



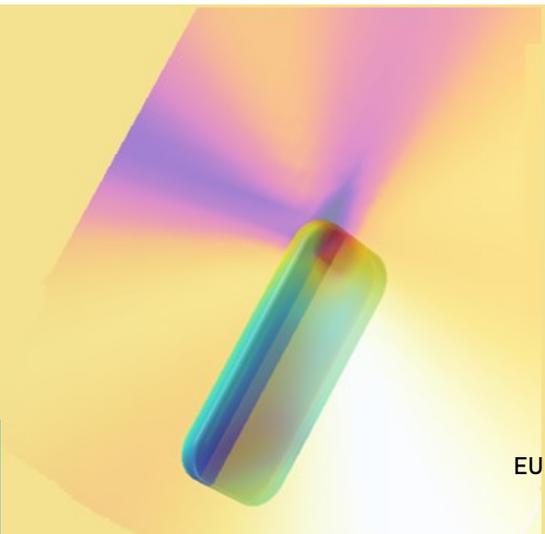
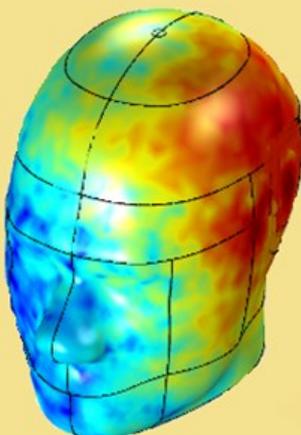
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Electromagnetic emissions from mobile networks and potential effect on health - Preliminary study

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Abstract

Radio Frequency (RF) Electromagnetic field (EMF) exposure from mobile phone networks and possible adverse health impact is an issue causing much concern among citizens and several public bodies. Despite extensive research on this subject, many questions have remained unanswered due to methodological inconsistencies and lack of data. This report provides a preliminary analysis, including a literature survey of recent government and research activities into the health impact of RF EMF exposure. This report also attempts to explore a possible relationship between RF EMFs and incidence of brain cancer based on publicly available national datasets. The preliminary results, presented in this paper do not reveal any such relationship, but more work is necessary to overcome the limitations of the existing data. The findings of the empirical study show that the level of uncertainties in the current state of art are still very high, and the report recommends pro-active initiatives, such as the collection of better quality data, standardization of experimentation protocols and collaboration between interdisciplinary research groups, that could improve the state of play. Finally, further research on the EMF exposure in mmWave frequency bands and any effects on human health (and possibly the environment) is recommended to supplement the current knowledge.

1 Introduction

Mobile telephony is now commonplace throughout the world. This wireless technology relies upon an extensive network of base stations, relaying information by radiofrequency (RF) signals. Over 1.4 million base stations exist worldwide and their number will increase significantly with the advent of the fifth generation (5G) technology.

In a growing demand market, 5G technology will meet the requirements of high data rates, very low latency and high reliability. It is designed to serve not only traditional communications but also industrial control communications which will help to digitize the economy and contribute to the digital transformation. Major application fields for the vertical engagement are automotive, manufacturing, Internet of Things (IoT), media, energy, eHealth, public safety and smart cities. To fulfil all these requirements, 5G differs from preceding generations in spectrum use, antennas and network topology [74, 75].

However, installing new 5G sites may be very challenging, especially in urban sites. Early 5G deployments will coexist for some time with existing 2G, 3G and 4G networks, resulting in an unavoidable, though small, cumulative increase in RF EMF¹ exposure levels (see also the recent study funded by the European Commission on mm-waves [72]). Therefore 5G network deployments will in many cases be constrained by the existing national EMF limits.

Together with the development of mobile communication technologies, there is public concern about potential health risks associated with the use of mobile phones and living in proximity to base stations.

Many citizens perceive that the risks from RF EMF exposure are likely, and even possibly severe. Among the causes of such levels of apprehension is misinformation circulating on social media, such as announcements of new and unconfirmed scientific studies, reinforcing suspicions of undiscovered or even deliberately suppressed hazards.

Concerns among the general public have recently led some municipalities to block 5G trials.

1.1 Context of the problem

This study was commissioned by DG CNECT to identify possible links between health effects and the spread of mobile networks. Due to the level of public concern the Commission intends to act in a proactive way and conduct an independent scientific study on the subject. Full transparency is a prerequisite for public trust. The EC also intends to carry out a validation of the scientific evidence on which the updated ICNIRP guidelines published in March 2020 [35] are based. The present study takes into account developments until the end of 2020.

1.2 Scope of the report

This study analyzes statistical data to explore relationships between the growth of mobile networks and the incidence of some pathologies such as brain cancer. The report does not address a possible link of other sources of radio frequency emissions including Wi-Fi, broadcasting, electric power lines and military communication systems. It contains an overview of previous studies to identify lacunae to address. The study is based on a broad analysis of historical data from the last thirty years, which covers the deployment of successive generations of cellular networks from 2G to the present.

1.3 Targeted audience

The report is intended for policy makers and scientists for informed decision making and improved coordination of research in this field.

1.4 Structure of the report

Section 2 describes the regulatory framework of electromagnetic field safety limits in Europe. The metrics, as well as the guidelines for setting up the regulatory framework are also presented.

¹ RF EMF and EMF are synonymous in the rest of this report.

Section 3 provides an overview of recent research activity into electromagnetic field exposure from mobile phones and its potential impact on health. The literature review is grouped in three areas, i.e. radio frequency (RF) emission studies, experimental studies focusing on the impact of RF electromagnetic fields on various health aspects of living organisms and statistical assessments of various diseases in the human population and their relationship to the development and use of wireless communication networks.

The methodology of the current analysis is described in Section 4. In particular, the datasets used and the implemented statistical analysis are explained.

Section 5 sets out the analysis of the datasets and presents the results. The constraints that were present are discussed together with the main findings.

Section 6 summarizes the conclusions of this preliminary analysis and makes recommendations for future research.

2 Regulatory context

2.1 EMF metrics

Radiofrequency (RF) EMFs (30kHz -300GHz) belong to the non-ionizing range of the electromagnetic spectrum; meaning that this radiation cannot remove electrons from the atoms or molecules comprising all materials, including air, water, and living tissues. By contrast, the ionizing part of the electromagnetic spectrum starts with ultra-violet light, and includes X- and gamma rays; all of which are exploited for their lethality to living tissues.

Safety limits for non-ionizing radiation are expressed in terms of basic restrictions and reference levels.

Basic restrictions address the fundamental quantities that determine the physiological response of the human body to EMFs. They apply to situations in which the body is present in the field. The most common measure for basic restrictions is the Specific Absorption Rate (SAR), which quantifies the rate at which energy is absorbed by the human body, as heat, when exposed to an RF electromagnetic field. SAR is calculated by:

$$SAR = \frac{\sigma \times E^2}{m_d} (W/kg)$$

where σ is the electrical conductivity of the exposed tissue (S/m), E is the root mean square value of the electric field (V/m) and m_d is the mass density of the sample under test (kg/m³). SAR is usually averaged over the whole body (whole body exposure), or over a small sample volume (typically 1g or 10 g of tissue) (local body exposure).

As the basic restrictions are difficult to measure directly, most standards provide derived reference levels for electric field, magnetic field and power density. The reference levels apply to situations where the assessment of electromagnetic field is not influenced by the presence of a body. The common metric for reference levels is power density. It is defined by:

$$S = \frac{P}{4\pi R^2} (W/m^2)$$

where P is the transmitting power of the antenna and R is the distance at which power density is measured.

2.2 EMF safety limits

In Europe, RF EMF exposure safety guidelines are based on limits developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [34], which was established in 1992 in the face of rising concerns among various public authorities about the potential adverse health effects of electromagnetic fields. Worldwide EMF safety levels are based either on the aforementioned guidelines or on standards developed by the IEEE (Institute of Electrical and Electronics Engineers, Inc.) International Committee on Electromagnetic Safety (ICES) [79].

Both sets of guidelines define different exposure limit values for the general public and occupational groups (i.e. healthy adults), with occupational limits being generally five times higher than those for the general public (i.e. including children, the old, and the infirm).

The ICNIRP 1998 guidelines [34] were recently revised in 2020 [35]. For the general public and for frequency bands used in mobile communications (non-ionizing EMFs) the limit values of power density are set to $f/200$ (f in MHz) for the 400MHz-2GHz frequency range and $10W/m^2$ for frequencies 2GHz-300GHz. The basic restrictions and the reference level values of the ICNIRP 2020 guidelines are presented in Table 1 and Table 3.

Table 1 ICNIRP’s basic restrictions for electromagnetic field exposure from 100kHz to 300GHz, for averaging intervals ≥ 6 min.

Exposure Scenario	Frequency Range	Whole-body average SAR (W/kg)	Local Head/Torso SAR (W/kg)	Local Limb SAR (W/kg)	Local S_{ab} AR (limbs) (W·m ⁻²)
Occupational	100kHz – 6GHz	0.4	10	20	NA
	6GHz – 300GHz	0.4	NA	NA	100
General Public	100kHz – 6GHz	0.08	2	4	NA
	6GHz – 300GHz	0.08	NA	NA	20

Notes:

NA signifies not applicable and does not need to be taken into account when determining compliance.

Whole body average SAR is to be averaged over 30 min.

Local SAR and S_{ab} exposures are to be averaged over 6 min.

Local SAR is to be averaged over a 10-g cubic mass.

Local S_{ab} is to be averaged over a square 4-cm² surface area of the body. Above 30 GHz, an additional constraint is imposed, such that exposure averaged over a square 1-cm² surface area of the body is restricted to two times that of the 4-cm² restriction.

Table 2 ICNIRP’s reference levels for exposure, averaged over 30min and the whole body, to electromagnetic fields from 100KHz to 300GHz (unperturbed rms values).

Exposure Scenario	Frequency Range	Incident Electric Field Strength E_{inc} (V/m)	Incident H-field Strength H_{inc} (A/m)	Incident Power Density S_{inc} (W/m ²)
Occupational Exposure	0.1 – 30MHz	$660/f^{0.7}$	$4.9/f$	-
	30 – 400MHz	61	0.16	10
	400 – 2000MHz	$3f^{1/2}$	$0.008f^{0.5}$	$f/40$
	2 – 300GHz	NA	NA	50
General Public	0.1 – 30MHz	$300/f^{0.7}$	$2.2/f$	NA
	30 – 400MHz	27.7	0.073	2
	400 – 2000MHz	$1.375f^{1/2}$	$0.0037f^{0.5}$	$f/200$
	2 – 300GHz	NA	NA	10

NA signifies not applicable and does not need to be taken into account when determining compliance.

f is the frequency in MHz.

E_{inc} , H_{inc} and S_{inc} are to be averaged over 30min, over the whole body space. Temporal and special averaging of each of E_{inc} and H_{inc} must be conducted by averaging over the relevant square values.

For frequencies of 100KHz to 30MHz, regardless of the far-field/near-field zone distinctions, compliance is demonstrated if neither E_{inc} nor H_{inc} exceeds the above reference level values.

For frequencies above 30MHz to 2GHz: (a) within the far-field zone: compliance is demonstrated if either E_{inc} , H_{inc} and S_{inc} does not exceed the above reference level values (only one is required); S_{eq} may be substituted for S_{inc} ; (b) within the radiative near-field zone: compliance is demonstrated if either S_{inc} or both E_{inc} and H_{inc} does not exceed the above reference level values; and (c) within the reactive near-field zone: compliance is demonstrated if both E_{inc} and H_{inc} do not exceed the above reference level values; S_{inc} cannot be used to demonstrate compliance, and so basic restrictions must be assessed.

For frequencies above 2GHz to 300GHz: (a) within the far-field zone: compliance is demonstrated if S_{inc} does not exceed the above reference level values; S_{eq} may be substituted for S_{inc} ; (b) within the radiative near-field zone, compliance is demonstrated if S_{inc} does not exceed the above reference level values and (c) within the reactive near-field zone reference levels cannot be used to determine compliance, and so basic restriction must be assessed.

The ICNIRP 2020 guidelines do not vary significantly from those of 1998. Adaptations have been made to the measurements methods and the safety limits for higher frequencies. Regarding the reference level values, reference levels corresponding to a wider range of frequencies have been added to cover 5G mobile communication technology.

The ICNIRP 1998 guidelines specified safety limits up to 10 GHz, while the ICNIRP 2020 guidelines cover frequencies up to 300 GHz. In addition, the 2020 guidelines define more detailed compliance rules, in particular for higher frequencies (up to 300GHz). There are some minor changes to the reference level values, caused by the removal of some reference values. These changes result in more conservative values, so make no difference to health protection against RF EMF exposure. Moreover, basic restrictions are also defined for periods <6 min.

A detailed analysis of the differences among the two sets of guidelines is published on ICNIRP's website².

2.3 Regulation in Europe

European EMF guidelines for non-ionizing exposure are mainly based on the ICNIRP 1998 guidelines, see e.g., Council Recommendation on the limitation of the exposure of the general public to electromagnetic fields (0Hz to 300GHz) [19]. This recommendation enabled Member States to put coherent and comparable recommended maximum exposure levels in place. All European Union Member States implemented measures to limit the exposure of the public to EMF, either by applying the provisions proposed by the Council Recommendation or their own stricter regulation. Since ICNIRP's guidelines were updated on March 2020 [35], the aforementioned Council Recommendation will also need to be updated in the near future.

The EMF policies in Member States are summarized in Figure 1. Belgium, Bulgaria, Croatia, Greece, Italy, Luxemburg and Slovenia have adopted stricter limits than those recommended [60, 5]. In Belgium limits differ between regions. For example, in Brussels the limit value is 1%-2% of the ICNIRP's reference levels depending on the frequency. The city of Paris in France has also approximately the same reference level values as Brussels. It should be noticed that these stricter policies apply, in most cases, to residential areas.

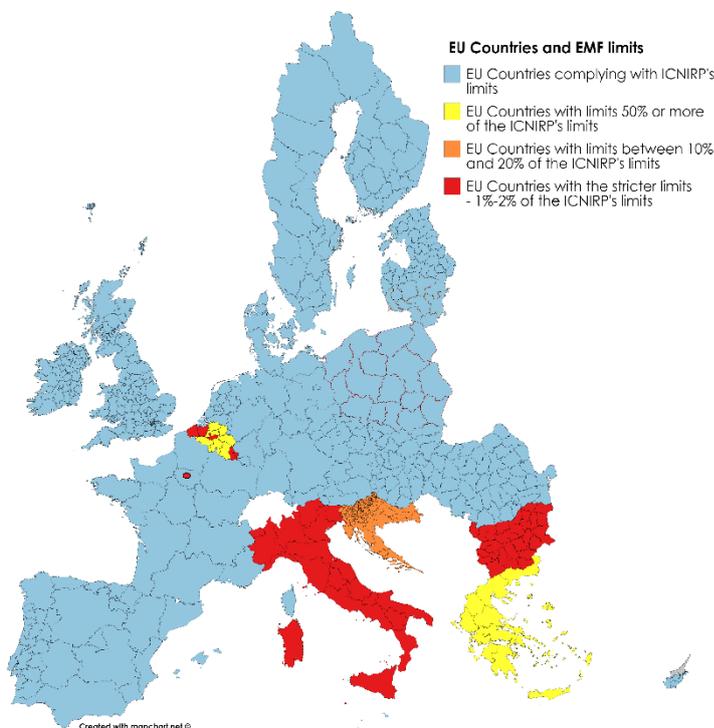


Figure 1 EMF limits in EU Member States (the percentages concern power density values).

² <https://www.icnirp.org/en/differences.html>

In Poland, the effects of low EMF exposure limits on network rollout were simulated. Results have shown how 5G networks will be restricted in terms of efficient spectrum, quality of service and dense cells (ITU-T K Suppl. 14 2019) [41]. For these reasons, the Polish authorities decided to harmonize their policy on permissible level of electromagnetic fields in the environment with the EC Recommendation [18]. Lithuania followed Poland's example³ [76].

The EC Guideline is also recognized in the EU legislation to protect workers [21]. Harmonized Standards under product legislation, notably the Low Voltage and the Radio Equipment and Telecommunications Terminal Equipment Directives (2014/35/EU, 2014/53/EU) [22, 23], ensure that the exposure levels of the Recommendation are not exceeded. To support these directives the EC has mandated the three European Standardization Organizations (ESOs) (CENELEC, CEN and ETSI) to develop conformity standards that define the requirements to protect human beings from hazardous effects which may be caused by exposure to electromagnetic fields, emitted by electrical apparatus [78].

In 2015, the European Commission requested the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) to provide an opinion on the possible health effects from exposure to electromagnetic fields (0 Hz - 300 GHz). The purpose of this Opinion was to update the SCENIHR Opinions of 2009 (Health effects of exposure to EMF and Research needs and methodology to address the remaining knowledge gaps on the potential health effects of EMF) in the light of newly available information, considering aspects with important knowledge gaps in the previous Opinions. SHENIHR concluded that there is weak or no evidence of RF EMF effect on different biological aspects of human body [66].

During the past years, there have also been several EU funded projects addressing the field of electromagnetic fields and health [55]. The latest completed project was the GERoNiMO (Generalised EMF Research using Novel Methods) which ended in the end of 2018. It focused on the evaluation of various health effects, the understanding of biological effects related to RF EMFs, the collection of exposure data and policy development in Europe to reduce exposure⁴. An ongoing project in this field is the 5GRFEX⁵. Its objective is to produce specific RF-EMF exposure measurement guidance for 5G Massive MIMO base stations which will be disseminated to technical, business and regulatory communities to support the development of effective regulation and enable 5G implementation that balances performance with public safety.

³ <https://sam.lrv.lt/lt/naujienos/elektromagnetines-spinduliuotes-normos-lietuvoje-suvienodintos-sueuropinemis>

⁴ (<https://cordis.europa.eu/project/id/603794>)

⁵ <http://empir.npl.co.uk/5grfex/>

3 Literature review

3.1 Identification of the main research areas

This section summarizes the state of art of the electromagnetic emissions from mobile base stations and mobile phones and their potential effect on health in the scientific domain. As mentioned in Section 0, this report does not address the health impact of other Radio Frequency emissions including broadcasting, Wi-Fi, military systems or electric power lines even if some studies reported in this section do also investigate such sources and make comparisons with mobile networks and mobile phone emissions.

The topic has been thoroughly investigated by the research community in recent years. In fact, research activities in this area go back decades. On the other hand, wireless communication technologies evolved significantly in recent years, and the evolution towards 5G (and 6G in the future) is the main subject of this report. Hence, this literature review focuses on findings published in the last 5 years; the exceptions are deemed to be of particular interest.

Three main areas of research emerge in the literature review in this field:

1. Radio Frequency (RF) emissions experimental studies where the RF emission power from consumer devices (mobile phones) or mobile base stations is measured and compared with the thresholds recommended by the regulations and international guidelines
2. Health impact due to RF emissions. In general, these studies are also experimental, but are focused on quantifying health effects of RF exposure (e.g., degradation) on human beings, animal beings and other forms of life.
3. Analysis of the statistical trends of the health diseases (e.g., tumours) in the human population in relation to the increase of presence of wireless communication networks or systems.

The first area of research concentrates on the measurement of the power emitted from mobile devices and systems (i.e., base stations and mobile phones), especially in real environments where the presence of attenuation and fading effects can alter power emissions significantly. These studies are increasingly frequent in literature because of the evolution of mobile communication standards (e.g., towards 5G) and the pervasiveness of wireless communication devices in general. In particular, the increasing density of cellular networks-base stations (e.g., from microcells to nanocells) has substantially intensified the RF power collected by the human body. On the other hand, these studies do not analyze the ultimate effect on humans (or animals) delegating this research to other research communities.

The second area of research tries to bridge the gap between RF emissions and health by examining directly the impact of RF emissions on human beings, and animals. Such studies collect and evaluate data on the health status either *actively*, by placing an RF source (i.e., mobile phone) near the subject (e.g., a person) during the experiment, or *passively*, when data is collected by existing RF systems. For example, the health status of employees in an office is monitored. A potential problem with active (where the term active is related to the previous definitions of *actively* and *passively*) studies is that they may create health hazards, which are discovered only later. Another problem is that there is a great variability in RF emission power even from fixed sources unless the signal characteristics and emission power can be controlled (e.g., by using a signal generator). On the other side, many researchers did not rely on a controlled environment but they have investigated the health effects by using commercial cellular networks..

The third area of research is not experimental, but searches for statistical correlations between health data (e.g., appearance of tumors in the population) and network information (e.g., presence of wireless communication networks or systems). Such correlations can be over time (along a number of years) or space (increase of tumors in a specific geographical area). One potential problem with this type of studies is that the emergence of health problems can take many years. In addition, the widespread use of wireless communication systems and networks is relatively recent. Even if such correlations exist, they may not be easy to find given the limited time covered by the study. In addition, other factors (e.g., life-style, diet or pollution) may be overlapping contributing factors that are difficult to isolate. Moreover, a correlation between two sets of data does not necessarily imply a causal relationship.

3.2 Search criteria and limitations of the literature review

The literature review presented in the next section is not meant to be exhaustive but it is rather focused on the identification of the key research gaps and future research directions on the basis of the analysis of the recent literature in the three research areas identified in the section above. Studies, which present similar results to the studies presented in this section, are not reported here.

Interested readers can refer to the following systematic studies for some specific areas:

- For the Relevance to Radiofrequency Radiation and Cancer, please consult [82].
- For the RF EMF exposure in everyday micro environments in Europe, please consult [61]

Not all the sources of radio frequency emissions were considered for this study: only the ones based on cellular networks including the mobile phone emissions.

The adopted search criteria for the publications were based on the search in the scientific databases www.sciencedirect.com, <https://pubmed.ncbi.nlm.nih.gov/> and <https://ieeexplore.ieee.org/Xplore/home.jsp>. for the following keywords with an AND/OR condition: "EMF", "RF-EMF", "health", "radio frequency", "cellular networks", "mobile phone", "mobile communication", "cancer", "tumor", "tumour". For the keywords with similar meaning like tumor and tumour the OR condition was applied instead of the AND condition.

After the initial search, a more detailed analysis of the retrieved studies was performed. In particular, the related work and literature review sections of the studies retrieved from the search above was analyzed to identify further studies of interest. Priority was given to peer-review publications, and publications in journals in the Science Citation Index and the Science Citation Index Expanded. In this preliminary study, priority was also given to human studies rather than animal or in-vitro studies, although some relevant animal and in-vitro studies were also reported.

To summarize, the following exclusion criteria were adopted to filter the studies reported in the initial search and the subsequent detailed analysis:

- Double publication or publication of studies significantly similar (from the results and findings point of view) to already reported studies in this report.
- Studies of speculative nature without scientific and/or experimental evidence. For example, indication of health risks without reporting the exposure values.
- Studies related to RF-EMF but not associated to mobile networks and mobile phones (e.g., exposure from WiFi networks)

3.3 Experimental studies: RF emission power evaluation of wireless communication networks and systems

In this sub-section, we analyse the papers dealing with measurements of RF emission power from wireless communication networks and systems in the field or laboratory.

A recent literature review on the radio frequency exposure due to recent deployment of wireless communication systems is presented in [42]. In turn, this review is an update of an older review related to studies up to 2015.

The review recognizes that mobile-cellular telephone subscription rates increased substantially from 91.7 per 100 inhabitants in 2005 to 118.2 per 100 inhabitants in 2017. The study in [42] reviewed a significant number of recent studies (in this sense, the work is similar to the study carried out by this report) with a specific focus on the reporting of the mean and median (V/m) radiofrequency electromagnetic fields exposure from cellular base stations in indoor, outdoor and transportation environments. We report here the main findings of the study [42]:

- Exposure to EMF was reported mostly higher in urban areas in comparison to rural/suburban areas. In particular, measured RF-EMF exposure levels were considerably higher in city centers. In addition, higher values of EMF were reported to be predominantly downlink in the studies. This

is due to the consideration that the downlink channel in cellular networks has higher emission power than the uplink channel.

- Outdoor RF-EMF exposure levels were higher in outdoor settings rather than indoor settings like private homes and schools.
- RF-EMF exposure is especially higher in transport environments, in particular train and tram stations with levels of 0.5 V/m or higher.
- A comparison of the RF-EMF exposure levels with pre-2012 studies found no major changes for the public transportation system or outdoor environments, with levels remaining below 0.3 V/m in most areas. This conclusion seems counterintuitive to the reported increase of wireless communication networks. On the other hand, the improved efficiency of the networks and the more sophisticated power control could explain this conclusion.
- Considering the great increase in numbers of mobile devices, the study recommended the research community to put more effort into the effects of the mobile devices.

An extensive experimental study on RF-EMF exposure was conducted in [26] where the authors created a lattice map of personal RF-EMF exposure from exterior mobile phone base stations, covering all 110 administrative regions in the city of Albacete (Spain) in 2015. For this purpose, the authors used the Satimo EME Spy 140 personal exposimeter device, making observations at 4s intervals. The conclusions of the paper showed that the collected EMF values never surpassed the international benchmark levels proposed by the ICNIRP [35].

The authors in [69] implemented a number of measurements campaigns on mobile phones to record the EMF in a laboratory in 2013. A test bench was set up to measure the emissions of different mobile phones using an EMR 300 probe, kept stationary while the cradle holding the device under test was positioned in height and distance. The levels of cell phone power density measured in these experiments were orders of magnitude below the FCC MPE limits (see [36] and [37] for the definition of the limits) for the general population. On the other hand, those limits were derived from exposure criteria quantified in terms of SARs for constant exposures and the FCC [38] has reported that laboratory-derived SAR values do not provide sufficient information to compare RF exposure levels between cell phone models under typical usage conditions.

The authors in [59] investigated in 2017 in Spain, the increase of EMF by cellular networks during large events where extra cellular base stations and large numbers of people are present in an urban environment with high concentration of mobile phones. Two Satimo EME SPY 140 personal exposimeters were used to collect EMF values during the Albacete fair. The results show a significant increase in personal RF-EMF exposure compared to that recorded during normal periods in the same area. However, the recorded measurements were still below the ICNIRP 2020 limits [35].

The authors in [67] collected EMF measurements in five cities (Brussels, Antwerp, Ghent, Bruges and Hasselt) in Belgium in a long time span between 2017 and 2019. The measurements were repeated on different days with different population densities and during day and night shifts. The highest average values of 2.63 mW/m² were detected in Brussels. Great variability in the measurements was linked to population density (values during the rush hour were higher than during the non-rush hours). The results were found to be repeatable.

The authors in [57] investigated the EMF impact of 5G technology in a laboratory in 2018. Results showed that 5G technology in high frequency ranges (at 28 GHz) can attain SAR values above the ones recommended by the IARC 2011 guidelines [33]. The authors then proposed a new protocol for 5G, which can limit the SAR values to be within the limits. This study is a good example of the possibility to proactively influence the design of wireless communication systems to limit SAR values and consequently the impact on the human body. The proposed design only reduced wireless communication link throughputs slightly.

Sanjay Sagar et al. [61], [62] conducted two sets of measurement campaigns in Europe and at international level between 2015 and 2017.

The first European study is reported in [61], which reviews the literature on EMF measurements in Europe. The measurements were related to different wireless communication systems and different environments including transportation, indoor and outdoor. Outdoor measurements indicated that higher

EMF levels were observed during the downlink of the base station (a result also shown by other studies in this section). The measured levels were significantly below regulatory limits.

The authors in [62] conducted several measurement campaigns in different microenvironments in Switzerland, Ethiopia, Nepal, South Africa, Australia and the United States of America between 2015 and 2017. The following RF emissions were considered: a) cellular base stations (downlink) and mobile phones uplink. The cellular base stations and mobile phone standards included 2G, 3G and 4G at 900 MHz, 1800 MHz and 2100 MHz frequency bands, b) Wi-Fi at 2.4 GHz and c) broadcasting (FM and TV). The measurement campaign was quite extensive since it was conducted in 94 outdoor microenvironments and 18 public transport vehicles using different measurement equipment (a backpack with antenna and receiver or an antenna mounted on a vehicle). The study demonstrated high EMF variability between 94 selected microenvironments from all over the world with mean values varying from 0.23 V/m to 1.85 V/m, with a clear trend that EMF levels tended to increase in urban environments. Downlink power from the base stations was the most important contribution among broadcasting, WiFi and uplink cellular communications.

The authors in [4] collected data on RF-EMF in kindergarten children in 2015 in Australia, as very young children can be especially vulnerable to potential negative effects of EMF (as highlighted in [4]). The authors conducted measurements in a wide range of frequencies including those used by GSM/UMTS/LTE, DECT and WiMAX systems. The measurements were conducted in indoor and outdoor environments. The highest reported values were of the order of 200/300 mV/m with higher measured power within a range of 300 meters from the base station (which is understandable anyway). EMF due to Wi-Fi was found to be very low compared to mobile phone base station exposure.

A large study on EMF exposure to children was conducted in [6] where personal environmental RF-EMF exposure ($\mu\text{W}/\text{m}^2$, power flux density) was measured in 529 children aged between 8 and 18 years in Denmark, the Netherlands, Slovenia, Switzerland and Spain using personal portable exposure meters for a period of up to three days between 2014 and 2016 and repeated in a subsample of 28 children one year later. The median total EMF exposure was $75 \mu\text{W}/\text{m}^2$ with downlink from the cellular networks as the largest contributor followed by broadcasting systems. Wi-Fi and DECT contributed very little to exposure levels.

The authors in [49] reported the measurements conducted in two European cities (Annecy, France, and Amsterdam, the Netherlands) in 2018 specifically for LTE standards. The study was prompted by the consideration that LTE network deployment can have a high deployment granularity (i.e., pico and femto cells) and that user to base station distances can be smaller than in GSM macro-cells. The measurements were conducted using Android applications on two smartphones (Samsung Galaxy S4 and LG Nexus 5). Two different cells were considered: small cells and macro cells. The results show that LTE small cells may increase cumulatively (by a factor of 7-46) the exposure expressed as RSRP (Reference Signal Received Power) on the downlink channel in comparison to LTE macro cells. On the other side, this may be due to the different distances of the smartphone from the small cells base station and from the macro cell base station. In dense urban areas the density of LTE small cells may increase in comparison to rural environments, which can increase the risks created by EMF exposure especially in the evolution to 5G [49].

An extensive study on the RF-EMF to which citizens are potentially exposed was conducted in Australia by the authors of [70] in 2018. The study focused on the collection of RF signals in the frequency range from 87.5 MHz to 5.8 GHz and 63 Australian adults (aged 18 to 72 years) were involved for a duration of 24 hours. Each adult was equipped with an ExpoM-RF device. Results were compared with the ICNIRP limits. The findings of the authors in [70] show that recorded RF-EMF is within the limits (<1% lower) and in accordance with the ICNIRP limits [34]. The main contribution (i.e., the highest value) was the downlink from cellular network base stations (GSM, UMTS and LTE were considered) followed by broadcast signals and then Wi-Fi. These results are consistent with those mentioned above, where downlink from cellular base stations is predominant.

The study presented in [31] in 2018 aimed to evaluate RF-EMF exposure when the base stations are in the vicinity of living environments in a location in Sweden. In particular, the authors evaluated power levels in apartments located under cellular network base stations installed on the roof of apartment buildings. Results showed that the detected EMF values were quite high (a maximum value of $0.112 \text{ W}/\text{m}^2$) in particular on balconies and in some bedrooms which might be occupied by children. While these EMF

values are still below the ICNIRP's reference levels for exposure in Sweden, they can be near the reference levels in more restrictive countries (see Figure 1). A follow up study in Sweden in 2019 [45] confirmed the previous results and it also showed that that good reception was possible despite limiting EMFs to acceptable levels.

Finding 1: Measurements of RF-EMF from cellular networks indicate that downlink power from mobile base stations is the most significant contribution to overall RF-EMF exposure of humans. There is a general consensus in literature on this finding.

Finding 2: Measurements of RF-EMF indicate that RF-EMF exposure is proportional to density of mobile users or higher cellular network traffic. For example, during major events with a large number of mobile users.

Finding 3: Measurements of RF-EMF indicate that RF-EMF exposure is usually significantly lower than the limits recommended by the regulations.

Finding 4: The results provided in literature for RF-EMF measurements in mobile phone networks are often not consistent. Recent studies recommend the definition of detailed procedures for the collection of RF-EMF measurements. A detailed set of testing scenarios (e.g., generation of specific traffic patterns in the mobile phone) would also be useful for the reproducibility of the results.

Finding 5: Some studies have shown that base stations of cellular networks located on rooftops might generate very high (i.e., at the same level or slightly beyond the regulations limits in the European countries with the most restrictive reference levels, (1% of values reported in Table 2)) levels of RF-EMF exposure in habitation spaces (e.g., apartments, balconies) in proximity of the base stations. The EMF levels depend on the configuration of the base station and the architecture of the building. The risk of high RF-EMF levels must be evaluated case by case.

Table 3 below provides a summary of the references identified in this subsection on the basis of the classification of:

- Field study/laboratory study/simulation: if the study was a simulation or it was conducted in a laboratory or in the field (e.g., realistic environment).
- Base stations/or mobile phones. If the studies were focused on the evaluation of the RM-EMF from mobile phones or base stations or both.
- Review/study. If the paper is a review of a research study.

Table 3 Summary table of the references for experimental studies: RF emission power evaluation of wireless communication networks and systems

Reference Id	Field Study/ Laboratory study/ Simulation	Base stations/ Mobile phones	Review/ Research study
[4]	Field study	Base stations	Research study
[6]	Field study	Base stations	Research study
[26]	Field study	Base stations	Research study
[31]	Field study	Base stations	Research study
[42]	N/A	N/A	Review
[45]	Field study	Base stations	Research study
[49]	Field study	Base stations	Research study

[57]	Simulation	Base stations/mobile phone	Research study
[59]	Field study	Base stations	Research study
[61]	N/A	N/A	Review
[62]	Field study	Base stations	Research study
[67]	Field study	Base stations	Research study
[69]	Laboratory study	Mobile phones	Research study
[70]	Field study	Base stations	Research study

3.4 Experimental studies: evaluation of health effects due to RF emissions

Because of the fact that this section is related to different health effects, the studies taken into account are grouped according to the respective health impact (Columns Health impact and Age category/human/vitro/animals in Table 4). Note that some studies can be classified in more than one category as reported in Table 5. One category is related to Review studies or studies which analyse the impact of RF-EMF for various health effects.

3.4.1 Studies in children

The authors in [27] conducted a study on indoor sources of residential radio frequency electromagnetic fields, personal cell phone and cordless phone use for children (ages 5-6 years) in the Netherlands in 2016. As it was not possible in many cases to survey the subjects under study (i.e., the children) the residential presence of indoor RF sources like cordless phone base stations and Wi-Fi systems was reported by the parents of the subjects under study, while the health evaluation (e.g., evaluation of the potential negative impacts of RF-EMF on cognitive flexibility and visual motor coordination) was assessed using the Amsterdam Neuropsychological Tasks directly on the children themselves. Results of the study showed that RF-EMF exposure from several sources (e.g., mobile phone, base stations) did not show consistent association with cognitive functions in children aged 5-6 years.

3.4.2 Impact on Human-skin

The authors in [3] assessed in 2018 the impact of sub TeraHz communication (400-650 GHz) on the upper skin layer modelled as a helical antenna in the sub-THz band. The authors developed a simulation tool of the human skin, taking into account the skin multi-layer structure together with the helical segment of the sweat duct embedded in it. The results from the model have shown that there is enough evidence from the model that the combination of the helical sweat duct and the wavelengths in the examined frequency approaching the dimensions of skin layers could lead to non-thermal biological effects. The results obtained from the simulation work were verified in series of in vivo experiments conducted on a number of subjects in the band 75-110 GHz.

3.4.3 Impact on Human-cognitive processes

The authors in [12] investigated the impact of RF-EMF on sensory and cognitive processes of adults in 2017 in Australia. The RF-EMF was generated using GSM at 920 MHz with different levels of power. Thirty-six subjects, 18 males and 18 females, aged 18-52 (M = 24.4, SD = 6.3 years), participated in the study. The subjects performed sessions of 30 minutes duration, under different exposure level conditions. Statistical analysis was used to compare the results. EEGs were recorded and visual tests were executed on the subjects to evaluate the impact of RF-EMF. The results did not find effects of RF-EMF exposure on the majority of the tests but a slight impact on a sensory related test. These effects, however, were not

dose dependent and given the number of comparisons made, could be attributed to chance since only 2 out of 56 indicators showed significant differences.

The authors in [71] have reviewed the literature on the impact of EMF from mobile phones on brain functions, which can be evaluated using a number of metrics, e.g. EEG in waking and sleeping conditions, Positron Emission Tomography (PET), performance of brain reactivity, etc. The review concluded that there are still inconsistencies in the methodologies adopted in conducting the experiments, which lead to conflicting results and no clear conclusions among the studies. For example, as reported in the study “determination of the absorbed dose is complex and depends on many external and internal factors, and thus adequate dosimetry measurement tools for evaluation of exposure are critical for quality of study results”. It is also noted that many studies are limited to GSM systems, which are being replaced by new wireless communication systems based on different technical characteristics (e.g., modulation, emission power and so on). It is recommended that new research activities should focus only on new communication standards.

3.4.4 Impact on animals

This category includes studies conducted on animals (e.g., Sprague–Dawley rats) or cells of animals (e.g., Chinese hamster ovary cells) to evaluate health impacts on living organisms.

The authors in [43] have investigated the impact of GSM on Chinese hamster ovary cells, which were exposed to a 900 MHz RF field (GSM) at an average specific absorption rate (SAR) of 2 W/kg for 4, 12 and 24 hours (h) in laboratory conditions in 2017. Cell membrane permeability, cell redox activity, metabolic and mitotic cell death and DNA damages were analysed. No effects were observed in the study but exposure for 24 h caused a statistically significant decrease in clonogenic ability, which prompted the authors to recommend further investigation in this area.

The author in [51] provides a commentary on the partial findings of the two-year study from the National Toxicology Program (NTP) on cell phone radiation in rats and mice exposed to CDMA- or GSM-modulated radiofrequency radiation published in [52]. The study focused on brain malignant gliomas and heart schwannomas. The findings from [52] showed that there was statistical correlation between the exposure to EMFs and the appearance of gliomas and schwannomas (see for a definition of these types of cancer). The results were peer reviewed by medical experts and the majority agreed that the results were reliable and statistically significant. The author in [51] discusses several criticisms, which were published in scientific journals and media on the results from [52]. In particular:

- The criticism that humans are different from rats and the EMF impact on mice may not be correlated with the potential impact on humans. The counterargument by the author in [51] is that mice have been used extensively in the medical sector to anticipate health issue in humans as described in IARC and EPA guidelines.
- The criticism that the results show a low statistical correlation. The counterargument by the author in [51] is that although the statistical correlation may be small, the potential negative health effects would still impact, tens of millions of people, who might be at risk of developing cancers in the huge human population of 7.8 billion persons (reported in November 2020).
- The criticism that EMF exposure levels in the NTP study were much higher (19–75 times) than the human exposure limits. The counterargument by the author in [51] was that some parts of the human brain or the body can be impacted much more than other parts of the body by radio frequency emissions thus reaching higher exposure levels even if the average level is much less.

In a similar context (impact of RF-EMF on rats), the authors in [53] presented the results of the study conducted by the Ramazzini Institute (RI), which performed a life-span carcinogenic study on Sprague–Dawley rats to evaluate the carcinogenic effects of RF-EMF in the situation of far field. The study started in 2005 in Italy and lasted a number of years. The RF-EMF is represented by the environmental exposure to the RF emissions generated by 1.8GHz GSM antenna of the radio base stations. This was one of the largest studies on RF-EMF on rats since the health effects of RF-EMF was evaluated on 2448 animals. The results have shown a statistically significant increase in the incidence of heart Schwannoma in male rats treated at the highest dose (50V/m). In addition, it was noted an increase in other cancer-related

conditions like malignant glial tumors in treated female rats at the highest dose (50V/ m), although this was not statistically significant. The authors of [53] recommend revising the IARC conclusions regarding the carcinogenic potential of RF-EMF in humans based on these results. The results of the large study conducted by the Ramazzini Institute was also evaluated by the authors of [54], which have also indicated statistical correlation for cancer in rats.

3.4.5 Impact on Human-reproductive system

The authors in [2] reviewed the literature with a specific focus on the impact of EMFs on male and female reproductive systems. The review shows that many studies have documented or reproduced results where there is a statistical correlation between EMF exposure and adverse metabolic effects. For example, reactive oxygen species (ROS) generation, which can cause oxidative damage in the target cells in male and female reproductive systems.

3.4.6 Impact on Human-sleep

The authors in [48] have investigated the impact of RF signals from a UMTS test signal generator (GUS6960S) on 22 subjects for a duration of two nights (the experiment was repeated twice). The study was carried out in Sweden in 2018. The subjects were exposed for 3.0 hours to controlled exposure for two consecutive days (19:45–23:00 hours, including 15-minbreak), followed by 7.5 hours of sleep. Quality of sleep was evaluated using different measures like Electroencephalogram (EEG) and surveys distributed to the people under test. The results from the sleep EEG showed no change after the evening RF-EMF exposure compared with sham, but power spectrum analyses showed a reduction of activity within the slow spindle range (11.0–12.75 Hz). This variation did not have an impact on the sleep time investigated in the study but it was assumed that it might have a negative impact on sleep quality in the long term.

Another study, which was conducted in Germany in 2019 [20], investigated the impact of RF-EMF emitted by GSM at 900 MHz and TETRA systems on sleep. Terrestrial Trunked Radio (TETRA) technology uses cellular wireless communication systems for public safety or utility applications. Body worn antennas were developed for this purpose to emulate the RF emissions from GSM and TETRA phones. A distinction between the terms emulate and simulate is made (see in Terminology). 60 young men and 30 elderly men participated in the study. The results do not provide evidence that RF-EMF exposure has negative effects in young and elderly men. The impact of RF-EMF seems to be marginal in young and elderly men.

In the same area of sleep impact, the authors of [32] investigated the impact of RF-EMF exposure in children of 7 years of age in 2011 in the Netherlands. The sleep quality was evaluated with the Child Sleep Habits Questionnaire (CSHQ) filled in by a parent. Taking into account that other studies have highlighted downlink signals as the main contributors to the fields, the study focused on the negative impact of downlink for three mobile network frequency bands (GSM900, GSM1800 and UMTS) and for DECT. Results show that cellular phones had a greater impact than DECT. In addition, sleeping problems in children were reported to be proportional to mobile phone use. On the other hand, the results of the study do not confirm the hypothesis that RF-EMF exposure is detrimental to sleep quality in 7-year-old children, but other factors related to the mobile phone usage may be more relevant.

3.4.7 Reviews and studies related to various health effects

A recent review [46] focuses on the health effects of 5G networks. The review aims to identify gaps or areas, which require further attention. In particular, the authors highlight that previous studies do not often take in consideration the specific characteristics of the more advanced cellular communication standards (e.g., 4G and 5G) because many studies are based on emulated or simulated approaches (see Terminology), which may not be fully representative of realistic scenarios. Another important aspect is that many studies do not take in consideration other potential negative stimuli (e.g., degraded health conditions or pollution), which may have a synergic effect with the RF-EMF. In the conclusions, the authors provide the following recommendations regarding future studies in 5G:

1. The majority of the data in previous studies was obtained under conditions, which do not reflect real-life situations. Future studies should include the information content of the signals, the specific frequencies and modulation used. The data collection scenarios should be based on these parameters derived from practical scenarios.
2. Other toxic stimuli (e.g., pollution) and their impact on possible adverse health effects should also be considered when evaluating RF-EMF emissions.

Regarding the millimetre wave frequency range [6 to 100 GHz], the authors in [81] have reviewed a large number of studies (94), both in vivo and in vitro (even if the majority of the studies were in-vitro), for the impact of RF-EMF on health. A significant number of studies showed the potential effects of the RF-EMF but there was no conclusive evidence that the health impacts were due to non-thermal effects. The available studies do not provide adequate and sufficient information for a meaningful safety assessment or for the question about non-thermal effects. In addition, the authors note the heterogeneity of the study design and the outcomes studied, which is a negative aspect. In particular, at these frequency ranges, the need for stringent temperature control is important (to distinguish between thermal and non-thermal effects) and the authors have noted that this aspect has been often neglected or at least undervalued in many studies. In addition, it is noted that it is important to define a test protocol with exact frequency ranges and power densities.

Another literature review paper took into account studies on the impact of RF-EMFs on humans, animals and micro-bacterial life, in the millimetre wave frequency range (30 to 300 GHz), which will be used by 5G [17]. The review reported a variety of negative effects on the impact of RF-EMF, especially at EHF frequencies in in vitro and animal models. More notably, these negative effects were observed for EMF values below the currently employed ICNIRP standards. The author advocates for a revision of the ICNIRP standards in view of the increased future deployment of 5G networks.

The author in [47] reviewed the status of EMF regulations and their impact on human health noting that the recent increase in the use of wireless mobile communication networks and mobile phones, can increase the risks. The author noted that there are still not completely convincing cases which demonstrate negative health effects. Nevertheless, the author issued a word of caution by reminding that negative health effects of tobacco were also not proven for dozens of years until final general acceptance of the link between tobacco smoking and lung cancer only came about in the late 1960s.

The authors in [7] provide a quite detailed analysis on a key issue concerning the literature on the impact of EMFs: the lack of uniformity among the protocols and configurations adopted to execute the measurements. Another important aspect is related to the limitations of the equipment used to conduct the measurements. In particular, the narrow portion of the RF spectrum analysed in the experiments (e.g., narrowband exposimeters). Other issues are related to the wrong antenna positioning, lack of corrections for near-field / far-field and inadequate calibration of measurement equipment. All these factors can hamper the quality of the results and produce conflictual or partial results. The author recommends the definition of common measurement protocols or the revision of existing ones to evaluate if there are gaps to be addressed. A similar recommendation to define standardized and repeatable protocols for data collection and assessment was also proposed by other authors [50].

The authors in [10] investigated the health effects of long duration phone calls on a large set of participants (more than 500 persons) including male and female subjects. The study, which took place in Korea from 2013 to 2015, did not measure EMF levels and was based on a survey. Results showed that headaches were correlated with long duration phone calls, especially in male subjects. However, it is not clear if the reported effects were due to non-thermal effects (which can be of more risk), thermal effects or just fatigue.

The authors in [68] investigated the correlation of RF-EMF and cancer development with a novel approach to exposure assessment in comparison to the initial approach adopted in 2011 by IARC. The methodology was mostly based on statistical analysis from the reports of a large population (1943 glioma cases, 1862 meningioma cases, and 5387 controls were included in the analysis). As described in [68], "despite the improved quantitative exposure assessment used in this study, the results do not support a positive association between occupational exposure to high-frequency EMF and either glioma or meningioma

risk". Still, the authors recommend the necessity for further research focusing on RF-EMF magnetic fields and tumour promotion, as well as possible interactions with other frequencies and with chemicals.

The authors in [24] investigated the impact of radio frequency emissions from mobile phones on anatomical based models. These models represent the head of a human being of different ages. The results of the evaluation show that localized SAR levels vary significantly for critical components of the brain. Models for younger people absorb proportionally more radiation in the eyes and brain – grey matter, cerebellum and hippocampus—and the local dose rate varies inversely with age. Taking into consideration that the brain develops more quickly in young people, the effect on the development of young human beings could be more severe. The paper concludes that more severe measures should be adopted for mobile phone usage by young people.

Finding 6: Most of the studies did not find significant impact of RF-EMF exposure (in particular from mobile phones) on the health of the human subjects.

Finding 7: Some studies have found negative metabolic activities in in-vitro cultures or mice when exposed to prolonged relatively high levels of RF-EMF, particularly in the millimeter frequency range.

Finding 8: Some studies recommend a review of the protocols for the RF-EMF exposure and the collection and recording of the measurements, which will be consistent to real-life situations and to the characteristics of 5G networks. Many findings are still based on the GSM wireless communication standard which is now 20 years old.

Finding 9: Some studies recommend investigating the correlation between RF-EMF and other potential toxic stimuli, like pollution or dietary habits.

Table 4 below provides a summary of the references identified in this subsection on the basis of the classification of:

1. Field study/laboratory study/simulation: if the study was a simulation or it was conducted in a laboratory or in the field (e.g., realistic environment).
2. Base stations/ mobile phones. If the studies were focused on the evaluation of the RM-EMF from mobile phones or base stations or both.
3. Review/study. If the paper is a review or a research study.
4. What type of health impact was taken in consideration (e.g., sleep impact, oxidation).
5. Specifically focused on an age category (e.g., children, old persons), or if it was conducted on cell cultures (e.g., vitro), animals (e.g., rats) or persons.

Table 4 Experimental studies: Summary table evaluation of health effects due to RF emissions

Reference id	Field study/ laboratory study/ simulation	Base stations/ Mobile phones	Review/study	Health impact	Age category /human /vitro/animals	Duration of the experiment A= order of hours B= order of days C= order of weeks D =order of months or more

[2]	N/A	Both	Review	Reproductive system	Human	N/A
[3]	Simulation and experimental validation	Both	Study	Skin non thermal effect	Human	A
[7]	N/A	Both	Review	All	Human	N/A
[10]	Field Study	Mobile phones	Review	All	Human	N/A
[12]	Laboratory study	Mobile Phones (emulated)	Study	Sensory and cognitive functions	Human	A
[17]	N/A	Both	Review	All	Human	N/A
[20]	Field study	Mobile phones	Study	All	Human	B
[24]	Simulation	Mobile phones	Study	Head	Human	A
[27]	Field study	Base stations	Study	All	Children	A
[32]	Field Study	Both	Study	Sleep	Children	C
[43]	Laboratory study	Both	Study	Impact on cells	Vitro	A
[46]	N/A	Both	Review	All	Human	N/A
[47]	N/A	Both	Review	All	Human	N/A
[48]	Laboratory Study	Mobile phones	Study	Impact on sleep	Human	A
[51]	N/A	Mobile phones	Review	All	Human	N/A
[52]	Field Study	Mobile phone	Study	Cancers	Rats	B and D
[53]	Field Study	Base station	Study	Cancers	Rats	D
[54]	Field Study	Base station	Study	Cancers	Rats	D
[68]	Simulation	Both	Study	All	Human	D
[71]	N/A	Mobile phones	Review	Brain functions	Human	N/A

3.5 Data analysis: correlation between health data and deployment of wireless communication networks and systems

The authors in [56] reviewed the literature on the association of cancers and the usage of mobile phones using different wireless standards. The review analyzed a large number of studies produced in the last 10 years. The conclusion of the study is that EMFs are a probable human carcinogen causing various types of tumors including brain tumor, primary breast cancer and the ones related to fertility and capacity to reproduce. The study underlines that research has been performed on technologies that have already been introduced, but it is very important to perform studies on new, untested technologies prior to their use. In addition, the adoption of precautionary principles is recommended with respect to exposure to EMFs, especially of young human beings.

The authors in [29] performed a literature review, associating emergence of cancers/tumors with the use of mobile phones or digital cordless systems. In particular, the authors compared their previous results [28] with the findings of the Interphone study [39, 40]. The study [29] is quite detailed with many references. However, it is not very recent (2013) and other studies mentioned in the current document are more recent. It is still worth to report some of the conclusions from [29]:

- Even if many studies are not conclusive, there is a consistent pattern of increased risk of glioma and acoustic neuroma associated with mobile and cordless phone usage from [28], [39, 40], indicating that further research is needed.
- Many studies focus on a limited time frame (2-3 years) while emergency of cancer is detected on longer time spans (5-10 years and more).
- Some bias or lack of completeness in the studies was observed. It is important that a uniform protocol will be adopted for future studies to mitigate the risk of bias.

Similar conclusions were also reported in a subsequent study in 2015 [30].

The authors in [44] investigated the association between cellphone technology and brain, central nervous system (CNS) and intracranial tumors. The Israel National Cancer Registry database was analyzed. As reported in [44], “over 26 years (1990-2015) no significant changes in the incidence of malignant brain, Central Nervous Systems (CNS) and intracranial tumors were observed, except for an increase in malignant glioma incidence in Jewish women up to 2008 and Arab men up to 2001, which levelled off in both subgroups thereafter”. In conclusion, the findings do not show in a consistent way a discernable effect of cellphone use patterns in Israel on incidence trends of brain, CNS and intracranial tumors.

Recent studies [13, 58] have shown that the incidence of brain tumors is increasing significantly in recent years. In particular, the authors in [58] note that the percentage rise is similar across the age groups, which suggests that widespread environmental or lifestyle factors may be responsible. The direct correlation with RF emissions is not identified as the main cause and it would require further investigation.

The authors in [15] tried to establish a relationship between the emergence of brain tumors and the use of mobile phones. The methodology was based on Bayesian structural time-series models in which the explanatory variables are functions of time and the parameters are time-varying. The emergence of Glioblastoma Multiforme (GBM) in different brain regions was estimated. The annual incidence of brain cancer in England in the period 1985-2005 was used to create a link to population-level covariates. Bayesian structural time series were used to create 2006-2014 counterfactual trends, and differences with measured newly diagnosed cases were interpreted as causal effects. The results show that an increase in excess of the counterfactuals for GBM were found in the temporal and frontal lobes, which is consistent with hypothesised temporal and spatial mechanisms of mobile phone usage. On the other hand, these results were mostly seen for older age groups, with largest effects in 75+ and 85+ groups, which do not seem associated to the frequent users of mobile phones. The authors concluded that “Although 1985-2014 trends in GBM in the temporal and frontal lobes, and probably cerebellum, seem consistent with mobile phone usage as an important putative factor, age-group specific analyses indicate that it is unlikely that this correlation is causal” (from [15]).

A previous study also investigated the correlation between the emergence of glioma type of cancer with mobile phone usage [16]. The study analyzed annual age standardized incidence rates of glioma in men and women aged 20 to 79 years in the Nordic countries from 1979 to 2008. The study did not find a clear trend change in the incidence of glioma in the adult population of the Nordic countries during this period. In addition, statistical inconsistencies in the results seem to indicate that there are biases and errors in the self-reported use of mobile phones, which would require further investigation.

Finding 10: Many studies reported statistical inconsistencies in the existing data sets especially those based on reported mobile phone usage.

Finding 11: Most if not all the reviewed studies did not report a significant correlation between the emergence of cancers and mobile phone usage.

Finding 12: Many studies reported the issue of the lack of availability of medical data sets with a large time span because the emergence of cancer may appear only on a very long time span (e.g., 10 years and more).

In comparison to the previous summary tables, Table 5 presented in this section provides a different set of summarized information because the scope of this sub-section is focused already on data analysis and correlation between cellular networks deployment and appearance of health problems.

1. Base stations / mobile phones: Whether the study was focused on the evaluation of the RF-EMF from mobile phones or base stations or both.
2. Review/study: Whether the paper is a review or a research study.
3. Type of health impact that was considered.
4. Specifically focused on an age category (e.g., children, old persons), or whether it was conducted on cell cultures (e.g., vitro), animals (e.g., rats) or persons.

Table 5 Data analysis: correlation between health data and deployment of wireless communication networks and systems

Reference id	Base stations/ Mobile phones	Review/study	Health impact	Age category /human /vitro/animals
[15]	Mobile phones	Study	Brain tumor	Human
[16].	Mobile phones	Study	Brain tumor	Human
[29]	Mobile phones	Review	Different types of cancers.	Human
[44]	Both	Study	Brain tumor	Human
[56]	Mobile phones	Review	Different types of cancers.	Human

4 Methodology

Having assessed the relevant literature, it was decided to perform an analysis exploring possible relationships between mobile phone use and brain cancer incidence. Crucial factors for defining the methodology were the dataset collection and the definition of the geographical area. The statistical method used for analysis, depending on the available datasets, was also important for the study. Based on the literature review and the available datasets the statistical analysis developed by de Vocht [14, 15] was adopted. The purpose of the analysis that was carried out was not only to explore a possible relationship between mobile phone use and brain cancer incidence, but also to assess limitations such as uncertainties (e.g. quality of data) that may impact the results of the analysis.

4.1 Datasets

4.1.1 Health data

Health data on cancer were drawn from the European Cancer Information System (ECIS), that is the web application developed and maintained by the JRC.F.1 unit (Health in Society), which provides the latest information on indicators that quantify cancer burden across Europe [77]. ECIS is based on a publicly accessible European database displaying aggregated statistics computed from national or regional population-based cancer registries records⁶. For more information about the collection of the data refer to [77]. The geographic granularity in the ECIS archive varies by country (national or regional registries), and the time coverage varies by registry: at the time it was accessed (November 2020), ECIS reported based on the 2015 enquiry to the registries, and therefore mostly includes time series from the 1980s to 2012, and also some covering a larger time span (from the late 70s until 2014). ECIS includes indicators of cancer incidence, mortality and survival for various cancer site definition detailing nearly 60 types of cancer, including brain and central nervous system (CNS). These indicators, available by geographical detail, can be also grouped by age and sex. Figure 2 depicts an example of the data that can be acquired from the ECIS database:

⁶ <https://ecis.jrc.ec.europa.eu/>

Incidence and mortality statistics, by registry and cancer site Share this view

Country/Registry: IT Varese | Sex: Both sexes | Cancer: Brain and other CNS | Age: All ages | Year: All years | Indicator: Incidence

Years	Number	Crude rate	ASR (W)	ASR (E Old)	ASR (E New)	Cumulative Risk
1978	45	5.8	4.9	5.9	6.7	0.6
1979	34	4.3	3.4	4.3	5.2	0.5
1980	51	6.5	5.5	6.5	7.3	0.6
1981	51	6.5	5.6	6.6	7.8	0.7
1982	53	6.7	5.4	6.7	8.2	0.8
1983	48	6.1	5.2	6.2	7.6	0.6
1984	53	6.7	5.6	6.5	7.5	0.7
1985	55	7.0	5.6	6.7	7.8	0.7
1986	39	5.0	3.7	4.8	6.0	0.6
1987	57	7.3	5.8	7.0	8.3	0.8
1988	51	6.5	5.1	6.0	7.1	0.7
1989	54	6.8	5.0	6.4	7.7	0.7
1990	51	6.4	4.2	5.7	7.0	0.6
1991	54	6.8	5.2	6.1	7.5	0.7
1992	67	8.4	6.0	7.5	9.3	0.8
1993	75	9.4	7.9	8.8	10.6	1.0
1994	63	7.9	5.5	6.8	9.0	0.8
1995	71	8.9	6.5	7.8	9.7	0.9
1996	84	10.5	6.8	8.7	11.2	1.1
1997	60	7.5	4.8	6.1	8.2	0.8
1998	77	9.6	5.7	7.6	10.1	0.9
1999	73	9.1	6.4	7.9	9.5	0.8
2000	76	9.4	5.8	7.6	9.7	0.9
2001	89	11.0	6.9	8.7	11.4	1.0
2002	70	8.6	5.1	6.4	8.8	0.8
2003	75	9.2	5.9	7.3	9.3	0.9
2004	86	10.4	6.2	7.8	10.4	1.0
2005	75	9.0	5.5	7.0	8.9	0.8
2006	84	10.0	6.3	7.7	9.9	0.9
2007	78	9.2	6.1	7.3	9.1	0.8
2008	66	7.7	4.8	6.0	7.5	0.7
2009	89	10.3	6.7	8.3	10.2	0.9
2010	89	10.3	5.6	7.3	9.8	0.9
2011	91	10.5	5.8	7.8	10.1	0.9
2012	89	10.2	5.8	7.2	9.6	0.9

Figure 2 Example of data extraction from the ECIS archive (time series of incidence and mortality statistics).

For this specific assessment and as explained in section 4.1.3, data were extracted for Austria and Denmark for the incidence of brain and other CNS cancer (C70-72 in ICD-10 excluding 9050-9055, 9140, 9590-9992). The total incidence for these types of cancer is shown in the following graphs (Figure 3, Figure 5). Figure 4 and Figure 6 show the cumulative risk of all types of cancer for the two countries respectively.

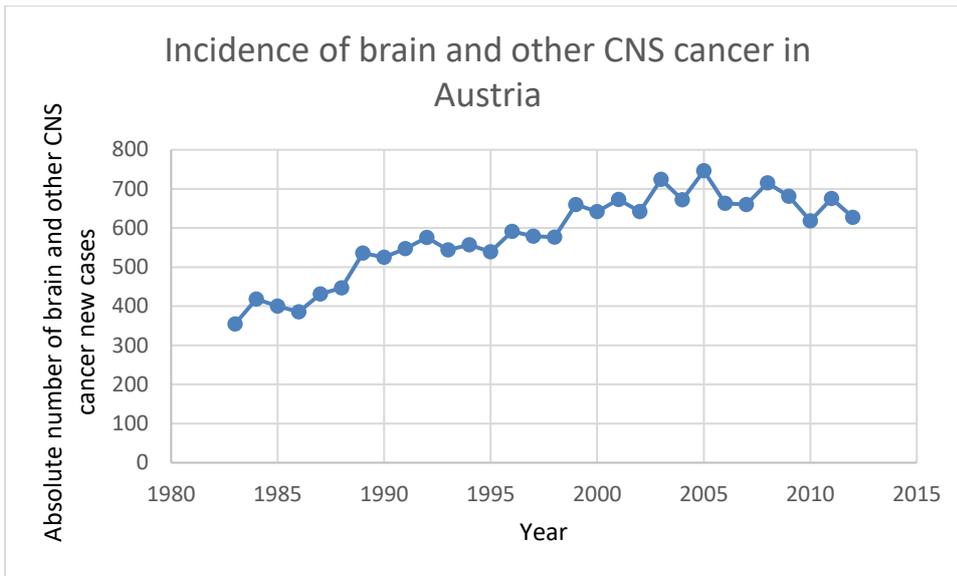


Figure 3 Incidence of brain and other CNS cancer in Austria (all age groups – both sexes – years 1983-2012).

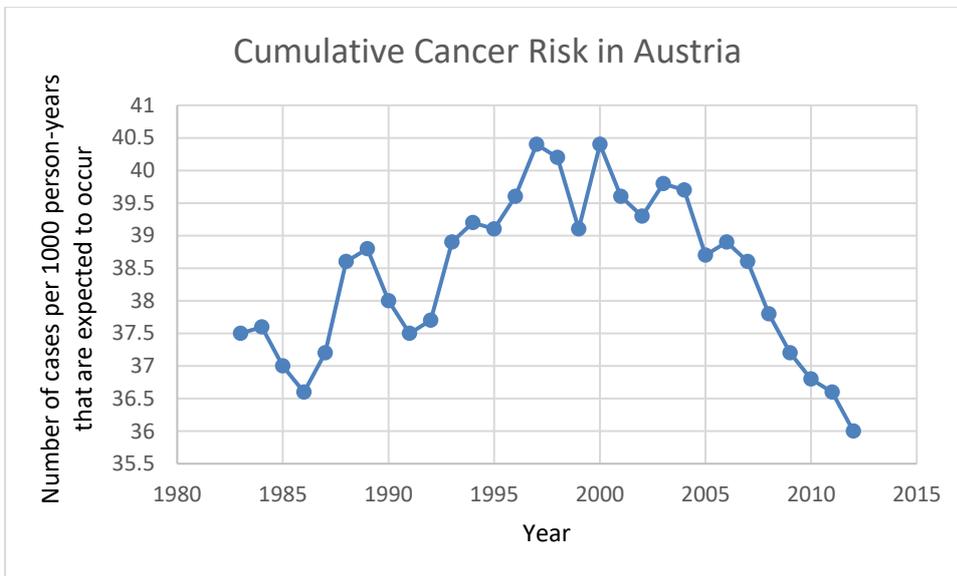


Figure 4 Cumulative risk of all types of cancers in Austria (all age groups – both sexes – years 1983-2012).

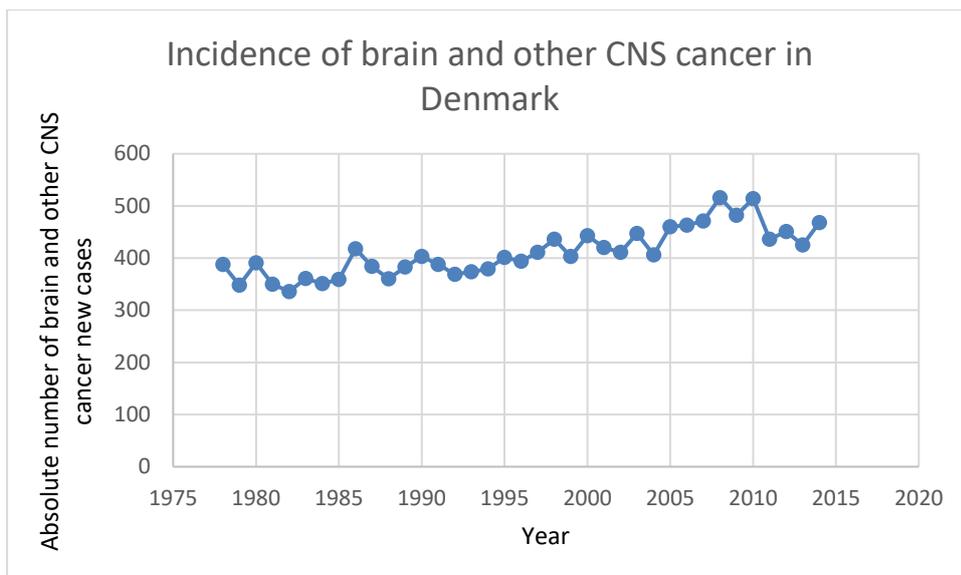


Figure 5 Incidence of brain and other CNS cancer in Denmark (all age groups – both sexes – years 1978-2014).

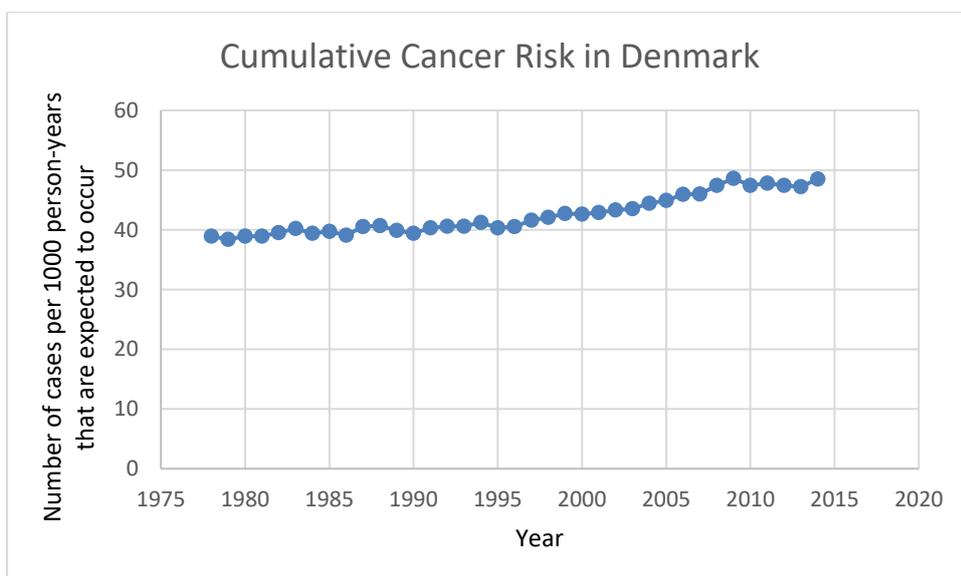


Figure 6 Cumulative risk of all types of cancers in Denmark (all age groups – both sexes – years 1978-2014).

Data was also grouped by ages. The following figures (Figure 7, Figure 8) display those data for Austria (time series from 1982-2012) and Denmark (time series from 1978-2014).

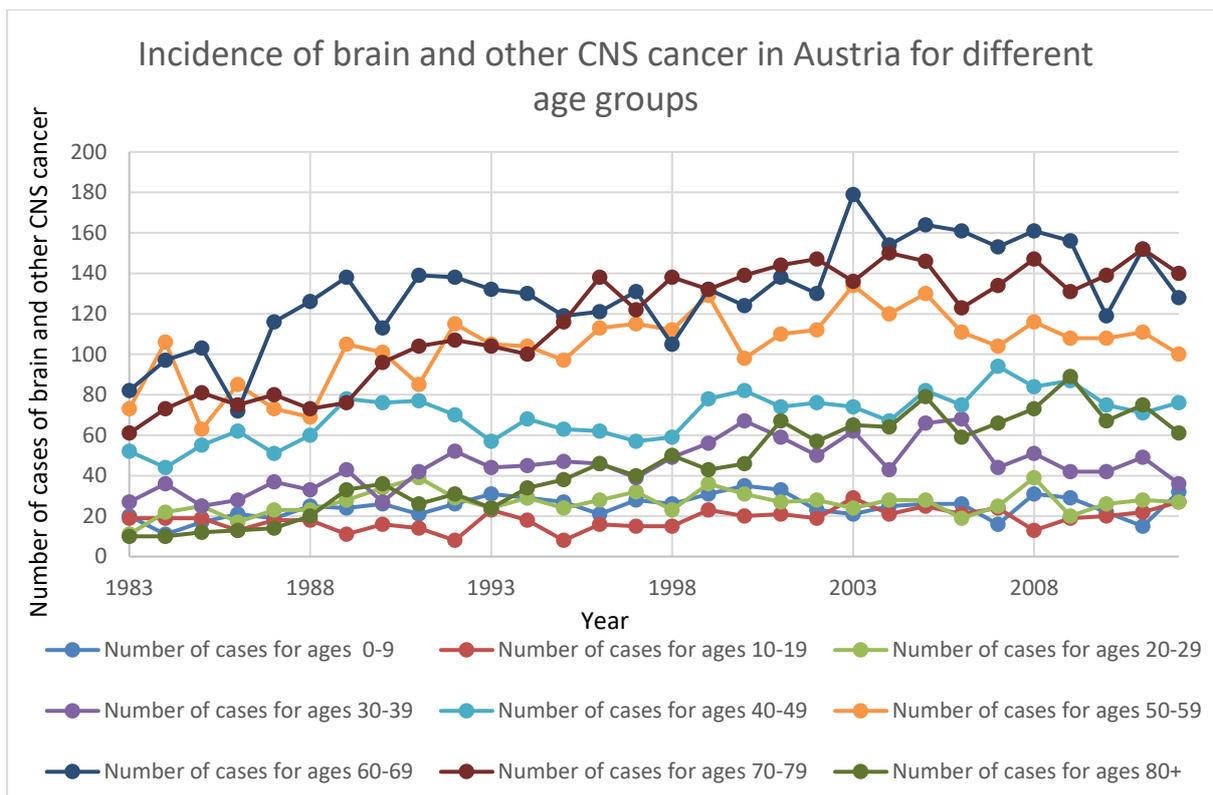


Figure 7 Incidence of brain and other CNS cancers in Austria for different age groups for the time period 1983-2012.

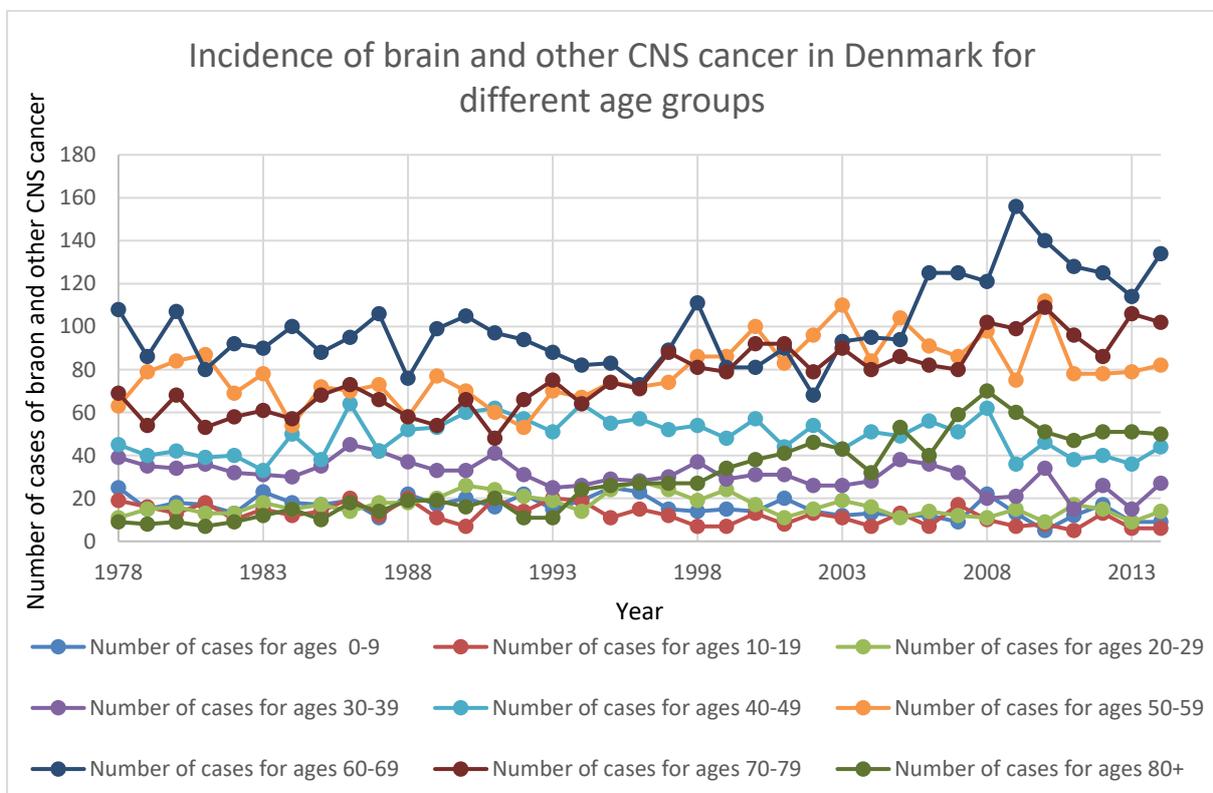


Figure 8 Incidence of brain and other CNS cancers in Denmark for different age groups for the time period 1978-2014.

4.1.2 Mobile network data

For mobile-network related data, the publicly available ITU-ICTEye database⁷ was used. It contains market and subscription data on a national and continental level. Figure 9 and Figure 10 show the number of mobile phone subscriptions, both prepaid and postpaid, for Austria and Denmark.

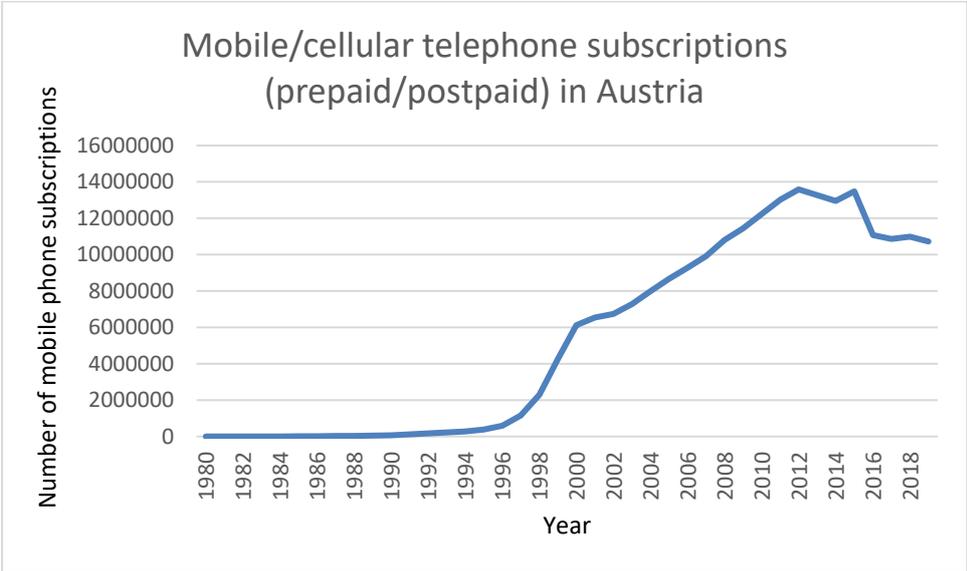


Figure 9 Mobile/cellular telephone subscriptions (prepaid and postpaid) in Austria (source ITU ICT-Eye).

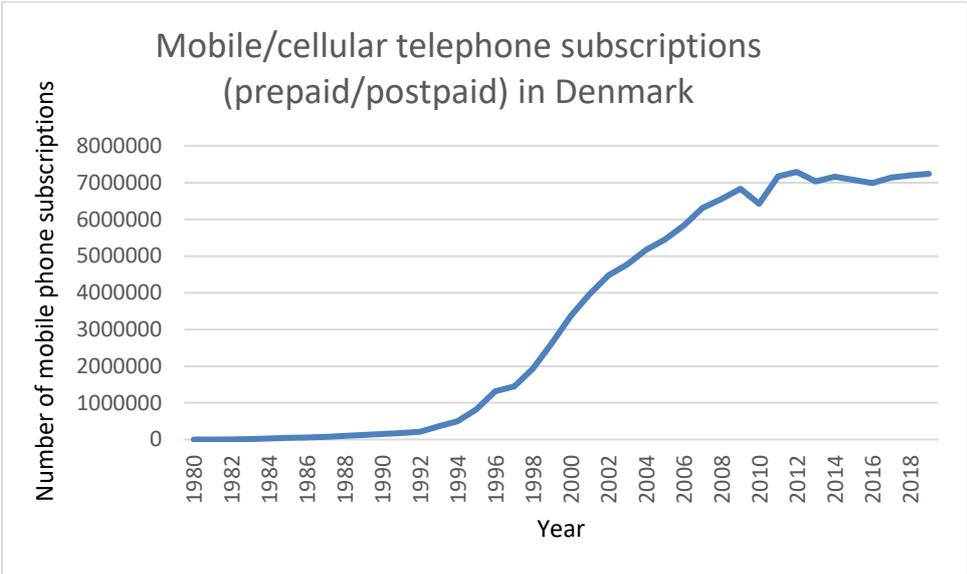


Figure 10 Mobile/cellular telephone subscriptions (prepaid and postpaid) in Austria (source ITU ICT-Eye).

4.1.3 Definition of the area under study

A general consideration for conducting this assessment was to find a region, including a major city, with a constant standard of living over the last thirty years so that other factors relating to health issues could be excluded. Since it is not possible to find a region where the standard of living has not altered over the last thirty years, we decided to include in the analysis factors that indicate the standard of living.

⁷ <https://www.itu.int/net4/ITU-D/icteye/#/>

Another limitation for selecting a region under study is that cancer incidence data are national for most countries. This excludes the possibility of selecting a major city. There are some countries in which registries operate on a regional level (e.g. Italy, France, Germany), but as mobile phone use data are also collected on a national basis we decided that the region under study should be a country, excluding the countries whose registries are regional.

Based on the availability of both cancer incidence and mobile phone use data, Austria and Denmark were selected for study in this assessment. For these two countries cancer incidence data cover a satisfactory time span on a national level.

4.1.4 Other data

To include more covariates in the analysis to make it as objective as possible, data from the World Bank were also used⁸. World Bank contains time series for various indicators for all countries from 1960 and on. Data sets used were country population growth, percentage of the urban population and Gross Domestic Product (GDP) per capita (per person) (Figure 13 and Figure 14).

4.2 Statistical Methodology

To assess the impact of mobile phone use on annual incidence of brain cancers, the causal impact method combined with Bayesian structural time series models was used [14, 15]. The time series from the 1980s up to an a priori specified point in time is modelled using other time series of covariates that may be correlated with the annual number of newly registered cases. The above mentioned specified time point refers to some intervention or an event expected to change the time series. In the analysis, this time point is assumed to be the time point at which, if mobile phone use was associated with increased brain cancer risk, this would be measurable in population-level data.

In terms of numbers, we assumed that this time point would be the point at which 15% of the population owned a mobile phone subscription that is the year 1997 for Austria and 1995 for Denmark.

Assuming that the relationship between the time series of the annual number of new cases and the time series of covariates that existed prior to the specified year remains constant in the period thereafter, the counterfactual “post-intervention” trend for the incidence of cancer is estimated from the time trends in the measured covariates by constructing a synthetic country model that describes what would have happened if the intervention had not taken place, that is, if mobile phones had not been introduced. The impact of mobile phone use can then be estimated by comparing the counterfactual time series with the measured annual number of registered new cases in the period from the intervention to the year of interest, according to the available data [1].

In order to apply this methodology to the data we used the *CausalImpact* package in R (Brodersen et al. 2015) [8]. Instead of using the default model constructed by the *CausalImpact* package, we also used the *bsts* package in R to specify our own model, based on Bayesian structural time series [65]. This provides a greater degree of flexibility since we can decide whether to add trend, seasonality or regression in the model, depending on the data.

For our analysis, we built a model using trend and regression since the data on cancer are annual and therefore do not display seasonal characteristics.

The regression component was based on a set of external covariates that contribute to the prediction, using Bayesian “spike and slab” priors to estimate the effect size of each covariate in each MCMC iteration (Markov Chain Monte Carlo). These priors are placed on the regression coefficients to enable selection of predictors. The “spike” determines the probability of a non-zero coefficient based on independent Bernoulli distributions and the “slab” is a weakly informative Gaussian prior with large variance (8, 64).

Prior probability of inclusion of each covariate was set at 0.5 and the prior degrees of freedom were set to the number of years of modelling minus 1. Expected model size was set to 4 and the prior expected explained variance to 77%. For all analysis 100,000 MCMC iterations were made.

Statistical significance level was set at 0.05.

⁸ <https://data.worldbank.org/indicator>

As brain tumors appear after some years, latencies of 5, 10 and 15 years (where possible) were used to assess whether mobile phone use at a certain time period might have an impact after 5, 10 and 15 years.

After implementing this methodology for the incidence of brain and other CNS cancers for all ages and since there seems to be an increase in absolute numbers in brain cancer incidence for ages above 50 years old in both countries (shown in Figure 7 and Figure 8), it was decided to also assess a possible impact of EMFs on the 50-59 and 60-69 age groups. In the analysis, instead of using population growth as a covariate, we used the total population of the specific age group for the respective time period. The other covariates remained the same.

5 Dataset analysis and Results

5.1 Dataset Analysis

The incidence of brain and other CNS cancer versus the percentage of the population having a mobile subscription (prepaid or postpaid is shown in the following figures for Austria and Denmark (Figure 11, Figure 12).

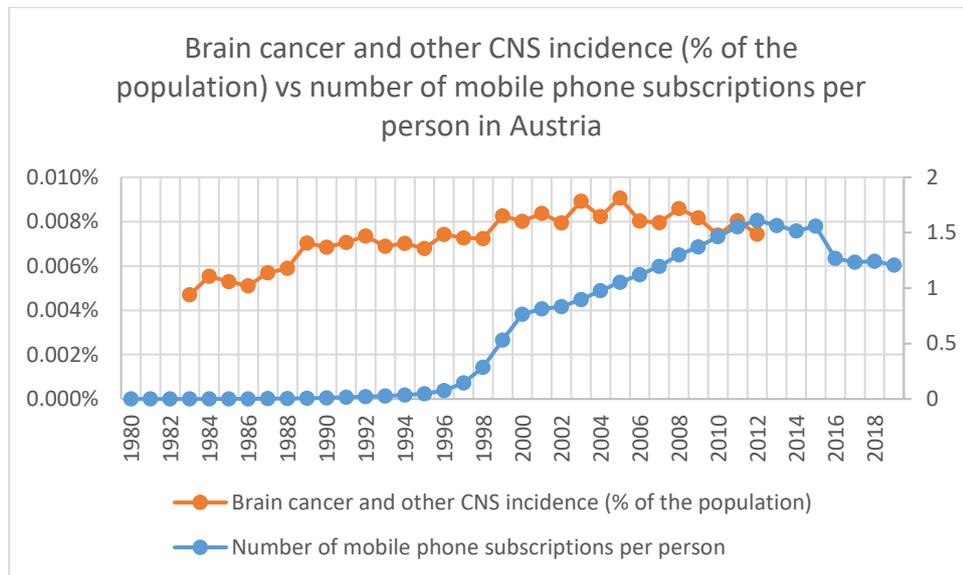


Figure 11 Temporal trend in incidence of brain and other CNS cancer (% of the population) vs number of mobile phone subscriptions per person in Austria.

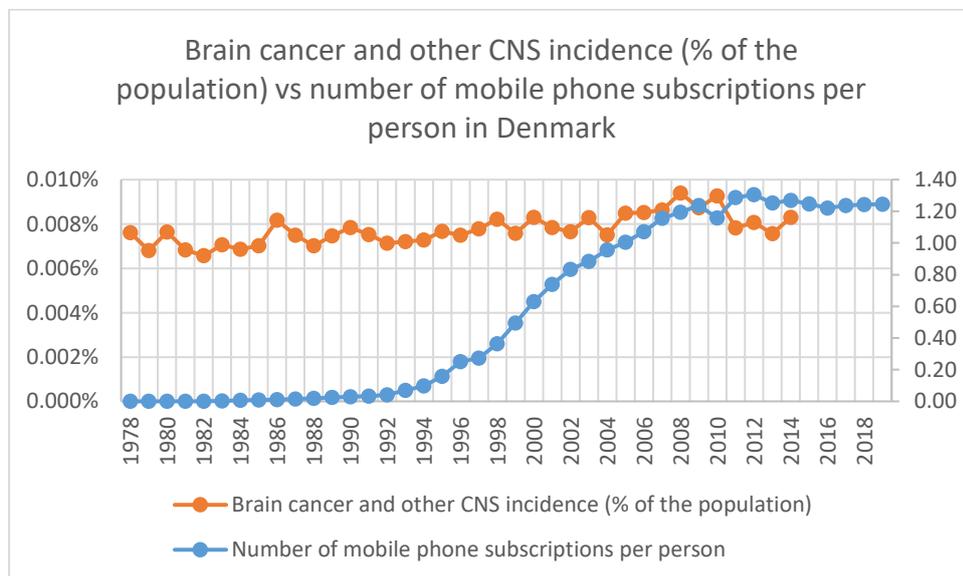


Figure 12 Temporal trend in incidence of brain and other CNS cancer (% of the population) vs number of mobile phone subscriptions per person in Denmark.

The temporal trends of the covariates selected for the assessment (population growth, percentage of population living in urban environments, growth per capita in thousands) and the cumulative risk of the incidence of all cancer types) are shown below for the two countries (Figure 13 and Figure 14). The cumulative risk of the incidence of all types of cancers (which was also used as a covariate for the modelling) was shown in the previous section (Figure 4 and Figure 6).

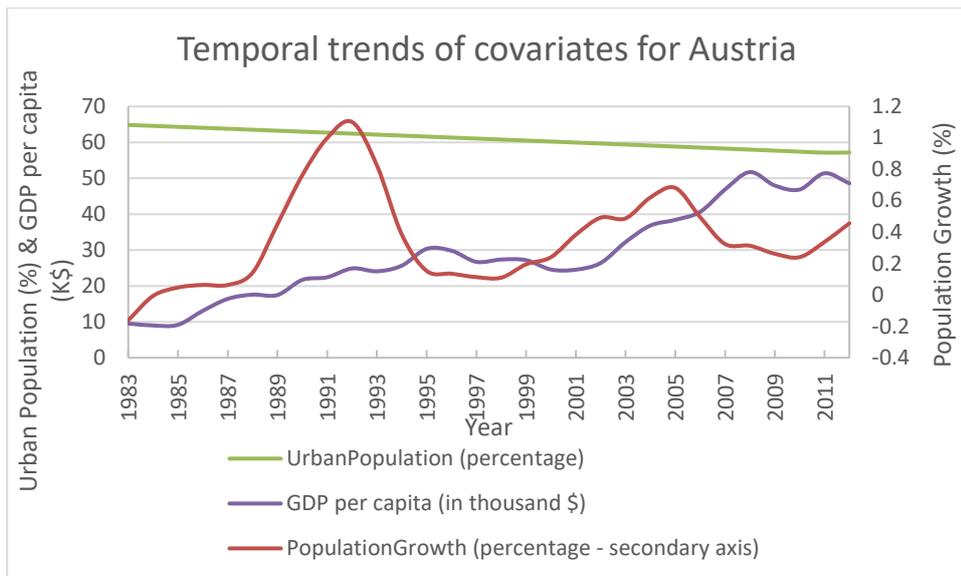


Figure 13 Percentage of population growth, percentage of urban population and GDP per capita in Austria for the years 1983-2012.

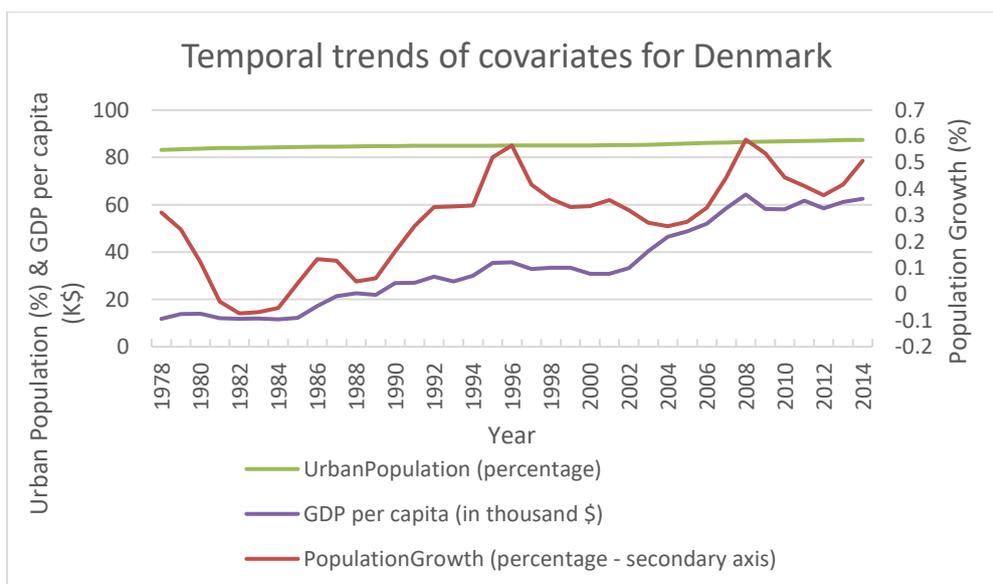


Figure 14 Percentage of population growth, percentage of urban population and GDP per capita in Denmark for the years 1978-2014.

After observing the time series of the data, the statistical analysis, as described in Section 4.3 was performed in R.

Results for Austria and Denmark are presented in Table 6, Table 7 and Figure 15 respectively for all ages. For Austria implied latency periods of 0, 5 and 10 years were implemented, while for Denmark 0, 5, 10 and 15 years.

Regarding the tables, the results of the analysis are presented in terms of absolute average effect (95% Confidence Interval (CI)), absolute cumulative effect (95% CI), relative effect (95% CI) and posterior probability of effect. The absolute average effect is the difference between the average value of the actual time series and the predicted ones for the post-intervention period. The absolute cumulative effect is the difference of the sum of the individual observations of the actual time series and the sum of the individual observations of the predicted ones for the post-intervention period. In relative terms, the relative effect shows the percentage of decrease or increase of the response variable in the post-intervention period, i.e. the number of brain and other CNS cancers after 0, 5, 10 or 15 years of the point at which 15% of the

population owned a mobile phone subscription. The posterior probability of effect indicates whether the observed behaviour is statistically significant ($p\text{-value}\leq 0.05$) or simply occurred by chance ($p\text{-value}>0.05$).

The figures of the results in R have three panels. The first panel (original) shows the data and a counterfactual prediction for the post-intervention period. The second panel (pointwise) shows the difference between the observed data and the counterfactual predictions. The third panel (cumulative) adds up the pointwise contributions from the second panel, resulting in a plot of the cumulative effect of the intervention.

Table 6 Inferred impact of mobile phone use on annual incidence of brain and other CNS cancer (for all ages) in Austria.

Implied lag (from 1997)	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0 years	86 (-86,253)	1377 (-1379,4041)	15% (-15%, 44%)	0.136
5 years	17 (-134, 160)	186 (-1474, 1765)	2.6% (-20%, 24%)	0.393
10 years	-25 (-146, 98)	-148 (-875, 589)	-3.6% (-21%, 14%)	0.336

Table 7 Inferred impact of mobile phone use on annual incidence of brain and other CNS cancer (for all ages) in Denmark.

Implied lag (from 1995)	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0 years	57 (-4.9, 124)	1132 (-97.6, 2481)	15% (-1.3%, 32%)	0.030
5 years	40 (-31, 107)	597 (-462, 1609)	9.6% (-7.4%, 26%)	0.100
10 years	43 (-7, 98)	434 (-70, 981)	10% (-1.6%, 23%)	0.041
15 years	-23 (-72, 22)	-144 (-358, 112)	-4.7% (-15%, 4.6%)	0.159

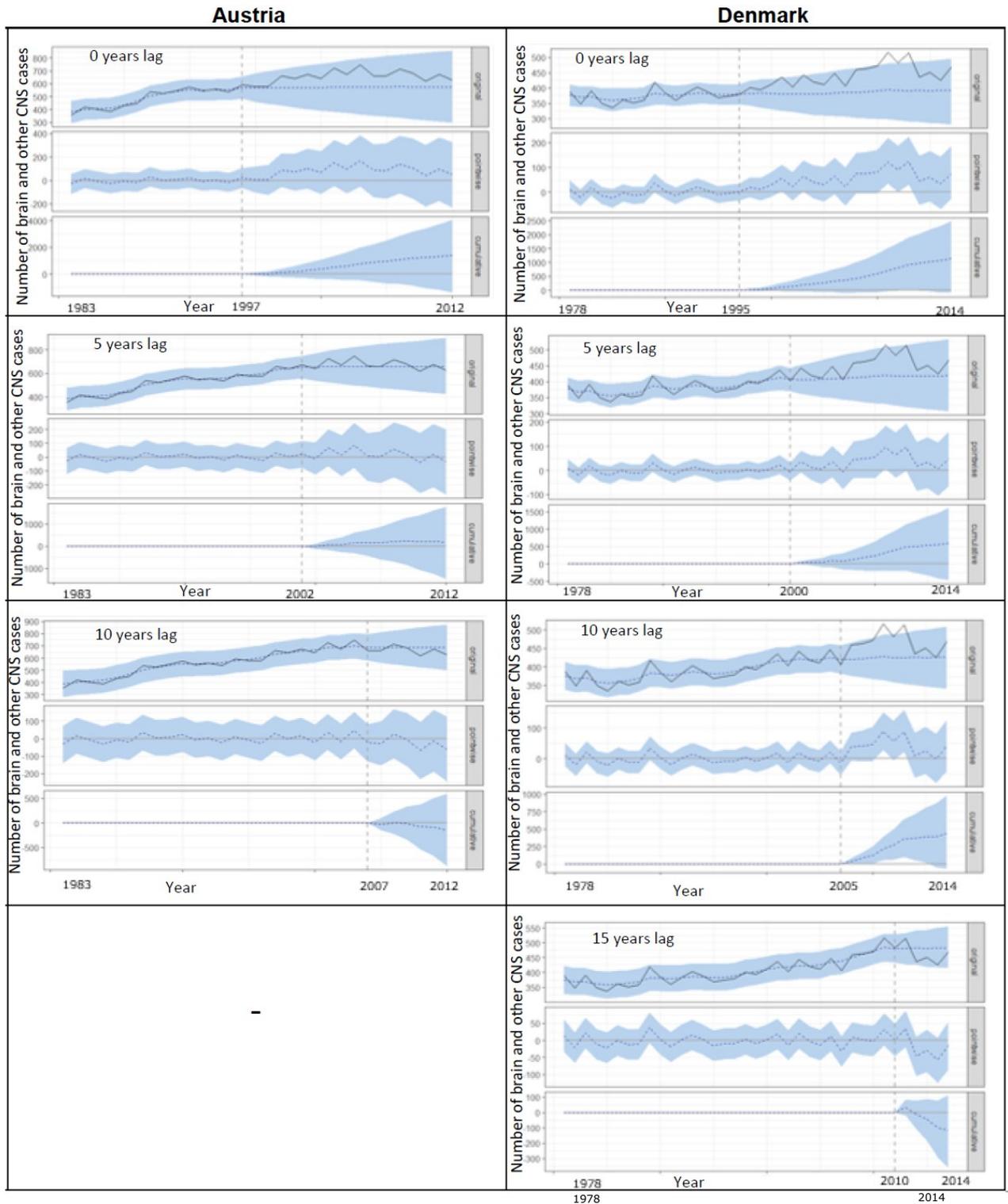


Figure 15 Actual (solid line) and modelled (dashed line) incidence trends for brain and other CNS tumors for all ages in Austria and Denmark for implied latency periods of 0, 5, 10 and 15 years (where applicable) from 1997 (Austria) and 1995 (Denmark) (first panel – original). The second and third panel show the pointwise and cumulative effect respectively. Blue lines correspond to 95% confidence intervals.

Inclusion probabilities of the covariates, indicating the extent to which they contribute to the prediction, are shown in Table 8 and Table 9 and vary between models. Prediction errors had an average value of 18.86% in the case of Austria and 10.08% in the case of Denmark.

Table 8 Inclusion probabilities of the covariates for Austria.

Covariate	Implied latency 0 years	Implied latency 5 years	Implied latency 10 years
Population Growth	52.86%	53.44%	54.11%
Urbanization Rate	48.12%	48.16%	48.39%
Growth per capita	54.25%	53.71%	56.11%
Cumulative Risk of Cancer Incidence	50.13%	50.53%	50.45%

Table 9 Inclusion probabilities of the covariates for Denmark

Covariate	Implied latency 0 years	Implied latency 5 years	Implied latency 10 years	Implied latency 15 years
Population Growth	54.31%	52.60%	51.15%	52.24%
Urbanization Rate	0.62%	6.66%	6.73%	22.19%
Growth per capita	58.53%	59.47%	54.53%	80.80%
Cumulative Risk of cancer incidence	19.33%	27.05%	30.66%	42.51%

The same analysis was performed for two different age groups for both countries. The age groups 50–59 and 60–69 were selected for the analysis because their respective time series showed that the incidence of cancer was increased in those age groups. Results for Austria are presented in Table 10 for the age group 50–59 and in Table 11 for the age group 60–69. Results for Denmark are displayed in Table 12 for the age group 50–59 and in Table 13 for the age group 60–69.

Table 10 Inferred impact of mobile phone use on annual incidence of brain and other CNS cancer (ages 50–59) in Austria.

Implied lag (from 1997)	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0 years	6.3 (–30, 37)	101.1 (–476, 588)	5.9% (–28%, 34%)	0.248
5 years	–2.1% (–33, 31)	–22.9 (–361, 340)	–1.8% (–28%, 27%)	0.418
10 years	–17 (–40, 9.4)	–104 (–238, 56.6)	–14% (–32%, 7.5%)	0.079

Table 11 Inferred impact of mobile phone use on annual incidence of brain and other CNS cancer (ages 60-69) in Austria.

Implied lag (from 1997)	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0 years	16 (-36, 72)	250 (-570, 1150)	12% (-28%, 56%)	0.225
5 years	9.6 (-28, 48)	105.3 (-313, 531)	6.8% (-20%, 34%)	0.247
10 years	-19 (-57, 19)	-112 (-339, 113)	-11% (-35%, 12%)	0.149

Table 12 Inferred impact of mobile phone use on annual incidence of brain and other CNS cancer (ages 50-59) in Denmark.

Implied lag (from 1995)	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0 years	18 (-18, 51)	351 (-360, 1017)	25% (-26%, 73%)	0.118
5 years	3.3 (-32, 36)	49.5 (-482, 544)	3.8% (-37%, 42%)	0.405
10 years	-7 (-36, 23)	-70 (-362, 232)	-7.4% (-38%, 24%)	0.302
15 years	1.6 (-19, 25)	7.8 (-97, 124)	1.8% (-23%, 29%)	0.457

Table 13 Inferred impact of mobile phone use on annual incidence of brain and other CNS cancer (ages 60-69) in Denmark.

Implied lag (from 1995)	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0 years	14 (-8.7, 43)	273 (-174.8, 854)	15% (-9.4%, 46%)	0.061
5 years	21 (-6.7, 50)	315 (-101.2, 748)	23% (-7.4%, 54%)	0.044
10 years	34 (4, 57)	337 (40, 570)	37% (4.4%, 62%)	0.016
15 years	-13 (-47, 17)	-64 (-237, 87)	-9% (-34%, 12%)	0.215

Figure 16 and Figure 17 illustrate the actual and modelled incidence of brain and other CNS tumours for age groups 50-59 and 60-69 for Austria and Denmark respectively for implied latency periods of 0, 5, 10 and 15 (where applicable) years. Blue lines indicate 95% confidence intervals.

Austria

Age group 50-59

Age group 60-69

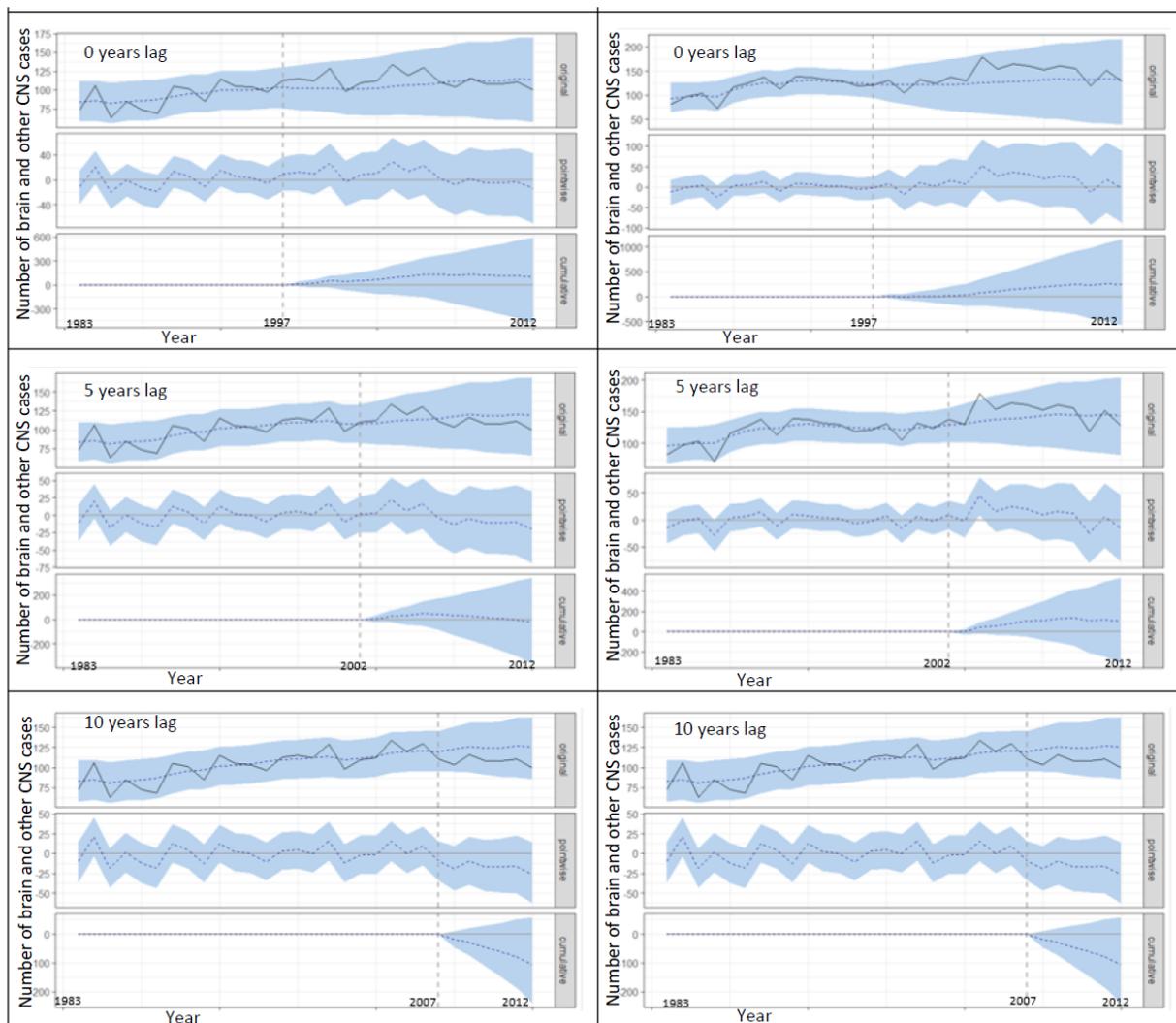


Figure 16 Actual (solid line) and modelled (dashed line) incidence trends for brain and other CNS tumours for ages 50-59 years and 60-69 years in Austria for implied latency periods of 0, 5 and 10 years. (first panel – original). The second and third panel show the pointwise and cumulative effect respectively. Blue lines correspond to 95% confidence intervals.

Denmark

Age group 50-59

Age group 60-69

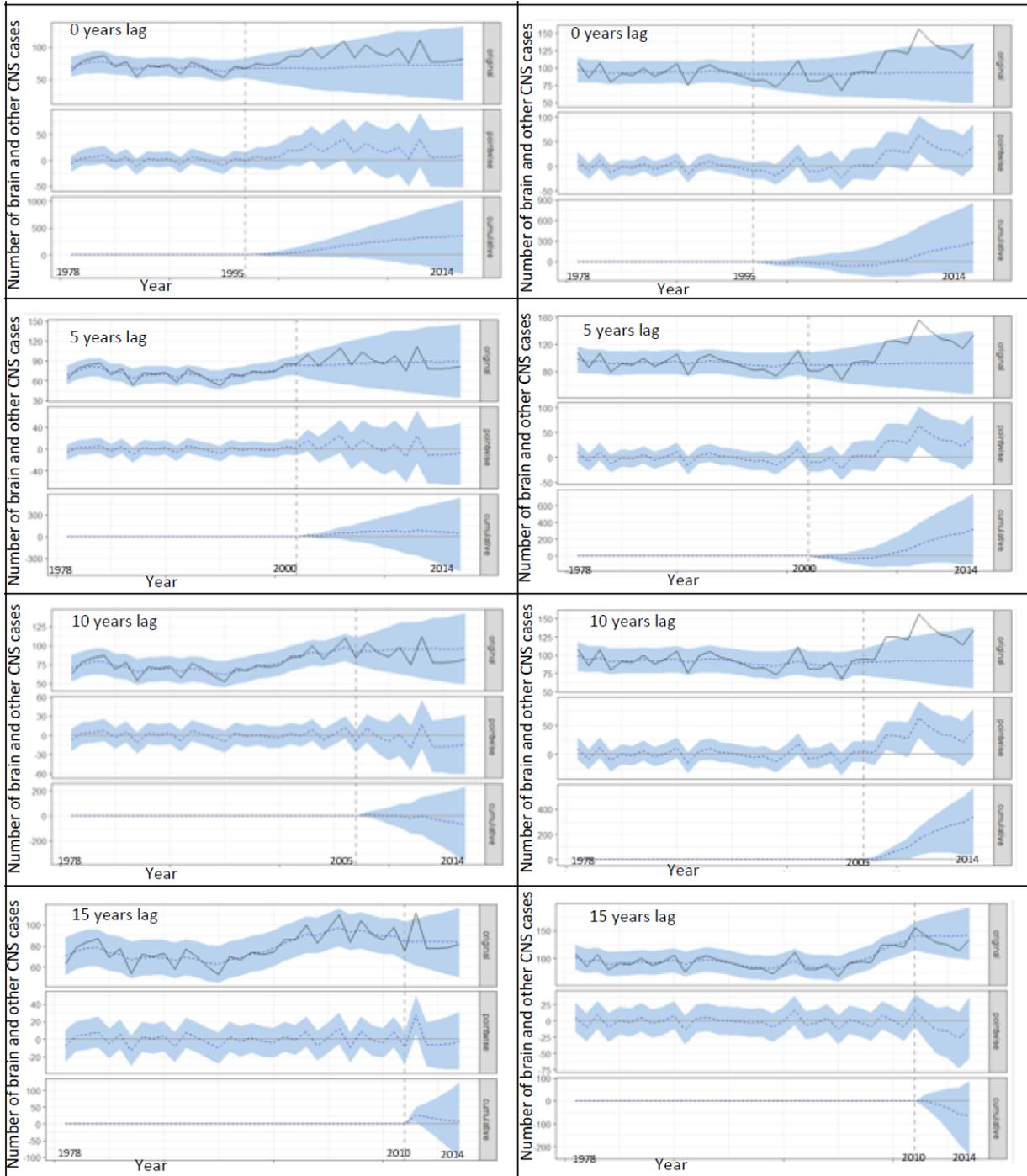


Figure 17 Actual (solid line) and modelled (dashed line) incidence trends for brain and other CNS tumors for ages 50-59 years and 60-69 years in Denmark for implied latency periods of 0, 5, 10 and 15 years. (first panel – original). The second and third panel show the pointwise and cumulative effect respectively. Blue lines correspond to 95% confidence intervals.

5.2 Results

Inspection of Figure 11 shows that in Austria brain and other CNS cancer incidence increases from 1983 to 2005 except for the years 1986 and 1993–1995 when newly registered cases were decreasing. After 2005 the number of brain cancer incidence seems to be decreasing or to be stable.

Figure 12 shows that in Denmark the incidence of brain and other CNS cancer is stable or slightly increasing from 1978–1995. After that period there is a small trend towards higher numbers, which peaked in the years 2008–2010.

The temporal trends of the covariates are shown in Figure 13 for Austria and Figure 14 for Denmark.

Population in Austria was slightly decreasing until the year 1984. From 1985 to 2019 the population was increasing (positive rate) by rates from 0.047% in 1985 to 1.1% in 1992.

In Denmark the total population was increasing except for the years 1981–1984. The growth rate varied from 0.04% in 1985 to 0.59% in 2008.

The growth per capita displays an increasing trend for both countries, while the percentage of urban population has a decreasing trend in the case of Austria and a slightly increasing trend in the case of Denmark.

Table 6 shows the results of the Bayesian modelling for brain and other CNS cancers for all age groups of the population in Austria for latency periods of 0, 5 and 10 years for Austria.

Table 10 and Table 11 show the results obtained from the Bayesian analysis for Austria for the age groups 50–59 and 60–69 for all the implied latency periods.

From the current analysis there is no evidence of an increase in the incidence of brain and other CNS cancers that was not predicted in the counterfactual synthetic time series for Austria regardless of the latency periods. Moreover, as far as Austria is concerned, the point estimates for the size of the effect are negative for implied latency periods of 10 years (for the selected age groups and for all the age groups), meaning that based on the counterfactual time series higher annual cancer incidences were expected.

Table 7 presents the results of the Bayesian modelling for brain and other CNS cancers for all age groups of the population in Denmark for latency periods of 0, 5, 10 and 15 years. Results indicate that there is a statistical significant increase in the incidence of brain and other CNS cancer that was not predicted in the counterfactual synthetic time series when applying no latency and when there was a latency period of 10 years. For the population belonging to the age group of 50–59 years there is no evidence of an increase in the incidence of brain and other CNS cancers that was not predicted in the counterfactual synthetic time series for all the implied latencies. Population of the age group 60–69 years displayed statistical significant increase in the incidence of brain cancers when implied latencies of 5 and 10 years were applied (Table 12, Table 13).

To further analyze this finding and since no statistical differences were found between the observed and the counterfactual time series for the age groups 50–59 years and 60–69 years when no latency was applied all age groups were studied when no lag was applied. Results are given in Table 14. As revealed by the results statistical significant increase in the incidence of brain and other CNS cancer was observed for the population over 70 years (70–79 and 80+ age groups). This increase cannot be attributed to mobile phone use since those people would most probably not be the early adopters of the mobile telephony technology. Moreover, a statistical significant decrease in brain cancer incidence was found for the population under 19 years old (relative effect of -22% for ages 0–19 and -40% for ages 10–19) and for the population belonging to the group 40–49 years old (relative effect of -28%).

Table 14 Inferred impact of mobile phone use (and all wireless technology) on annual incidence of brain and other CNS cancer for all age groups in Denmark when no latency was implied.

Age Group	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0-9	-4 (-9.9, 1.9)	-80 (-197.9, 38.7)	-22% (-54%, 11%)	0.043
10-19	-6.5 (-17, -0.19)	-129 (-339, -3.86)	-40% (-104%, -1.2%)	0.024
20-29	0.12 (-13, 14)	2.35 (-261, 286)	0.73% (-81%, 89%)	0.492
30-39	-4.8% (-29, 19)	-95.3 (-570, 374)	-15% (-87%, 57%)	0.339
40-49	-19 (-33, -3.6)	-376 (-653, -71.5)	-28% (-48%, -5.3%)	0.016
50-59	18 (-18, 51)	351 (-360, 1017)	25% (-26%, 73%)	0.118
60-69	14 (-8.7, 43)	273 (-174.8, 854)	15% (-9.4%, 46%)	0.061
70-79	23 (-5.9, 43)	450 (-118.8, 853)	34% (-9%, 64%)	0.047
80+	24 (7.6, 39)	488 (152.7, 772)	127% (40%, 200%)	0.005

The same analysis for all age groups separately was performed when a latency of 10 years was applied. In the age group of 60-69 years there was a statistical significant increase in the incidence of brain and other CNS cancers for this implied lag but it was decided to further investigate the increase in the statistical significant increase that was observed for all the population. Table 15 displays the results. As shown, statistically significant increase in the incidence of brain cancer was observed for the age groups 60-69 and 80+. The population of these age groups would have been 50-59 and 70+ years old in 1995 respectively; again it is unlikely that this increase in brain cancer incidence was due to mobile phone use. The same assumption can be made for the statistical significant increase of the brain cancers for the age group 60-69 years when the implied latency was 5 years.

In addition, for the population under 59 years old, although no statistical significant decrease was observed, the point estimates for the size of the effect are negative for implied latency periods of 10 years, meaning that based on the counterfactual time series higher annual cancer incidences were expected.

Table 15 Inferred impact of mobile phone use (and all wireless technology) on annual incidence of brain and other CNS cancer for all age groups in Denmark when a latency of 10 years was implied.

Age Group	Absolute average effect (95% CI)	Absolute cumulative effect (95% CI)	Relative effect (95% CI)	Posterior probability of effect
0-9	-1.9 (-12, 9.5)	-19.3 (-115, 95.3)	-14% (-83%, 68%)	0.310
10-19	-0.084 (-9.2, 11)	-0.841 (-92.3, 109)	-0.91% (-99%, 117%)	0.456
20-29	-3.8 (-16, 8.1)	-38.4 (-156, 81.2)	-23% (-95%, 49%)	0.241
30-39	-1.3 (-15, -13)	-12.6 (-150, 126)	-4.6% (-54%, 45%)	0.418
40-49	-3.6 (-20, 13)	-36.2 (-195, 126)	-7.3% (-40%, 26%)	0.299
50-59	-7 (-36, 23)	-70 (-362, 232)	-7.4% (-38%, 24%)	0.302
60-69	34 (4, 57)	337 (40, 570)	37% (4.4%, 62%)	0.016
70-79	9.3 (-13, 31)	93.5 (-131, 315)	11% (-15%, 37%)	0.187
80+	15 (-1.8, 31)	150 (-17.9, 312)	39% (-4.7%, 82%)	0.038

The afore mentioned results for the whole of the population are illustrated in Figure 15, Figure 16 and Figure 17 for the various age groups studied and for both countries.

5.3 Limitations

The present analysis was an attempt to indicate whether there is a possible relationship between mobile phone usage and brain cancer incidence. Data on cancer incidence and mobile phone use were drawn from publicly available databases to assess whether electromagnetic fields emitted by mobile phones have a causal effect on the incidence of brain and other CNS cancer. However, there were some important limitations, which are discussed below.

Since mobile phone use was widely increased from 2012 and onwards with the introduction of 4G networks, it would be useful to study also this period. However, data on cancer incidence so far available in ECIS was limited to the period before the introduction of these networks. In the future, this assessment could be repeated including data on cancer incidence of more recent years (after 2012).

Another limitation of the study is the fact that both mobile phone use and cancer incidence data is collected on a national basis, which is normally a very large geographical scale. For the purpose of the study and so that the population under study can be as homogenous as possible, regional or even localized databases would be more suitable rather than national aggregates. In this way a future analysis could explore a possible link between electromagnetic fields and health in a population which would be exposed not only to similar electromagnetic fields but also to similar confounding factors such as pollutants and possible carcinogens that exist in the environment (water, soil, air). This kind of analysis, which would involve the collaboration between additional research areas, would improve the understanding and knowledge on this complex topic.

For mobile network data it would also be useful to consider other aspects such as: trends in the traffic volume (data and voice), network deployment, cell density and ownership of mobile devices.

Another factor that adds an important constraint to this study is that all types of incidence of brain and other CNS cancers were included. As literature reveals, only certain types of brain cancer are possibly linked to the use of mobile phone use [11, 29, 9, 63].

The current study does not specifically link brain tumors to mobile phone use. It associates a possible relationship to a certain time point when this would be measurable in population data. This makes it

possible that another causal factor (e.g. air pollution) be the reason of this possible association. The methodology could be further improved in future to include more factors that might relate to cancer incidence in the assessment (e.g. air pollution, progress in diagnosis methods). Nevertheless, it gives an indication of the number of brain cancer incidence over the years and how this number would have evolved if no wireless equipment would have been used.

However, due to time constraints in this study, it was not possible to overcome the above limitations.

5.4 Findings of the analysis

Despite the limitations of this analysis, the main finding is that there is no evidence of an increase in the incidence of brain and other CNS cancers that was not predicted in the counterfactual synthetic series for Austria and Denmark. Although there is an increase in this number when applying a latency period of 10 years in Denmark, this increase is only observed in the population aged over 60 years old and possibly would be attributed to other factors and not mobile phone use, since this age group would not be one of the first adopters of the mobile technology.

Nevertheless, more research is essential taking into account the limitations and uncertainties discussed in 5.3 and exploring ways to overcome them. The methodology that was followed is an example of an empirical statistical analysis. A number of alternative methodologies could have been applied; this would show the added value of a research community that would jointly analyze the data that will be available in the future.

6 Conclusions and future work

This study is a preliminary attempt to explore possible links between RF-EMF exposure from mobile phone networks and health issues. The assessment was based on existing literature as well as on statistical analysis of publically available medical data on brain and other CNS cancer incidence using methodologies widely adopted by the research community. Health data on cancer were drawn from the European Cancer Information System (ECIS), which provides the latest information on indicators that quantify cancer burden across Europe.

The literature review focuses on studies mostly published in the last five years, taking into consideration most health aspects (e.g., appearance of cancers, sleep effects, cognitive capabilities) of human beings. This work tries to analyze scientific studies independently of whether or not they find effects of electromagnetic fields on human health. It also reviews laboratory animal studies and experiments on cells (e.g., in vitro cultures).

The following key observations and findings are identified:

1. In the majority of the studies reviewed by the current report, exposure levels were reported significantly lower than the EMF reference levels set by ICNIRP's guidelines.
2. Measurements of RF-EMF from cellular networks indicate that downlink power from mobile base stations is the most significant contribution to overall RF-EMF exposure of humans. There is a general consensus in literature on this finding. In addition, RF-EMF exposure is proportional to the density of mobile users or the level of mobile network traffic.
3. Some studies have shown that base stations of cellular networks located on rooftops might generate very high (i.e., reported exposure in a similar range to the reference levels of the most restrictive member states in Europe) levels of RF-EMF exposure in habitation spaces (e.g., apartments, balconies) in proximity of the base stations.
4. Most studies focusing on the impact of RF-EMF exposure on human health (e.g. cancer, sleep and cognitive functions) did not report any significant health effects in their findings.
5. Some laboratory studies on animals and cells have found negative metabolic activities in in-vitro cultures or mice with prolonged exposure to RF-EMF (Incident E-field strength of 50 V/m at 1800 MHz, which is still below the ICNIRP levels [35]).
6. Studies suggest that other toxic stimuli (e.g., pollution) and their cumulative impact (possible adverse health effects) should also be considered when evaluating possible effect of RF-EMF emissions on health.
7. Most of the reviewed studies did not report a significant correlation between the emergence of cancers and mobile phone usage, except for some studies (even if not conclusive) that report that there is a consistent pattern of increased risk of glioma and acoustic neuroma associated with mobile and cordless phone usage indicating that further research is needed.
8. Many epidemiological studies reported the issue of the lack of availability of sufficient medical data sets with a large time span because the emergence of cancer may appear only on a very long time span (e.g., 10 years and more).
9. The current statistical analysis by the JRC found no evidence of an increase in the incidence of brain and other CNS cancers during the years that followed the evolution of cellular networks in the regions under study. Despite the different types of identified uncertainties, the above finding is in agreement with the conclusions of the literature review, which does not report a significant correlation among the emergence of cancers and the mobile communications.

Based on the above observations, the following potential future developments of this report are suggested:

1. Because of the fact that RF-EMF exposure of current cellular networks is proportional to their density (e.g., large number of mobile base stations with small cell areas) and communication traffic more research is needed in dense cell areas, taking into account specific exposure conditions of the population under study.

2. One significant gap in the research is that most studies are using different exposure scenarios. More work is needed in defining a specific standardized protocol when assessing EMF impact on biological functions for the specific technology that is used, so that findings can be reproduced or compared more easily.
3. More research is needed to supplement the current knowledge on the impact of mmWave frequencies that will be used by 5G networks and beyond as indicated by some researchers who also claim that there is only a small number of conducted studies in these frequencies and they lack consistency [81].
4. Further analysis should be carried out using a joint effort of several disciplines of the research community, as well as recent (covering a longer time span and in particular data covering the period after 2012 when mobile phone use increased significantly with the introduction of 4G networks) and better localized data, in order to overcome some of the limitations of this analysis.
5. Although there is some ongoing research in this field in Europe more projects could be funded in the Horizon Europe programme to further investigate the issue of electromagnetic fields and possible implications on health and environment. In this sense, the definition of 'environment' should include the radio environment.

The JRC could support the definition of protocols and standards in terms of exposure to 5G signals under various traffic scenarios, adherent to real situations, measurement and analysis of the exposure and the results. In addition, the JRC is conducting research on the evaluation of electromagnetic fields emitted by 5G networks using massive MIMO antennas and dense small cells.

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Terminology

Table 16 Terminology used in this report.

Term	Description	Reference
Base station	The base station (also defined as “base transceiver station”, BTS, in some standards) is a set of electronic equipment that sends and receives radio waves. It is usually located near the middle of a cell, to radiate equally over the surface area of the cell.	Light Deployment Regime for Small-Area Wireless Access Points (SAWAPs). 2019 [25]
Cell	A “cell” (as in “cellular network”) is a service area with signal coverage.	Light Deployment Regime for Small-Area Wireless Access Points (SAWAPs). 2019 [25]
Cell site	A “cell site” is the base station’s location.	Light Deployment Regime for Small-Area Wireless Access Points (SAWAPs). 2019 [25]
Cellular	“Cellular” is a specific type of wireless network based on standards produced by 3GPP. But there are also many kinds of non-cellular wireless networks: Wi-Fi, Bluetooth, fixed microwave, satellite television, etc.	Light Deployment Regime for Small-Area Wireless Access Points (SAWAPs). 2019 [25]
Clonogenic	Clonogenic assay is an in vitro cell survival assay based on the ability of a single cell to grow into a colony.	[43]
Cumulative risk of incidence of cancer	Cumulative incidence is the probability or risk of individuals getting the disease over a specified age-span. Cumulative risk is expressed as the number of cases per 1000 person-years that are expected to occur in a given population between the specified age limits (e.g. between birth and the age 84 years) if the cancer rates were as those observed in the specified time period in the absence of competing causes. Cumulative risk permits comparing between populations of different age structures.	ECIS - European Cancer Information System [77]
Emulate	Emulate has the meaning that a wireless communication system is emulated with another equipment (e.g., a signal generator), which generates a similar (e.g., same RF emission power and similar modulation) signal to the real wireless communication system. This approach may be preferred when it is not possible to control all the transmission parameters of the wireless communication systems. The disadvantage is that the emulation may not be fully compliant with the real wireless communication system deployed in the field.	This report.
Exposure	Exposure occurs wherever a person is subjected to electric, magnetic or electromagnetic fields, or to contact currents other than those originating from physiological processes in the body or other natural phenomena.	ITU-T K.52 (2018) [73]

Glioma	A cancer of the brain that begins in glial cells (cells that surround and support nerve cells).	
Incidence of cancer cases	Incidence is the number of new cases arising in a given period in a specified population. This information is collected routinely by cancer registries. It can be expressed as an absolute number of cases per year or as a rate per 100,000 persons per year. In the current report the absolute number of new cases per year was used.	ECIS - European Cancer Information System [77]
Limits	Maximum values defined by reference levels for limiting exposure to EMFs that will provide a high level of protection for all people against substantiated adverse health effects from exposures to both short- and long-term, continuous and discontinuous radiofrequency EMFs.	This report and ICNIRP 2020 [35]
Maximum Permissible Exposure	RF intensity of exposure measured by power density in milliwatts per square centimeter (mW/cm ²).	ICNIRP 2020 [35]
Reference levels	Reference levels have been derived from a combination of computational and measurement studies to provide a means of demonstrating compliance using quantities that are more easily assessed than basic restrictions, but that provide an equivalent level of protection to the basic restrictions for worst-case exposure scenarios.	ICNIRP 2020 [35]
Schwannoma	Schwannoma is a rare type of tumor that forms in the nervous system. Schwannoma grows from cells called Schwann cells. Schwann cells protect and support the nerve cells of the nervous system. Schwannoma tumors are often benign, which means they are not cancer. But, in rare cases, they can become cancer	[80]
Simulate	Simulate means that the health impact and/or the RF emissions are not physically generated but are simulated using a mathematical model eventually implemented with a programming language to produce results comparable with the real equipment. This approach may be used when the safety of the subjects should not be compromised (e.g., because of high power levels of the RF emissions) or when the equipment is not available (even in emulated form) because it is too expensive or complex to deploy.	This report.
Wi-Fi	The term Wi-Fi indicates wireless network protocols, based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access.	This report.
Wireless	"Wireless" is a term for "radio", often used to avoid confusion with "radio broadcasting" (FM, AM or DAB audio programming)	Light Deployment Regime for Small-Area Wireless Access Points (SAWAPs). 2019 [25]

List of abbreviations and definitions

3GPP	3 rd Generation Partnership Project
5G	5 th Generation mobile networks
BS	Base Station
BSTS	Bayesian structural time series
CI	Confidence Interval
CNS	Central Nervous System
EC	European Commission
ECIS	European Cancer Information System
EEG	Electroencephalogram
EMF	Electromagnetic Field
GDP	Gross Domestic Product
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ITU	International Telecommunication Union
LTE	Long Term Evolution
MCMC	Markov Chain Monte Carlo
MIMO	Multiple Input Multiple Output
MPE	Maximum Permissible Exposure
RF	Radio Frequency
RSRP	Reference Signal Received Power
SAR	Specific Absorption Rate
SCENIHR	Scientific Steering Committee on Emerging and Newly Identified Health Risks
TETRA	TErrestrial TRunked RAdio

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