainly on the effects on sleep, cognitive functions, neurological diseases, fertility, the cardiovascular system and cancer. Possible specific effects in children were then investigated in an expert appraisal published in 2016[30]. Among the effects identified with regard to cancer, ANSES had concluded in 2013 that there was a "limited" level of evidence of a link between exposure to radiofrequencies and the risk of development of vestibulo-acoustic nerve neuroma. The Agency had also considered that a slight increase in the risk of glioma (brain tumour), limited to "intensive" users of mobile phones[31], was "possible". The Agency had however noted that no data were available for induction times of more than 15 years for this type of tumour.

Advances in knowledge have prompted a new update of the Agency's expert appraisal, this time focusing exclusively on the carcinogenicity of radiofrequencies. This is because the huge number of scientific results available means that it is now no longer possible to carry out expert appraisals simultaneously on all the possible effects for all the organs and biological systems of the human body, within a reasonable timeframe and while maintaining both the quality and robustness of assessments based on a full analysis of the available data.

In response to a request from the Ministry of Health, ANSES undertook expert appraisal work to update its previous conclusions on the link between exposure to radiofrequency electromagnetic fields (3 kHz to 300 GHz) and the occurrence of cancer in humans. The Agency stresses that the Working Group responsible for carrying out this expert appraisal adopted a suitable method for assessing the level of evidence, implementing the recommendations of its Scientific Board on risk assessment methods[32], and keeping in line with international standards. Based on a literature search that was as comprehensive as possible, nearly 250 original scientific articles were selected on the basis of criteria on their

[27] Research and development agreement No. 2017-CRD-11: https://www.anses.fr/fr/system/files/RapportFinal-CRD_Radiofrequences_ANSES-LISIS-2021.pdf.
[28] https://www.anses.fr/fr/system/files/ANSES-Ft-PrincipesExpertise.pdf.
[29] https://www.anses.fr/fr/system/files/AP2011sa0150Ra.pdf.
[30] https://www.anses.fr/fr/system/files/AP2012SA0091Ra.pdf.
[31] i.e. more than 1640 hours of accumulated exposure.
[32] https://www.anses.fr/sites/default/files/Rapport_methologique_ACCMER.pdf.

relevance to the topic and on the quality of the experimental protocols and data analyses, in particular. All these publications were systematically analysed separately by several members of the Working Group. The results of these studies were then pooled, discussed and debated within the group, in order to develop conclusions for all the epidemiological studies, the experimental studies on animals and lastly, the studies investigating biological mechanisms of action, particularly at cellular level. The arguments and conclusions on the link between exposure to radiofrequencies and the development of cancer formulated by the group of experts therefore result from a process of adversarial development, incorporating all the available scientific data in all their diversity and heterogeneity, while analysing their strengths and weaknesses and the links between them.

In 2024, before the expert appraisal was completed and the conclusions adopted by the group of experts, the Agency organised a public consultation in order to collect scientific comments on the expert appraisal report and supplement, where necessary, the data identified by the experts. The comments received from interested stakeholders (scientists, associations active in the area of exposure to radiofrequencies, mobile phone operators and manufacturing associations, citizens) were analysed as part of the expert appraisal. The final report takes account of the requests for further information or clarification, in order to improve understanding[33]. A day of discussions was also held in January 2025 to present the results of the public consultation and give contributors the opportunity to directly question members of the Working Group. The expert appraisal work therefore takes account of these productive exchanges, whose value was emphasised by all the participants.

ANSES endorses all the conclusions of the WG on "Radiofrequencies and cancer", set out in its expert appraisal report and reiterated by its Expert Committee on "Physical agents and new technologies" in Section 3 of this opinion. The results of several large-scale epidemiological studies have been published in recent years, along with new analyses of older studies, which in 2013 had led ANSES to conclude that there was a "possible" link between exposure to radiofrequencies and a low risk of brain tumours. The update of the scientific data now reveals that, taken as a whole, the epidemiological studies do not provide conclusive evidence of the development of cancer in humans. After combining the different types of data (epidemiological, toxicological, mechanistic), therefore, the expert appraisal reached the following finding: "it is not possible to conclude from the available data whether or not exposure to radiofrequencies has a carcinogenic effect on humans". This is expressed for each of the organs and physiological systems analysed, as well as for an overall whole-body approach. The pathway that led to this result, based on the literature review and application of the method described in Section 3, is shown in Annex 3 of this conclusion, in Figure 3.

To put this result in context, it should be compared with IARC Group 3[34] "*not classifiable as to its carcinogenicity to humans*". As a reminder, this group, which is lower in terms of the level of evidence of carcinogenicity than Groups 1, 2A and 2B, includes around half of the 1000 substances, mixtures or processes assessed by IARC since 1971.

However, ANSES's conclusion does not mean that any assumption of the existence of carcinogenic effects has been ruled out. It was obviously formulated on a particular date and in light of knowledge taken into account up to May 2025. The recommendations on advancing knowledge should make it possible to document the limited evidence observed for some

[33] A version of the expert appraisal report submitted for the public consultation and combining these comments is available in PDF format as an annex to be downloaded from the Agency's website.
[34] https://monographs.iarc.who.int/wp-content/uploads/2019/07/Preamble-2019.pdf.

organs or physiological systems, concerning the development of tumours in animals or the induction of mechanisms.

While knowledge of the hazard (in terms of carcinogenicity) posed by radiofrequencies is accumulating and strengthening the scientific basis for conclusions relating to this hazard, the characterisation of exposure to these electromagnetic fields, which would enable health risks to be assessed, is still incomplete.

In 2025, 98% of people aged 12 years and over in France have a mobile phone, 91% of them a smartphone. Traditional voice use seems to be declining, replaced by practices such as the use of loudspeakers or earpieces, thus reducing direct exposure of the head to radiofrequencies. Yet at the same time, the development of mobile internet use (videos, social media, etc.), encouraged by technological developments (4G, 5G) and the increasing density of the network of base stations, is leading to a gradual increase in environmental exposure to radiofrequencies, particularly in urban areas with a higher density of equipment.

As a result, ANSES adopts the recommendations made by its expert groups, with a particular emphasis on those mentioned below.

Regarding knowledge about the carcinogenicity of radiofrequencies, the Agency recommends pursuing research into epidemiology and relevant experimental models (*in vivo* and *in vitro*), in accordance with the procedures and priorities defined by its expert committee. Additional studies to those carried out by the US National Toxicology Program on the carcinogenicity of rodent exposure to radiofrequencies have been undertaken by other research teams. The results of these studies, carried out in recent years and partly based on the initial experimental protocols, have not yet been published. The Agency therefore recommends that the carcinogenicity of radiofrequencies be reassessed in the longer term in *in vivo* animal models.

Furthermore, during the expert appraisal, the analysis of studies into the mechanisms of interaction between electromagnetic fields and living organisms, particularly at cellular level, showed that as well as the links with cancer, exposure to radiofrequencies could have an effect on fertility. The Agency therefore notes the relevance of conducting a similar reassessment of the links between exposure to radiofrequency electromagnetic fields and possible effects on fertility.

Regarding the population's exposure to radiofrequencies, ANSES stresses the importance of monitoring its progression. The results of measurements taken to monitor compliance with regulatory exposure limits for electromagnetic fields in the environment could therefore be leveraged to better characterise population exposure. Coupled with future simulation data produced as part of the work of the ANFR and CSTB for the Fourth National Environmental Health Action Plan (PNSE4)[35], measurements of exposure in the environment, combined for example with the results of research into actual exposure to mobile devices[36], could be used to characterise people's exposure and its changes over time. Exposure data are currently very heterogeneous, produced or hosted by different public and private players, and available in the form of different indicators. Their exploitation is a challenge, but also an opportunity to identify levers to guide future research.

[35] https://sante.gouv.fr/IMG/pdf/pnse4.pdf.
[36] Such as the European GOLIAT project (https://projectgoliat.eu/) and the exploratory investigation project on exposure to radiofrequencies in real-life situations, funded by ANSES.

Beyond the conclusions of this expert appraisal on the carcinogenicity of radiofrequencies, ANSES considers that limiting people's exposure to electromagnetic fields must remain an objective. The Agency maintains its previous recommendations on the topic, stressing the need for developments in technologies, networks and uses of digital wireless tools to be accompanied by a limitation of individual exposure, whether this is environmental or from the terminals. In particular, the Agency reiterates its recommendation to reduce exposure in children by encouraging moderate use of mobile phones and favouring uses that keep the phone away from the body (earpieces, loudspeaker), and to obtain the best quality connection possible (generally via Wi-Fi rather than mobile networks indoors).

ANSES also points out that the effects of electromagnetic radiation, including carcinogenesis, are not the only group of health effects to be considered with the use of wireless technologies. Its recommendation to limit exposure to electromagnetic fields is therefore part of a more comprehensive approach to the rational use of these technologies. In particular, ANSES has documented the proven effects on sleep of blue light from screens (including smartphones), as well as the effects of sedentary behaviour, which is strongly tied to time spent in front of a screen. It is also currently finalising its work on the impact on adolescents of the use of social media.

Lastly, ANSES stresses that the development of new network infrastructures raises questions about their energy and environmental impact. ANSES notes the desirable convergence of sobriety objectives in terms of both energy and exposure to electromagnetic fields, concerning base station networks and terminals. In particular, the use of wired connections should be favoured for indoor internet access, especially for all non-mobile uses.

Pr Benoit Vallet

KEY WORDS

Radiofréquences, cancer, tumeurs, exposition, champs électromagnétiques.

Radiofrequencies, cancer, tumour, exposure, electromagnetic fields.

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ANNEX 1: FORMAL REQUEST

2016 -SA- 0 1 7 6

COURRIER ARRIVE
0 8 AOUT 2016
DIRECTION GENERALE

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MINISTERE DES AFFAIRES SOCIALES ET DE LA SANTE

Direction générale de la Santé
Sous-direction Prévention des risques liés à l'environnement et l'alimentation
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D-16-020547 -164

Paris, le 2 - AOUT 2016

The Director General for Health
To
The Director General
of the French Agency for Food, Environmental and Occupational Health & Safety
14 rue Pierre et Marie Curie
94701 Maisons-Alfort

Subject: Request for an analysis note on the preliminary results of the US National Toxicology Program study (animal exposure to radiofrequencies)

In May 2016, the scientific team responsible for the US National Toxicology Program study (animal exposure to radiofrequencies) released the preliminary results of the study in order to collect the views of the scientific community.

I would like you to:

1. initially, send me a note analysing these preliminary results. This is due for 15 November 2016.
2. secondly, considering the final results of the study, inform me whether these results are likely to change the classification of radiofrequencies as "possibly carcinogenic to humans (Group 2B)" established by the International Agency for Research on Cancer in 2011.

Regarding the deadline for replying to the second point, this will be examined on the date of publication of the final results of the NTP study.

Le Directeur Général de la Santé,

Professeur Benoît VALLET

14, avenue Duquesne – 75350 Paris 07 SP – Tél. 01 40 56 60 00

ANNEX 2: PROCEDURES AND EXAMPLE OF HOW TO READ THE TABLE FOR DETERMINING THE LEVEL OF EVIDENCE

The table (Figure 1) is read from left to right, following the relative weight of the different lines of evidence. A fictitious example of a pathway is presented at each step to illustrate the process of determining the level of evidence in a given organ:

1. line of evidence from human epidemiology data (one of the lines in the first column, on the left). Example: **"Inconclusive"** evidence;
2. line of evidence from *in vivo* data on tumour induction in animals (one of the lines in the second column from the left, in the line determined at step 1). Example: **"Limited or inconclusive"** evidence;
3. line of evidence from data on the induction of biological mechanisms linked to cancer (one of the lines in the third column from the left, in the lines defined at step 2). Example: "**Strong suggestion of induction in humans *in vivo***". This column only contains information on the different types of models that have an impact on the final level of evidence;
4. the level of evidence resulting from the sequence of lines of evidence is read in the last column, on the right. Example: the classification of the level of evidence derived from the previous lines of evidence given as an example is necessarily "**Possible effect on humans**". Any other line of evidence concerning the mechanistic data would give a level of evidence of "**No conclusion possible**".

In IARC's approach, the evidence categories "inconclusive data" and "no data" are combined. The Working Group wished to separate them to take account of the fact that an inconclusive line of evidence could result from a limited volume of work showing an effect in comparison with a large mass of data showing no effect. To include these few positive results in the process, the "inconclusive" epidemiological lines of evidence led to a higher level of evidence than "no data".

ANNEX 3: EXPRESSION OF THE LEVEL OF EVIDENCE OF THE CARCINOGENICITY OF RADIOFREQUENCIES FOR THE WHOLE BODY

Figure 3 below illustrates the pathway that leads from the epidemiological data, data from *in vivo* animal studies and from mechanistic studies to the expression of the level of evidence of carcinogenicity associated with exposure to radiofrequency electromagnetic fields for the whole body in humans.

Line of evidence in human epidemiology: evidence linked to the development of a tumour or cancer	Line of evidence in animals: evidence linked to the development of a tumour or cancer from *in vivo* data	Line of evidence of induction of biological mechanisms linked to cancer from a combination of biological mechanisms	Level of evidence in humans (whole body)
Sufficient	*Does not affect the classification*	*Does not affect the classification*	Proven effect for humans
Limited	Sufficient	Strong suggestion of induction in humans *in vivo*	Proven effect for humans
		Other levels of mechanistic evidence	Probable effect on humans
	Limited or inconclusive	Strong suggestion of induction in humans *in vivo*	Probable effect on humans
		Other levels of mechanistic evidence	Possible effect on humans
Inconclusive	Sufficient	Strong suggestion of induction in humans *in vivo*	Proven effect for humans
		Strong suggestion of induction in human models (primary cells and organs)	Probable effect on humans
		Strong suggestion of induction in human lines and animal models	Possible effect on humans
		Other levels of mechanistic evidence	No conclusion possible
	Limited in some organs, inconclusive in others	Strong suggestion of induction in humans *in vivo*	Possible effect on humans
		Strong mechanistic evidence in the male reproductive system, limited evidence in some organs, inconclusive evidence in other organs	It is not possible to conclude whether or not radiofrequencies have a carcinogenic effect on humans
No data	Sufficient	Strong suggestion of induction in humans *in vivo*	Probable effect on humans
		Strong suggestion of induction in human models (primary cells and organs)	Possible effect on humans
		Strong suggestion of induction in human lines and animal models	Possible effect on humans
		Other levels of mechanistic evidence	No conclusion possible
	Limited or inconclusive	*All levels of mechanistic evidence*	No conclusion possible

Figure 3: Expression of the level of evidence of the carcinogenicity of radiofrequencies for the whole body