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Electromagnetic fields related to the current rollout of 5G mobile networks
Technical aspects and biological effects in the upper frequency range (FR2, above about 24 GHz)

Statement by the German Commission on Radiological Protection

Adopted at the 339th meeting of the German Commission on Radiological Protection on 27/28 October 2025

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**Elektromagnetische Felder des Mobilfunks
im Zuge des aktuellen 5G-Netzausbaus**

**Technische Aspekte und biologische Wirkungen im oberen Frequenzbereich
(FR2, oberhalb von ca. 24 GHz)**

Stellungnahme der Strahlenschutzkommission

This translation is for informational purposes only, and is not a substitute for the official statement. The original version of the statement, published on www.ssk.de, is the only definitive and official version.

Preface

Germany began rolling out fifth-generation mobile networks (5G) in 2019. This is the next logical step in the development of the 2G, 3G and 4G digital cellular mobile communication systems, which all operate by transmitting radiofrequency electromagnetic fields. The 5G wireless standard offers new capabilities beyond voice communication and broadband data transmission. It is therefore regarded as a core technology for the digitalisation of industry, automated and networked transport systems, the Internet of Things and many other technological developments.

In view of the rollout of 5G mobile technology, the SSK was commissioned by the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety in April 2019 to carry out an overall assessment of the effect of electromagnetic fields of mobile communication systems on humans, especially in comparison with the mobile communication networks operated at the time, and to identify research needs. In addition, advice and recommendations should be developed, in particular, to minimise the exposure of the population and to regulate the treatment of mobile communication networks with regard to the exposure of the population.

In order to carry out this advisory task, the Commission on Radiological Protection set up a working group to assist the Committee on Non-Ionising Radiation, consisting of the following members:

– Dr. Christian Bornkessel, Technische Universität Ilmenau
– Prof. Dr. Heidi Danker-Hopfe, Charité – Universitätsmedizin Berlin
– PD Dr. Thomas Kleine-Ostmann, Physikalisch-Technische Bundesanstalt, Braunschweig
– Prof. Dr. Mats-Olof Mattsson, SciProof International; Strömstad Akademi (S)
– Prof. Dr. Martin Röösli, Swiss Tropical and Public Health Institute, Allschwil (CH)
– Dr. Gernot Schmid, Seibersdorf Labor GmbH (A)
– Prof. Dr. Myrtill Simkó, SciProof International; Strömstad Akademi (S)
– Prof. Dr. Matthias Wuschek, Deggendorf University of Technology.

The SSK is grateful to the Federal Office for Radiation Protection (BfS) for providing extensive background information and specialist support.

Prof. Dr. Matthias Wuschek	*Dr. Beate Volkmer*	*Prof. Dr. Ursula Nestle*
Chair of the EMF and 5G Mobile Networks Working Group	Chair of the Committee on Non-Ionising Radiation	Chair of the German Commission on Radiological Protection

CONTENT

1 Introduction

The SSK was commissioned by the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety in April 2019 to carry out an overall assessment of the effect of electromagnetic fields of mobile communication systems on humans, especially in comparison to the mobile networks operated at that time, and to identify research needs. In addition, the aim was to develop guidance and recommendations in particular to minimise public exposure and for the regulatory treatment of mobile communication networks with regard to public exposure.

After reviewing the results of the German Mobile Telecommunication Research Programme (DMF), the SSK concluded in its 2011 statement ("Biological Effects of Mobile Phone Use – An Overview –"; SSK 2011) that even the at that time most recent research findings did not provide any new evidence of health effects caused by exposure to RF-EMF from mobile communication systems, meaning that the protection schemes on which the established limits were based did not need to be reconsidered.

However, the statement also indicated that the overall problem of the biological and health-related effects of the radiofrequency fields from mobile networks could not be definitively clarified, but that there was still a need for further research. In addition, it was determined that due to the ongoing dynamic development of new mobile technologies and the use of new frequencies and transmission methods, it would be advisable to conduct accompanying research, exposure level monitoring and exposure assessments. The specifications of 5G mobile communication systems distinguish between two distinctly different frequency ranges FR1 (approximately 0.4 GHz to 7 GHz) and FR2 (approximately 24 GHz to 71 GHz, 'millimetre waves') for the transmission of radio signals. In FR2, therefore, more transmission bandwidth is available. However, as the potential range of a base station and the penetration capacity of radio waves in buildings decrease significantly with increasing transmission frequency, FR2, unlike FR1, is hardly suitable for a nationwide coverage of larger areas via terrestrial base stations. Instead, FR2 is used for the transmission of large amounts of data in locally limited areas.

As in 2019 the frequency occupancy plans in this frequency range had not yet been finalised at international level and therefore the national procurement procedures had not yet started everywhere, the use of FR2 for 5G mobile communications was still in the initial phase at that time. By contrast, the deployment of 5G networks in the FR1 area had already begun in Germany and other countries in 2019.

Therefore, right from the start, the established working group decided to draw up two separate statements on the basis of these two significantly different fields and speeds of development of 5G technology. A first statement, adopted by the SSK in December 2021 and published in March 2022 (SSK 2021), dealt only with the technical, biological and health aspects of 5G mobile communications in the frequency range of up to around 7 GHz (FR1), which had then already been used intensively for mobile communications for a long time. The assessment of the 5G technology for the millimetre wave range (FR2), which may be used more intensively in the future, has been postponed until after the finalisation of the first statement, in particular because the scenarios of usage were still unforeseeable in 2019.

The evaluation of 5G technology in FR2 frequency range, which is now available here supplements the first statement. Parts 1 and 2 of the statement should therefore be considered as a single, coherent document.

The second part of the statement also describes and evaluates the current state of research in the field of biological and health effects of radiofrequency electromagnetic fields (RF-EMF) in the relevant frequency range from 24 to 71 GHz.

First of all, the first part of the scientific background (Chapter 3) presents physical characteristics as well as the technical parameters of 5G mobile systems in the frequency range FR2 which are relevant when considering exposure. In addition, the physical interactions between radio frequency and the human body in the millimetre wavelength range and the current legal regulations to protect the public from the effects of RF-EMF are discussed in more detail.

The second part of the scientific background (Chapter 4) describes and assesses the state of research on the biological and health effects of RF-EMF from mobile communications in the FR2 frequency range.

The effects of RF-EMF from mobile communications on electrically or electronically operated implants (e.g. pacemakers, defibrillators) are not covered in this statement since questions in this field are part of the (technical) field of operational safety of electric and electronic devices in electromagnetic fields or generally of electromagnetic compatibility (EMC) of systems and devices. The Commission on Radiological Protection believes that this complex issue should be considered from the perspective of electromagnetic compatibility (EMC) as part of the technical standardisation of electrically or electronically operated implants.

Furthermore, this statement only addresses the risks concerning the health of humans and not the risks concerning their environment (wildlife).

Note on the explanation of technical terms in the following chapters:

Naturally, such a document contains a variety of technical, biological and medical terms. These are explained in more detail in the scientific background of this statement (Chapters 3 and 4) or in Chapter 7 ‘Definitions’. In Chapter 2, therefore, a repeated explanation of the technical terms is omitted.

2 Statement

On behalf of the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety, the Commission on Radiological Protection (SSK) was commissioned to assess whether, from the current point of view of research, the fundamentals on which the limits for exposure from radio frequency (base station transmitters and user devices) applicable in Germany are based remain fully valid. The trigger for this advisory mandate was the launch of the 5G mobile network expansion in Germany in 2019.

In December 2021, the first part of the opinion was adopted by the Commission on Radiological Protection, which only deals with the technical, biological and health aspects of RF-EMF in the frequency range currently intensively used for mobile communications up to around 7 GHz (FR1). This frequency range is also used by the base station and user equipment of the 5G networks currently in operation throughout Germany.

Due to the lack of applications at the time, it was decided to assess the millimetre wave range above about 24 GHz (FR2) in a separate statement. This is now available with this document.

With regard to the **technical aspects** of 5G mobile communications in the frequency range FR2 (Chapter 3 of this document), the SSK identifies the following relevant differences to the frequency range FR1 and summarises the following:

- In principle, FR2 has higher path loss than FR1. As a result, the maximum possible transmission distance decreases, and directional radiation of the antennas used is mandatory. Therefore, FR2 is mainly used for indoor communications, fixed outdoor radio links or outdoor Line of Sight (LoS) communications, e.g., when high data transfer rates are required.

- Even more clearly than in the frequency range FR1, beamforming antennas in the frequency range FR2 can selectively and in a demand-oriented manner focus the available transmission power on certain areas. This means that an increase in exposure is to be expected especially where there is a large density of active user devices. In other local areas not covered by antenna beams, mean exposure will be lower compared to static illumination.
- As in the case of 5G in the FR1, the always-on signalling power continuously emitted from the 5G base station into the radio cell (i.e. the proportion of the total power continuously emitted for the purpose of signalling and synchronization of the user devices) is significantly lower than in the case of 2G/3G/4G. Especially in times of low utilization of the system, this implies that the ratio between actual and maximum exposure is lower than for precursor technologies.
- Due to the higher frequencies used in FR2, radiation absorption takes place on the surface of the body, so that the skin and the cornea of the eye are potential target tissues for harmful effects. The known metrological methods for demonstrating compliance with the limit values for protection against negative health consequences of radio transmitters operated in close proximity to the human body must be extended or adapted accordingly for devices transmitting in FR2 frequency range. International standardization bodies are currently working towards this.
- In principle, 5G base stations in FR2 frequency range in Germany are subject to the same legal and executive regulations that apply to radio transmitter sites in FR1 frequency range and that have been in operation for many years. This applies to both, systems with equal or more than 10 W EIRP and with less than 10 W EIRP.
- In principle there is also the option to operate private 5G campus networks in both FR1 and FR2 frequency ranges. It is foreseeable that the operators of such networks will require additional information regarding their obligation to ensure the protection of persons in the vicinity of base station antennas, since these operators are usually little experienced in the field of ensuring health protection from radio transmitter sites.

On the state of research on **the biological and health effects of** high-frequency fields in the FR2 frequency range (Chapter 4), the SSK comments as follows:

- Compared to the frequency range FR1, the number of experimental studies for the frequency range FR2 is low. This is especially true for human experimental studies.
- Epidemiological studies in FR2 have mainly examined occupational radar exposure in the military or in the police. Most studies that addressed EMF exposure, have not found any increased risks for diseases such as cancer. However, the studies are method-logically not robust. For example, exposure levels have been insufficiently quantified in most studies, or possible confounders have not or only rudimentarily been considered.
- Human experimental studies show that the perceptual threshold for temperature rise at the surface of the skin caused by the high-frequency electromagnetic fields (RF-EMF) in the frequency range FR2 is about 1 °C.
- In two out of three available studies on the threshold for thermal pain, a statistically significantly increased pain threshold was observed during a 30-minute exposure to millimetre waves at field strengths partly above the limit values. Overall, only very small

samples with heterogeneous exposure parameters within and between studies have been investigated so far.

- The majority of in vitro and in vivo animal studies in the FR2 exposure range have shown biological reactions (usually as a result of thermal exposure). However, no conclusions can be drawn with regard to the biological and health effects of exposures in the frequency range FR2, as the studies are very heterogeneous and low in number. There was no consistent relationship between power density, exposure duration or frequency, and the effects of exposure. The available in vivo studies, which were mostly concerned with warming the skin and eye, do not provide adequate and sufficient information for a meaningful, reliable risk assessment. In addition, the studies (in vivo and in vitro) do not provide sufficient information to answer the question of the presence of health-related non-thermal effects.

Currently available data is insufficient and therefore does not yet allow any conclusions to be drawn regarding possible health-related effects of exposure to radiofrequency electromagnetic fields in FR2 below the applied limit values in Germany. In summary, however, it can be stated that the currently available data does not indicate that there are potentially negative biological effects from FR2 other than those based on thermal effects in body tissue, which are already known from FR1.

In view of the potential future use of FR2 in Germany (see section 3.1.2) and the currently insufficient data, it is necessary to further investigate potential health risks.

From the aspects discussed in this statement, the following particularly relevant issues arise, for which improved data are needed and which should be addressed in future research projects (see also the corresponding conclusions in chapters 3 and 4):

- Due to the local concentration of radiation absorption in the skin and the cornea of the eye observed in FR2, detailed knowledge of the absorption processes is of particular importance. Although research results are already available on this topic, many specific questions still appear to remain open at present. Addressing these questions seems to be a very complex task, in particular because of the great biological variability of the skin along the human body and changes due to the aging process. Current limit value recommendations are based on numerical calculations using very simple planar layer models of the skin, exclusively with regard to thermal effects, taking safety factors of varying degrees of validity into account. Further systematic studies considering the anatomical and macroscopic fine structure of human skin – such as sweat glands or hair follicles (including their variability and age-related changes) – to establish anatomically sufficiently differentiated absorption models could contribute to a further development of the limit value recommendations.
- Since only a few 5G test installations in the FR2 frequency range are currently available in Germany, the currently available exposure level data come from simulation-based estimates or from measurements in other countries. In the case of an operational network setup of 5G transmitters in the frequency range FR2 in Germany, it is recommended to accompany them in terms of exposure level measurement technology, taking into account, for example, the exposure-relevant characteristics of beam steering antennas.
- Operators of 5G campus networks should be informed as part of the licensing process of their obligations to ensure the protection of people from electromagnetic fields (general public and occupationally exposed persons).
- Further studies on biological effects should primarily consider those frequencies of the FR2 which are intended for future use.

- Since many studies are qualitatively insufficient in terms of scientific methodology or at least have significant weaknesses, the design and conduct of future studies need to be significantly improved. This applies to epidemiological studies and human experiments, and in particular to in vivo and in vitro studies.
- Human experimental studies on biological and health effects: These should focus on the effects mediated in particular through the skin, including the effects on components of the nervous and immune systems.
- In humans and/or in animal models: Analysis of possible long-term effects of exposure to frequencies of the FR2 on the entire nervous system, in particular those mediated through the skin (e.g., behaviour, cognitive performance, neurophysiology, pain perception).
- Animal experimental studies: These should examine the most exposed organs, especially the skin and the eyes.
- In vivo/in vitro studies: Effects of FR2 exposure on the skin flora, in particular on the microorganisms that are part of the immune system, should be investigated. In addition, in this context, it is recommended to investigate the immune response.
- Studies on in vitro models (skin, cornea, and conjunctiva of the eye, etc.) to investigate thermal effects should be encouraged.
- To improve the data situation, there is a need for research into possible non-thermic mechanisms of action.

Four EU projects are currently underway (ETAIN, GOLIAT, NextGEM, and SEAWave, see Annex A-4), from which answers to some of the outstanding questions are expected.

3 Scientific background regarding technology and regulation

In this first part of the scientific justification, important physical-technical parameters of 5G mobile radio systems in the frequency range FR2 relevant to exposure considerations are presented first (e.g., general technical parameters, wave propagation, physical interaction with the human body). Particular attention is paid to the similarities and differences compared to 5G systems in the FR1 range. Furthermore, examples of typical application scenarios of 5G in the FR2 frequency range can be found here. In addition, some regulatory aspects are presented and discussed.

3.1 Technical aspects of 5G technology in FR2

3.1.1 Wave propagation (FR2 compared to FR1)

The wave propagation in the frequency range FR2 is basically determined by the same physical laws as in the frequency range FR1 and can be fully described with the help of the Maxwell equations. However, the higher frequencies (FR1: 410 MHz to 7.125 GHz, FR2: 24.25 GHz to 71 GHz) result in different propagation characteristics. The higher frequencies f are associated with shorter wavelengths $\lambda = c/f$ (FR1: 4.2 cm to 73.2 cm, FR2: 4.2 mm to 12.4 mm), where $c \approx 3 \cdot 10^8$ m/s is the speed with which the radio waves propagate in free space. While the radio waves in the FR1 are centimetre and decimetre waves, the FR2 is often already referred to as millimetre waves.

With radio transmission near the ground, electromagnetic waves never spread completely freely, but are influenced by the properties of the earth's surface and the atmosphere. Above frequencies in the megahertz range and thus for frequencies in both the FR1 and FR2, the ground is a good reflector. Wave propagation is different for ground waves that are bent along the earth's surface and follow the earth's curvature and for space waves that propagate on the ground without diffraction (Unger 1994). In the frequency ranges FR1 and FR2 used for mobile communications, only the skywaves are important.

The attenuation of electromagnetic waves between a transmitter and a receiver in the open space increases squarely with the distance due to the reduction of the power density in space. An additional effect is that with increasing frequency, the active surface of the receiving antenna with the same bundling property of the antenna (expressed by the antenna gain, a numerical factor, which is usually expressed logarithmically, i.e. in decibels [dB]; cf. Chapter 7 ‘Antenna gain’), which leads to an additional reduction of the power supplied to the recipient. According to the Friis formula, these two effects can be described as free space path loss α_{dB}. The following shall apply:

$$\alpha_{\mathrm{dB}} = -10 \lg\left(\frac{c}{4\pi r f}\right)^2 \approx -147.5 \text{ dB} + 20 \lg\left(\frac{r}{m} \cdot \frac{f}{Hz}\right).$$

Here c is the speed of light, f is the frequency and r is the distance between transmitting and receiving location. While a 100 m FR1-5G connection at 700 MHz has a free space path loss of about 69 dB, this connection at 3.6 GHz already has a path loss of about 84 dB. In the FR2 at 30 GHz, the loss is about 102 dB.

In order to overcome the high path loss in FR2, the use of antennas with a high directivity and thus high gain is unavoidable. While in FR1 antennas with a lower gain are used (passive sector antennas) and beamforming takes place only at higher frequencies (e.g. in the 3.6 GHz band), many elements have to be used in FR2 antenna arrays, which thus have a correspondingly high antenna gain. Usually, more than the 32 or 64 individual antennas currently used in the FR1 are necessary in the array. Nevertheless, the possible transmission distance remains more limited than in FR1, so that the FR2 is mainly used for the transmission of large amounts of data over short distances in the range of a few tens of meters to a few 100 meters.

Accordingly, there is a stronger focussing of radiation in FR2. Typically, in FR2 compared to FR1, the focussing of the radiation is about five times stronger, resulting in 3-dB beam widths of only a few degrees. In FR1, passive sector antennas have a typical gain between 13 dBi and 18 dBi (for ‘dBi’ see chapter 7 ‘antenna gain’). Beamforming antennas in the 3.6 GHz band typically have gain values between 23 dBi and 25 dBi. The antenna gains in FR2 are larger than 25 dBi.

The higher the frequency, the more a ray-optical view of the wave propagation becomes possible. Due to the significantly higher frequencies, a quasi-optical wave propagation results in FR2. While the transmission in FR1 is largely non-directional, a strongly directional connection is usually realized between the transmitter and receiver in FR2, which can take place on the direct path (line-of-sight – LOS) or on an indirect path by means of one or more reflections on objects (non-line-of-sight – NLOS). Both the transmission in FR1 and the more directional transmission in FR2 can cause selective fading due to destructive interference from multipath propagation. However, there are also mobile communication concepts that use multi-path transmission positively to increase transmission capacity (MIMO concepts, cf. section 3.1.3).

Apart from the necessarily more directional signal propagation in FR2, the wave propagation in FR1 and FR2 is also different in terms of reflection, transmission and diffraction or the shadowing by objects. Due to the shorter wavelengths in FR2, scattering tends to play a greater role, as structures of objects and surfaces (e.g. rough plaster) have dimensions in the wavelength range. This results in mostly diffuse reflection on surfaces and tends to reduce transmission through walls compared to lower frequencies (Possenti et al. 2023). Due to the strong bundling of radiation and the spatially more clearly defined shadowing by objects compared to the strong diffraction at lower frequencies, a propagation path is more often blocked, e.g. when an object is in the propagation beam. In principle, the so-called penetration loss due to obstacles such as buildings and trees due to reflection and transmission losses is much higher than in FR1 and leads to a further reduction of the range. In addition to the signal frequency and the structure and thickness of the material to be penetrated, the loss of penetration depends heavily on the electric conductivity and permittivity of the material as well as on the incidence angle and the polarization of the electromagnetic wave.

As a consequence of the above-mentioned propagation effects, the radiated fields of indoor transmitters in FR2 are essentially limited to the specific room, so that it is usually not possible to cover several adjacent rooms (as is often the case with Wi-Fi networks). The advantage, on the other hand, is that different networks that are operated in the same building, for example, can interfere with each other to a lesser extent. Transmitters that are located outside of buildings can hardly be received indoors or not at all.

Table 3.1 shows the expected range and the indoor coverage of buildings by outdoor transmitters for FR1 and FR2 in comparison. The possibly dynamic shadowing of the communication connection by objects leads in FR2 to particularly strong path losses up to a complete disruption of the connection. These effects can only be countered by suitable beamforming algorithms.

Tab 3.1: Range and indoor coverage in 5G

	5G Ultra high band **FR2** **26 GHz**	**5G High band** **FR1** **3.5 GHz**	**5G Mid band** **FR1** **1.8 GHz**	**5G Low band** **FR1** **700 MHz**
Range (typical)	200 m	1 km	2 – 3 km	5 – 8 km
Indoor coverage	no 	difficult 	good 	very good 

Overall, with a change in the reception location on a scale of a few meters the interaction with objects in FR2 leads to a much larger reception level variation than in FR1. This phenomenon, known as shadowing, can be statistically modelled by a shadowing loss and must be included in the link budget. A greater variability of the signal transmission with regard to the reception level but also with regard to the dominant propagation paths and the associated reception directions (angle of arrival) is to be expected.

In addition to the interaction with objects, the absorption of the atmosphere also plays an important role in the wave propagation in FR2. Some molecules present in the atmosphere (especially oxygen O_2 and water vapour H_2O are relevant here) interact very strongly with electromagnetic radiation. This leads to absorption resonances and thus to significant additional attenuation. Figure 3.1 shows the specific attenuation of the atmosphere as calculated by the International Telecommunication Union (ITU) for standard conditions (ITU 2016). In addition to the free space path loss, the O_2 molecule leads to a maximum attenuation at about 60 GHz and the H_2O molecule to an air moisture-dependent attenuation maximum at about 23 GHz.

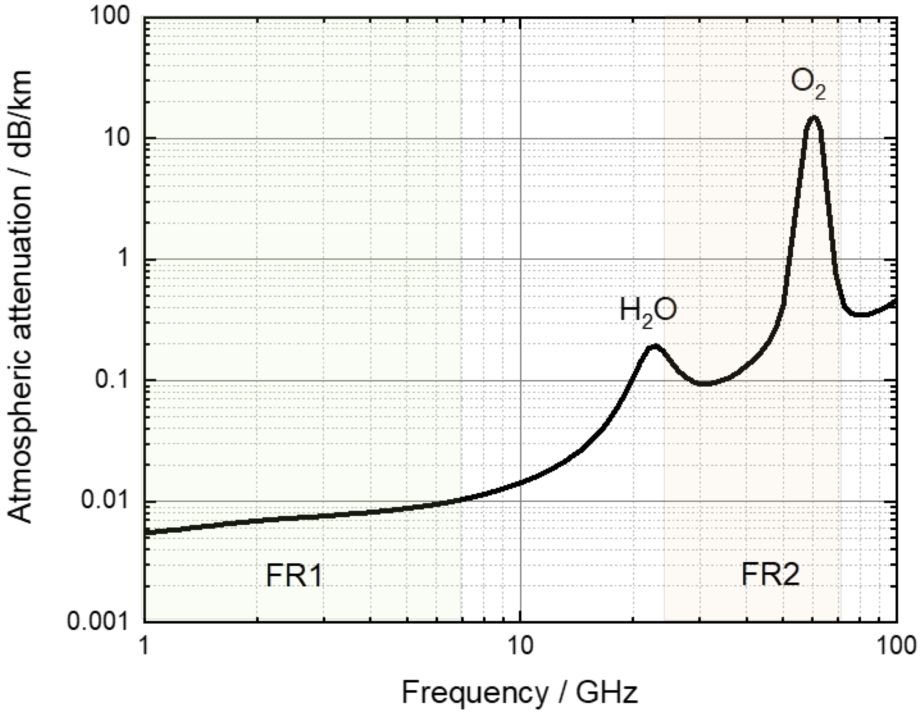

Figure 3.1: Specific additional atmospheric attenuation of the standard atmosphere (pressure 1013.25 hPa, temperature 15 °C, absolute humidity 7.5 g m^{-3}), based on the data of ITU (2016).

If mobile communications do not happen exclusively within buildings, wave propagation is also influenced by precipitation. Hydrometeors such as raindrops, snowflakes and hail lead to significant additional attenuation depending on the precipitation rate. With the help of ITU models for rain attenuation (ITU 2005) and for fog and cloud particles (ITU 2019), the additional specific attenuation can be determined depending on frequency, polarisation and rain rate. Figure 3.2 shows the additional rain attenuation for horizontal polarisation for four different drop rates (Moroder 2021).

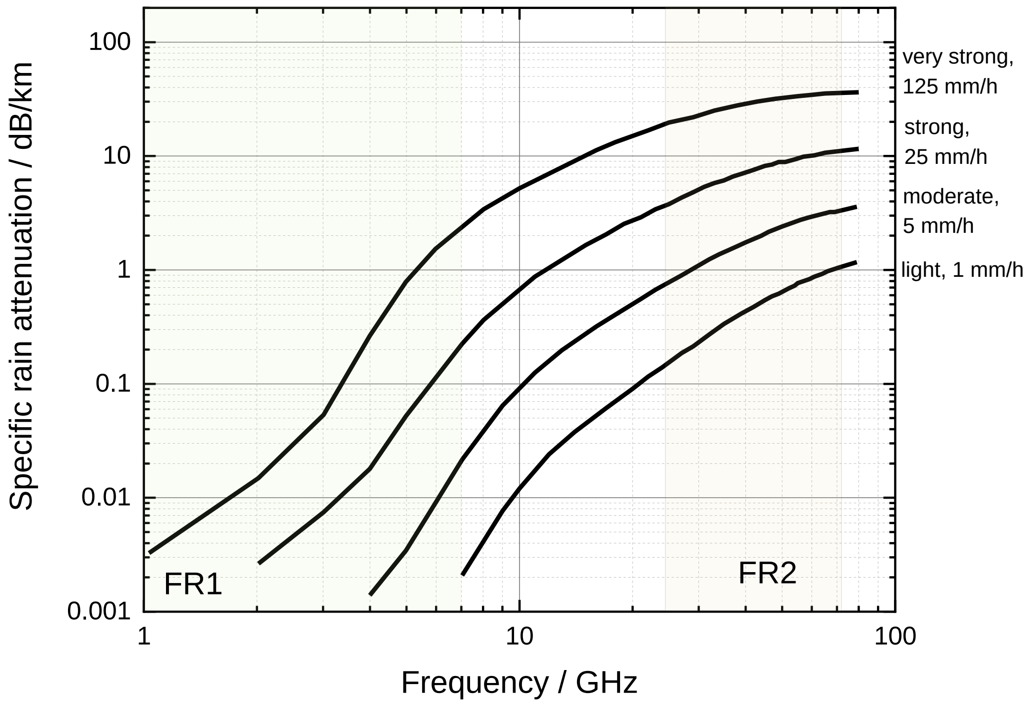

Figure 3.2: Specific rain attenuation for horizontal polarisation depending on the precipitation rate according to ITU-R P.838-3 (ITU 2005), based on the data of Moroder (2021).

In summary, FR2 tends to have stronger path loss than FR1 and thus the maximum possible transmission distance decreases. For an efficient radio link, a directional radiation of the electromagnetic waves is necessary. Due to the transmission properties of the atmosphere and the strong weather dependency of the transmission, FR2 is only to a limited extent suitable for outdoor use (especially if there is a line-of-sight between the transmitting and receiving – antennas).

3.1.2 Possible typical application scenarios

According to the discussed propagation properties, 5G in the frequency range FR2 is not suitable for improving the general large-area network coverage, since the maximum ranges in the range of a few hundred meters are too small and hence coverage inside buildings by transmitters outside is virtually excluded. Instead, the use of FR2 is suitable as a supplement to the general network coverage in applications where particularly high bandwidth requirements exist. For example, bandwidths of up to 800 MHz are currently available in the frequency range 24.25 GHz to 27.5 GHz through allocation procedures of the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railways (Bundesnetzagentur, BNetzA). The following are some possible examples for applications:

Fixed Wireless Access (FWA)

Fixed Wireless Access (FWA) is also referred to as 'radio DSL' and describes the wireless connection of a household or a smaller company to the fixed line network in order to avoid a fibre optic, cable or conventional DSL connection. 4G LTE already offered solutions with 50

Mbit/s or even several 100 Mbit/s, for example in places where no or only a poor DSL connection was available. 5G FR2 is being considered for the connection of users with data rates in the Gbit/s range and is already being tested. Hardware specially developed for this purpose is used (Customer Premises Equipment – CPE).

Indoor communication

With appropriate bandwidth requirements, it is conceivable to supply the interiors of buildings with 5G in FR2. The advantage is that used frequencies can be easily reused in adjacent buildings. However, the 5G supply is in competition with Wi-Fi solutions, which, for example, from Wi-Fi 7 (IEEE standard 802.11be), offer many of the 5G functionalities such as handover between access points and massive MIMO at very high data rates in the Gbit/s range and can probably be implemented more cost-effectively and more easily, since the administration can be carried out independently without network operators or installation of a campus network.

Backhauling

Backhauling refers to the connection of a subordinate network node, for example a 5G mobile base station, to the communication core network. Such connections are traditionally realized with a radio link in the microwave area, if a fibre optic connection is difficult or not possible. The implementation in the 5G standard in the frequency range FR2 enables the simple and flexible commissioning of such radio relay systems as an integral part of the 5G network. The connection takes place via precisely aligned high-gain antennas and enables data rates in the Gbit/s range over distances of up to a few kilometres.

Industrial automation

As part of the digitalisation of industrial production (Industry 4.0), the flexible interconnectted-ness of a large number of devices and tools, sensors and products is required, some of which are subject to real-time requirements with low latency. If high data rates are required (e.g. in virtual reality applications in production), the use of FR2 may be necessary.

Small cells

Small cells are radio cells operated at low transmitting power, the range of which is only a few tens to a few hundred meters. They are used to increase the capacity of mobile networks in high-traffic areas. On the one hand, the use in urban areas with many network participants is conceivable (street level small cells), where the base station can be accommodated partly in already existing public amenities such as billboards or advertising pillars and on street lamps. On the other hand, it can also be used in places where many people come together, such as airports and train stations, football stadiums and exhibition and event centres. Where appropriate, installation in directly accessible installations poses a challenge in terms of compliance with personal protection limits, which must be addressed by structural measures (e.g. installation only from a certain height).

Interconnectedness of vehicles

The interconnectedness of vehicles is constantly progressing and enables new functionalities, especially in the field of safety and ultimately also automated and interconnected driving. Wi-Fi and mobile network-based solutions (Cellular V2X) are in direct competition in the realisation of radio links between vehicles and road infrastructure. If very high data rates are required during transmission, the use of the FR2 is also to be expected.

e-Health

In the medical field, for some applications, such as teleoperations, very high data rates are associated with high latency requirements. In other areas (e.g. mobile MRI and computed tomography), very large amounts of data are generated, which need to be transmitted quickly and securely. In these cases, the use of FR2 base stations is plausible.

3.1.3 General technical parameters, antennas

This section summarises important exposure-relevant parameters, based on the explanations in section 3.1.1; their effects on and the exposure will be discussed in the next section. The exposure-relevant parameters include the following points:

- frequencies,
- antennas and radiation characteristics,
- transmission and radiated power,
- network expansion.

Frequencies

The frequency range at FR2 ranges from 24.25 GHz to 71 GHz. This corresponds to free space wavelengths of 4.2 mm to 12.4 mm, which is why FR2 is also referred to as the ‘millimetre wave range’. The significantly higher frequencies compared to the frequency range FR1 are associated with a significantly lower penetration depth of the electromagnetic waves in body tissues; the penetration depth is the depth in the tissue at which the electric field strength has dropped to approximately 37% of the value at the surface. ICNIRP (2020) quantifies the penetration depth into human skin tissue as 8.1 mm at 6 GHz, as only 0.92 mm at 30 GHz and as 0.49 mm at 60 GHz. The circumstance of low penetration depths in the millimetre wave range is 3.2 discussed in detail in section 3.2.

The frequency range above 20 GHz to 100 GHz is already used by numerous radio applications. These include, for example, radio services via satellites, military radio applications, radio link services, short-range radio applications, industrial radio and amateur radio. Full body scanners at airports (above 10 GHz, e.g. a manufacturer's equipment at 70-80 GHz) and radar applications in the transport and automotive sectors (frequency ranges around 24 GHz, 77 GHz and 96 GHz) are particularly relevant for the exposure of the general public.

In FR2, 5G uses the same access and modulation methods as in FR1 (multi-carrier method OFDMA with digital carrier modulation) (SSK 2021).

Antennas and radiation characteristics

Similar to the frequency range FR1 above about 3 GHz, so-called massive MIMO antennas can be used in the frequency range FR2. In FR2 these consist of up to several hundred individual elements, which can be controlled separately in groups and therefore allow both beamforming or beam focussing, as well as a beam steering. Due to the higher number of elements, a much stronger focussing takes place in FR2 than in FR1, which is necessary at least to partially compensate for the higher free space path loss. While beamforming in the 3.6 GHz band typically results in antenna gains of 23 dBi to 25 dBi, the antenna gains in FR2 are significantly greater with up to 32 dBi (Törnevik 2023). This results in narrower half-power beam widths of the emitted beams with, for example, about 4° (horizontal) and 12° (vertical) with an antenna with 32 dBi gain (Törnevik 2023).

As with massive MIMO antennas in FR1, the beam pattern is divided into a section with signalling data (broadcast beam) and a section with traffic data (traffic beams). While the signalling data is transmitted to the entire radio cell to enable user devices to be booked into the network, the traffic beams are dynamically aligned to the user devices. Depending on the number of users, several spatially separated beams can be formed. For example, Ericsson is currently using antennas (AIR 5322), which can emit up to four locally separated beams with two polarisations each (Törnevik 2023,Unger 2022).

If at an identical location an FR2-5G antenna is used together with an FR1 antenna for the same radio cell, the signalling information may also be transmitted via FR1 antenna alone (Walther 2022); signalling via FR2 becomes obsolete. This makes the metrological assessment of the maximum possible exposure based on the signalling information much more difficult.

Transmission and Radiated Power

Massive MIMO antennas for FR2 are offered, for example, by system technology manufacturers Ericsson, Nokia and Huawei. The transmission power at FR2 is in a range of about 0.5 W to 3 W corresponding to 27 dBm to 35 dBm; the gains come up to 32 dBi, depending on the configuration of the antenna. The radiated power (EIRP) resulting from the product of transmission power and antenna gain is between 52 dBm and 68 dBm at a maximum, according to the manufacturers(Törnevik 2023).

Due to the significantly lower transmission power (0.5 W to 3 W) compared to massive MIMO antennas in the FR1 (transmission power up to 200 W), despite the up to 7 dB higher gains (factor 5), significantly lower radiated power results (EIRP, 78 dBm for FR1 with a transmission power of 200 W and a gain of 25 dBi in comparison to a maximum of 68 dBm in FR2).

Network rollout

In Germany, there are currently no commercial mobile networks at 5G in FR2. Individual network operators run small-scale test networks; One example is Vodafone with the Red Bull Arena in Leipzig in the frequency range between 26.7 GHz and 27.5 GHz with a bandwidth of 800 MHz.

Commercial networks in FR2 frequency range are operated in Australia, Singapore, Japan, India, Italy and the USA, among others.

3.1.4 Estimation of exposure (measurement, simulation)

Information on the maximum possible exposure and the resulting safety distances can be theoretically estimated or measured from the information on the maximum radiated power. They are relevant in Germany for monitoring the installations considering the legal aspects of exposure or for issuing the site certificate.

From the maximum EIRP of 68 dBm as derived from the above and a legal limit of 61 V m^{-1} (equivalent to 10 W m^{-2}), maximum safety distances in the main beam direction of about 7 m can be calculated under free space conditions. This value applies to a maximum utilization of the system, and provided that one beam or several beams with maximum gain are directly focussed onto the measuring point.

For the antenna of the manufacturer Ericsson AIR 5322, test reports are available on the Internet, in which the safety distance for the general public and for occupational health and safety purposes in different directions from the antenna was calculated on the basis of the antenna diagrams (Ericsson 2021). For an EIRP of 62 dBm (nominal), the safety distance stated for the general public is a maximum of about 4 m. Due to the 6 dB lower EIRP compared to the above example based on free space propagation, only about 3.5 m would actually be expected. The difference is due to the fact that Ericsson's calculation takes into account tolerances. Although Ericsson also takes into account the reduction of the maximum time-averaged transmission power due to TDD (a factor of 0.75 corresponding to -1.25 dB), the overall distance is about 15% greater due to the tolerances taken into account (2.4 dB corresponding to a factor of 1.74).

Colombi et al. (2022) describe measurements of the maximum exposure at two base stations at 28 GHz and 39 GHz with 50 dBm radiated power each in a test network. The maximum values measured in 10 m were below 0.03 W m^{-2} which corresponds to a limit value of 0.3% in terms of power density and 5.5% in terms of electric field strength.

For a test setup, Deutsche Telekom has measured the exposure at maximum utilization of the system provoked by a user device with a spectrum analyser: At horizontal distances between the transmitter and the measuring point between 4 m and 27 m, electric field strength values of less than 5 V/m to 25 V/m resulted in a measuring height of 3.6 m; this corresponds to limit values between 8% and 41% in terms of electric field strength.

In contrast to the maximum possible exposure that is relevant for approval, the time-limited actual exposure at a defined place of exposure is highly dependent on:

– whether and for how long, within a six-minute normative period, one or more traffic beams are targeted at the exposure site and how many radio resources (i.e. frequency carriers and time units) are allocated to that beam; and
– how many traffic beams are being generated in other directions at the same time.

For example, measurements of the time-averaged actual exposure (averaged over 30 minutes here) were carried out in a ‘5G Smart Apartment’ in Australia in three user scenarios (Wood 2023). The percentage of the legal limits was found to vary between 0.00003% and 0.0015% in terms of power density; this corresponds to the range between 0.05% and 0.4% in terms of electric field strength. Liu et al. (2024) present measurements of the electromagnetic fields at five measuring points in the vicinity (up to a distance of 45 m) of three 5G base stations in the 28 GHz band in Tokyo. A height scan of 10 cm to 200 cm without artificially generated data traffic was carried out per measurement point, as well as measurements at a constant height (height of the maximum field strength during the height scan) during a time of one minute with provoked data traffic through a user device. The device was placed 50 cm away from the measuring antenna and downloaded a 10 GB file during the measurement. The height scan results averaged over 3 s without provoked traffic vary between about 55 dB and 94 dB (µV m^{-1}) depending on the height and type of antenna (horn antenna or omnidirectional antenna); this corresponds to electric field strengths between 0.0006 and 0.05 V/m or 0.0009% and 0.08%. The values averaged over one minute with user device provoked traffic reach maximum values up to about 118 dB (µV m^{-1}) corresponding to 0.79 V m^{-1} or 1.3%.

Numerous other results of exposure measurements in commercial networks and test networks on 5G FR2 can be found on an interactive website of the GSMA (GSMA 2025).

Conclusion

Overall, similar to 5G in FR1, beamforming allows for a much more selective and demand-driven concentration of available transmission power in specific areas than in previous mobile technologies. This means that an increase in exposure is to be expected especially where there is a large density of active user devices. In other local areas not covered by beams, mean exposure will be lower compared to static coverage. Overall, this results in a shift in exposure compared to conventional mobile communication technologies. Furthermore, as in the case of 5G in FR1, it should be noted that the always-on signalling power continuously emitted from the 5G base station into the radio cell (i.e. the proportion of the total power continuously emitted, among others, for the purpose of signalling and synchronization of the user devices) is about a factor of 10 lower than in the case of the 3G/4G systems (SSK 2021). Especially in times of low utilization of the system, this implies that the ratio between actual and maximum exposure is lower than for precursor technologies.

3.2 Physical interaction mechanisms

Due to the significantly higher frequencies used in FR2 compared to FR1, there are also significant differences in the absorption distribution in the human body. While the penetration depths in the human body can still be in the range of a few centimetres at FR1 frequencies, the electromagnetic radiation used in FR2 is almost completely absorbed in the outermost tissue layers (within a few millimetres) in the millimetre wave range. Interactions with millimetre waves therefore mainly affect the skin and the anterior areas of the eyes (cornea, sclera, conjunctiva). The heat entered into these tissues by radiation absorption is not accessible to a routine measurement on the human body, but must be determined by simulations and experiments with body phantoms (Kazemipour et al. 2016). Within certain limits, the latter can be used to validate electromagnetic simulations. The calculation of the heat input based on electromagnetic simulations requires a model of human tissue containing both valid electromagnetic (electric conductivity and permittivity) and thermal properties (thermal conductivity, specific heat capacity, metabolic heat generation and heat transport by blood perfusion in the tissues involved, as well as a representative ambient heat transfer coefficient).

The low penetration depth of electromagnetic radiation implies that simplified body models can be used e.g. of the skin and the eye and that there is no need to discretise the whole human body with its numerous different tissue types in a detailed voxel model. The electric and thermal parameters are available in online databases (Andreuccetti et al. 1997, Hasgall et al. 2022), but not free of uncertainties. Theoretical work in the frequency range 100 GHz to 1 THz with parametric modelling of the natural variability in structure and composition of the tissue showed for a greatly simplified planar tissue layer model and using statistical methods a significant influence of tissue structure and composition on the resulting absorption and tissue heating (Zilberti et al. 2014, Zilberti et al. 2015). This fundamental finding has also been confirmed in recent work for the frequency range (FR2) that is of interest here. In particular, a realistic modelling of the different skin layers in the calculation models is required in order to reliably map the absorption properties. For example, it could be shown that neglecting the stratum corneum can lead to an underestimation of the power absorbed in the tissue, since the stratum corneum as a matching layer for the incident wave can lead to a significantly higher transmission factor than would be the case for a skin model without a horny layer (Christ et al. 2020b, Christ et al. 2021). Due to the low water content, the resulting low loss factor and the low thickness of the stratum corneum (typ. 0.04 mm at > 95% of the body's surface), only comparatively little radiation is absorbed in the stratum corneum itself. The majority of radiation from absorption is in the epidermis and dermis.

The numerical calculation of the resulting tissue heating is split into a two-stage process, which includes on the one hand the solving of the electromagnetic field problem of the wave propagation in the tissue and the associated power input and on the other hand the solving of the thermal problem by calculating the temperature increase taking into account the temporal and spatial heat transport. Today's common simulation platforms treat the electromagnetic and thermal field problems separately. In a first (electromagnetic) simulation run, the specific absorption rate (SAR) in each voxel is calculated. Based on this, the calculation of the temperature development inside the body model is carried out by means of a numerical solution of Pennes' bioheat transfer equation (BHTE), which in its most general case contains five terms for describing the following processes: Heat conduction, blood perfusion effect, metabolic heating, electromagnetic heating and heat storage. The product of the previously calculated SAR and the specific heat capacity is mapped as an electromagnetic heat source term for each voxel in the BHTE.

With regard to the resulting exposure-associated increase in tissue temperature in humans, the metabolic heat production and blood perfusion applied in the calculation model are of decisive importance, the latter in particular being regarded as dynamically variable in reality, at least at high exposure intensities, which cannot typically be mapped in the current calculation models. However, the remaining uncertainties can be quantified by means of variation analyses of the aforementioned parameters.

In addition, the heat transfer coefficient between the skin surface and the surrounding air (usually used as a boundary condition for the BHTE in the calculation models) is of great importance (varies in reality depending on skin moisture, clothing, hair, convection, etc.).

In connection with the increasing use of higher frequencies and the absorption thus concentrated on the body surface, absorption analysis in the skin on a microscopic scale has recently also become the focus of research projects. First, the absorption in different layers of the epidermis was analysed using a multilayer model and based on this the absorption distribution within epidermal cells (Jerbic et al. 2023, Jerbic 2024). It is shown that the modelling of the cell organelles has a significant influence on the absorption distribution within the cell (taking into account the cell organelles, the absorption maximum shifts significantly outwards towards the cell membrane). However, the influence of the cell organelles when considered for the calculation result in FR2 does not appear to be very pronounced. It should also be noted that there are large uncertainties regarding the material properties of the microscopic cell structures used in the calculations.

To illustrate the physical mechanisms in very small organisms, it should be mentioned that for some years there have also been studies that deal, for example, with the absorption of high-frequency radiation in insects, since these animals or parts of them are in the resonance range of the waves in terms of size, which can basically increase the absorption. The results of studies based on numerical calculations with 3D models of different insect species show that the total body absorption in the FR2, depending on the size of the insects, can be significantly (by more than a factor of 10) greater than in the FR1 (Herssens et al. 2022, Jeladze et al. 2023, Thielens et al. 2020, Überbacher et al. 2011). However, recent work suggests that absorption takes place to a large extent in the chitinous carapace of the animals (Jeladze et al. 2023). The biological significance of these issues in practice is unclear.

The known physical effects and the specific absorption behaviour of millimetre waves open up a number of potential therapeutic applications. At the forefront of the research are applications related to pain therapy, inflammation, arthritis, cancers and additional treatment for infections such as COVID-19 (Radzievsky et al. 1999, Jing et al. 2024). The assessment of the evidence for such therapeutic effects is not part of the advisory mandate for this statement. It should be noted that the levels of exposure in these studies are generally significantly higher than those that may occur in mobile phone applications. In contrast to classical hyperthermia with the aim of heating deep tissues or organs by applying radio frequency (typically 13.56 MHz to 2.45 GHz) electromagnetic fields, a therapeutically potentially usable tissue temperature increase occurs at millimetre waves due to the low penetration depth into only the uppermost tissue layers. However, direct therapeutic effects of millimetre waves in deep tissues or organs could be achieved with endoscopic procedures by placing the radiating antenna in the target tissue or organ.

3.3 Current ICNIRP recommendations

In the current recommendations of the International Commission on Non-Ionising Radiation Protection (ICNIRP), for the first time very detailed considerations are made with regard to the absorption mechanisms in the centimetre and millimetre wave ranges. Due to the fact that in the frequency range above a few GHz absorption takes place almost exclusively on a surface level (i.e. in the upper skin layers), the local exposure limit recommended by ICNIRP (both for occupational exposure and for the general public) in the frequency range above 6 GHz is not set as the maximum specific absorption rate averaged over 10 g of body tissue and over 6 minutes time intervals ($SAR_{10\,g}$ measured in W kg^{-1}), but as the absorbed power density S_{ab} (in W m^{-2}) averaged over 6 minutes, and averaged over 4 cm^2 or 1 cm^2 of surface area (for frequencies > 30 GHz), respectively[1]. Due to the near-surface absorption, S_{ab} correlates significantly better with the temperature increase caused in the tissue than SAR_{10g}. For very short (pulsed) exposures, ICNIRP (2020) specified additional basic restrictions for the frequency range above 6 GHz as exposure-time-dependent values for the absorbed energy density U_{ab} in order to prevent local overheating by high-energy pulses with pulse durations in the range of or significantly below the thermal time constant in the tissue.

In order to facilitate routine verification of compliance with the basic restrictions, ICNIRP (2020) also set reference levels for the incident power density S_{inc} and the incident energy - density U_{inc} for the frequency range above 6 GHz. With the intention of setting the reference levels conservatively in order to ensure that compliance with the basic restrictions is implicitly guaranteed if the reference levels are not exceeded, the reference levels were stipulated on the basis of attempts to establish the relationship between S_{inc} and U_{inc} and the resulting S_{ab} and U_{ab} under conservative (worst case) assumptions. Since the ICNIRP (2020) recommendations were published, there has been a lot of research on whether the reference levels laid down therein actually ensure compliance with the basic restrictions for all conceivable exposure situations (Christ et al. 2020a, Christ et al. 2020b, Diao et al. 2020, Diao et al. 2021, Li et al. 2023b, Li et al. 2024, Miura et al. 2021, Morimoto und Hirata 2022, Taguchi et al. 2022). In fact, it was possible to identify specific exposure situations in which exceeding the basic restrictions cannot be ruled out, even though the reference levels are complied with. However, situations with relevant discrepancies (exceeding S_{ab} by a factor of up to 4, although S_{inc} is at the reference level) concern only specific situations in the near-field of the source when the real part of the component of the Poynting vector normal to the skin is used as S_{inc} for the assessment (Christ et al. 2020a)[2]. In all other and thus most typical exposure situations, it can be assumed, based on the available data, that the reference levels set by ICNIRP (2020) ensure compliance with the basic restrictions.

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[1] The basic restrictions for 'local exposure' are used to avoid harmful small-scale tissue temperature increases, for example caused in near-surface tissue layers by a user device operated in close proximity to the human body. In contrast, the basic restrictions for whole body exposure are used to limit the exposure-associated increase in body core temperature. The latter is particularly relevant in the case of a largely uniform exposure of the entire body. According to ICNIRP 2020, a basic restriction in shape of an SAR averaged over the entire body mass (averaged over 30 minutes) is also set for whole body exposure in the frequency range above 6 GHz.

[2] Using the magnitude of the Poynting vector as S_{inc} significantly defuses the situation (Christ et al. 2020a).

3.4 Verification of user devices for compliance with the reference levels and basic restrictions

The verification of compliance with the basic restrictions for exposure to radio transmitters operated in FR2 near human bodies introduces new requirements for dosimetry. The SAR measurement technology established in FR1 for these purposes, with which a metrological determination of the spatial distribution of the induced electric field strength in a body phantom filled with tissue-simulation liquid is possible and which accordingly makes it possible to draw conclusions about the SAR distribution, encounters hard limits in FR2 mainly due to the low penetration depth. In addition to adjustments to the higher transmission frequencies and measurement bandwidths in FR2, design adjustments are therefore also required, or completely new measurement concepts have been developed for this purpose. IEC/IEEE TR 63572 (IEC 2024) summarises the most important measurement methods currently under development for the determination of S_{ab} in the course of user device testing. Essentially, all procedures follow one of the three basic principles below (hybrids from the basic principles are also conceivable):

a) *Measurements of electric field strength with special pseudo-vector field probes in a body phantom with tissue-simulating liquid*
As with the established SAR measurement in FR1, the body phantom serves, on one hand, to realistically simulate the interaction with the field source and, on the other hand, to model the absorption losses in the tissue. In addition to the special structure of the phantom shell and the composition of the tissue-simulating liquid, the structure of the field probes used differs fundamentally from the corresponding components of the established SAR measurement technology. The field probe consists of two miniature E-field sensors arranged orthogonally to each other (in a plane orthogonally to the field probe shaft). During the measurement, the field sensor plane is arranged in parallel to the phantom surface at each examined measuring point and rotated gradually around the probe axis (normal axis to the phantom surface), with a measurement of the signals received by the two E-field sensors at each angle position. This procedure is repeated in several measuring points along a typically matrix-like measuring point grid. From the polarization ellipses obtained in this way at the individual measuring points, a complete reconstruction of the near field can be approximated using mathematical algorithms (Pfeifer et al. 2019) and thus S_{ab} can be determined from the values measured by the probe with a spatial resolution of less than 0.5 mm.

b) *Measurements of electric field strength in air behind a realistically reflective surface of a thin layer of material*
The reflective surface only serves to simulate a realistic interaction with the field source (reflection on the body surface), but does not cause significant losses, i.e. the radiation penetrating the material layer is only weakened to a small extent, so that a measurement of the electric field strength can be carried out in air at a distance of several centimetres behind the surface. From the measurements of the electric field strength distribution behind the surface, including the properties of the material layer, S_{ab} can be deducted.

c) *Surface temperature measurement on the back of a thin skin phantom layer*
In this method, the skin phantom layer serves on one hand, to realistically simulate the interaction with the field source and, on the other hand, to model the absorption losses in the tissue and on the other hand to reproduce the radiation absorption and temperature distribution in the skin phantom layer as identical as possible to the corresponding processes occurring in real skin. S_{ab} can be inferred from the temperature distribution measured by means of an infrared camera on the back of the skin phantom layer.

The basic normative requirements for the measurement, simulation and computational determination of S_{inc} in the near-field of antennas for the purpose of verifying compliance with the corresponding reference level for local exposure from radio transmitters operated in close proximity to the human body in FR2 are laid down in IEC/IEEE 63195-1 (IEC 2022a) and IEC/IEEE 63195-2 (IEC 2022b).

If S_{inc} does not exceed the applicable reference level, compliance with the basic restriction for the locally absorbed power density S_{ab} may be assumed. International standardization work for measurement and numerical calculation methods to determine the power density S_{ab} absorbed in the tissue for the purpose of direct comparison with the corresponding basic restriction is currently underway.

3.5 Legal regulations for protection against high-frequency exposure from mobile base stations

3.5.1 Relevant legislation for installations above 10 W EIRP

The Federal Immission Control Act (BImSchG 2013) contains the legal basis for the Twenty-Sixth Ordinance on the Implementation of the Federal Immission Control Act (Ordinance on Electromagnetic Fields, BImSchV 2013) and thus provides the legal basis for setting limit values for electromagnetic fields.

Among other things, the ordinance lays down requirements for the installation and operation of fixed high-frequency systems (frequency range: 9 kHz to 300 GHz), which in principle also includes fixed radio equipment, and thus also 5G base stations in the frequency ranges FR1 and FR2. The 26th BImSchV applies if a radiated power of 10 W EIRP is reached or exceeded at a plant site by the existing antennas.

The Ordinance on the verification procedure for limiting electromagnetic fields (BEMFV 2002) details the procedures for verifying the compliance with the limit values of the 26th BImSchV (BImSchV 2013) for fixed radio equipment. The Federal Government/States Working Group on Immission Control provides further guidance for the practical implementation of the 26th BImSchV (LAI 2014).

3.5.2 Limits stipulated by the 26th BImSchV

For the frequency range (FR2) relevant here, the 26th BImSchV (BImSchV 2013) adopted the reference levels and summation rules from the ICNIRP Recommendations of 1998 (ICNIRP 1998) and the World Health Organisation (WHO) of 1998, on which the EU Council Recommendation (EU 1999) for electric, magnetic and electromagnetic fields is based, too (Deutscher Bundestag 2013).

According to the specifications of the 26th BImSchV, the exposure limits for fixed high-frequency installations must not be exceeded at the highest operational utilisation of the generating plants, including the high-frequency background radiation from other fixed high-frequency installations at all locations intended for the permanent or temporary presence of people.

For evaluation purposes, the 26th BImSchV only lists limit values for the field strengths (reference levels) and no limit values for the equivalent power density and no basic restrictions. In addition, § 5 of the Ordinance contains a rigid (dated) reference to the 2009 edition of DIN EN 50413 (DIN EN 50413:2009-08) on measurement and calculation procedures for determining the field strength and power density values, in which no statements are made as to a possible spatial averaging of the fields, so that this cannot be applied either.

3.5.3 Regulations concerning installations below 10 W EIRP

For transmitters with less than 10 W EIRP, which are often used in systems for the wireless network coverage within buildings, the specifications of the 26th BImSchV (BImSchV 2013) are not applicable, so the operator does not have to apply for a site certificate from BNetzA for these installations. (If necessary, the only requirement is to report when the system is put into or taken out of service.)

In this case, however, one is not in a legal vacuum, but in particular the Act governing the distribution of radio equipment on the market (Radio Equipment Act – FuAG 2017)), which transposes into national law the Radio Equipment Directive 2014/53/EU (RED, EU 2014) on the harmonisation of the laws of the Member States relating to the distribution of radio equipment on the market, is also applicable in Germany. In this respect, the Radio Equipment Act refers to the European Union's specifications regarding personal protection from high-frequency fields. Among other things, the Radio Equipment Act, s 4(1)(1) stipulates that radio equipment (regardless of its output power) must in principle be operated in such a way that persons are not put at risk.

The safety of radio equipment required by RED (EU 2014) is usually demonstrated by compliance with the relevant harmonized standards listed under RED in the official journal of the EU. The journal currently lists the product standard EN 50401 (EN 50401:2017) for mobile base stations that emit radio signals in the frequency range from 110 MHz to 100 GHz. This standard requires compliance with the limit values of the EU Council Recommendation on the limitation of exposure of the general public to electromagnetic fields 1999/519/EG (see EN 50401:2017, Chapter 5). For the practical implementation of the conformity assessment, reference is made, among others, to EN (IEC) 62232 (DIN EN 62232).

In order to demonstrate the safety of 5G base stations in FR2 frequency range with an EIRP of less than 10 W, the operator may ultimately apply the same field strength limits as those established by the 26th BImSchV (BImSchV 2013) for fixed radio transmitters with an EIRP of 10 W or more are predetermined, since the 26th BImSchV is based on the same reference levels as EU Council Recommendation 1999/519/EG (EU 1999).

Since the RED (EU 2014) refers to the to the EU Council Recommendation 1999/519/EG (EU 1999) it should be possible to carry out an assessment of compliance with the basic restrictions as an alternative to a conformity assessment on the reference levels (field strength) for installations with an EIRP of less than 10 W. Since the EU Council Recommendation for frequencies above 10 GHz uses the incident power density S_{inc} – instead of the SAR – as a basic restriction, from a technical point of view, the operators of an installation operated in FR2 could also demonstrate compliance by means of appropriate power density measurements or calculations in the vicinity of the antennas.

3.5.4 Approval and control of stationary radio equipment

The verification of compliance with the BEMFV (BEMFV 2002) is carried out by the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railways (BNetzA) for fixed radio installations with an EIRP of 10 W or above.

The operator shall notify BNetzA of the commissioning or substantial modification of such fixed radio equipment at least two weeks before commissioning. Decommissioning must be reported immediately.

The time of commissioning or decommissioning of a stationary radio transmitter site in public radio networks with an EIRP of more than 0.1 W and less than 10 W (e.g. a small cell base station or a radio supply system inside buildings) shall be reported to BNetzA within four weeks of commissioning or decommissioning.

The BNetzA typically verifies compliance with regulatory limits for radio equipment with an EIRP of 10 W or more prior to the equipment being put into service. Additional checks on installations already in operation are provided on a routine basis to a certain extent, or upon notification by third parties, or when irregularities are detected

Compliance with the specifications of the 26th BImSchV (BImSchV 2013) is ensured by BNetzA's 'site certificate procedure' for stationary radio equipment from 10 W EIRP (i.e. also for 5G base stations in the frequency ranges FR1 and FR2). In the event of a new installation or substantial modification of a radio transmitter site, the operator must provide BNetzA with all technical and other system data (e.g. plant plans) necessary for the calculation of the electromagnetic fields occurring in the vicinity of the equipment. BNetzA then calculates horizontal and vertical safety distances for the highest operational load from these data, taking into account both all other equipment present at the site and the high-frequency background exposure caused by radio transmitter sites in the vicinity.

The site certificate is issued if limit values have been exceeded only within the 'controllable area' (i.e. the area where access is not possible in general but only to instructed persons), but not outside of it. The installation may therefore only be operated if no persons are permitted within the controllable area, unless they are persons instructed in exposure to high-frequency fields who, for example, have to be present within the controllable area due to occupational duties (e.g. maintenance personnel, roofers).

It is also possible to issue the final site certificate only on the basis of measurements carried out on site. In this case, measurements are used to check whether the requirements of the 26th BImSchV are met in all places around the plant that are not restricted to the general public. Therefore, no safety distances are explicitly stated in site certificates based on measurements. The same has applied for some time now to sites where BNetzA has used a new programme based on field-theoretical calculation methods ("Wattwächter") for the purpose of arithmetic conformity check.

The site certificate is issued for the installation configuration requested by the operator. Insofar as technical changes to the facilities at the site significantly deviate from the mode of operation requested (in particular if the planned changes could lead to an increase in the safety distances), it is first necessary for further operation that the operator applies to BNetzA for a new site certificate. Without this document, the operation of the site with the changed parameters is not permitted.

In view of the current implementation practice in Germany, it can therefore be assumed that at radio transmitters site with an EIRP of 10 W or more, which are equipped with or can be supplemented with 5G base station antennas in the frequency range FR1 and/or FR2, the compliance with the protection specifications of the 26th BImSchV (BImSchV 2013) for the general public is ensured by the site certificate procedure of the BNetzA.

For sites below an EIRP of 10 W, the responsibility for ensuring personal protection lies with the plant operator. The BEMFV (BEMFV 2002) does not contain any specifications for this. To this end, the plant operator must ensure compliance with the specifications of the FuAG (FuAG 2017) or the RED (EU 2014), as already explained in section 3.5.3.

In June 2023, the four German mobile network operators (Deutsche Telekom Technik GmbH, Vodafone GmbH, Telefónica Germany GmbH & Co. OHG, 1&1 Mobilfunk GmbH) declared in a voluntary self-commitment (Mobilfunknetzbetreiber 2023) that:

- for small cells of any design with EIRPs of 2 W to 10 W in the indoor and outdoor area rules for an equally valid protection scheme are applied and
- small cells whose antenna's lower edge is installed higher than 2.30 meters above the ground or the intended accessible area. For these installations, operators pledge to install and operate them in such a way that, in all places intended for permanent or temporary presence, the limit values of the 26th BImSchV (BImSchV 2013) are guaranteed to be adhered to.
- Where, in exceptional cases, a lower installation height is required due to local conditions, for example because of insufficient ceiling height in underground car parks, garages and corridors, operators confirm to construct and operate the installations in such a way that the limits of the ICNIRP guidelines (ICNIRP 2020) are safely undercut in all places intended for the long-term or temporary presence of human beings. If necessary, compliance with the basic restrictions can demonstrate implicit "touch compliance".
- The assessment is carried out according to the limit values of the 26th BImSchV or, in the exceptional cases mentioned above, according to the ICNIRP Guidelines 2020. The current standards on measurement and calculation methods are taken into account.

The four major German mobile network operators accordingly pledge to ensure that their systems with EIRPs of less than 10 W also by analogy comply with the specifications of the 26th BImSchV (BImSchV 2013) or, alternatively, the basic restrictions according to the EU Council recommendation 1999/519/EG (EU 1999) or the recommendations of the current ICNIRP guidelines from 2020 (ICNIRP 2020), respectively.

However, this self-commitment does not include operators of private 'campus networks' (universities, research institutes, industry, agriculture, logistics, etc.), which can also install and operate 5G networks (FR1 or FR2) in the area of their properties.

It is foreseeable that campus network operators will require additional information on the obligation to ensure the protection of persons from the fields radiated by radio transmitter sites, as they often operate such a mobile communication network for the first time. As a result, they are generally not as well informed about the applicable legal requirements as is the case with the highly experienced operators of national public mobile communication networks in this field.

In addition, according to the BEMFV (BImSchV 2013) there is only an obligation to notify BNetzA of the commissioning of radio transmitter sites with an EIRP of less than 10 W if it is an installation in a public telecommunications network. The antenna locations of operators of private 5G campus networks with an EIRP of less than 10 W are therefore not known to BNetzA in detail, it only knows the operator of the network because of the licensing for the use of frequency.

In summary, it can therefore be stated that in Germany 5G base stations in the frequency range FR2 are in principle subject to the same legal and executive regulations as the mobile network transmitter sites in the frequency range FR1, which have been in operation for many years. This applies to both, systems with more than 10 W EIRP and with less than 10 W EIRP.

However, it is possible to operate private 5G campus networks in both FR1 and FR2 frequency ranges. It is foreseeable that operators of such networks will require additional information regarding the obligation to ensure the protection of persons in the vicinity of base station antennas, since they are usually little experienced in the field of personal protection from radio transmitter sites.

3.6 Summary assessment of the technical and regulatory aspects of 5G technology in the FR2 frequency range

The results of the technical part of this statement can be summarised as follows:

- In principle, FR2 has higher path loss than FR1. As a result, the maximum possible transmission distance decreases, and directional radiation of the antennas used is mandatory. Therefore, FR2 is mainly used for indoor communications, fixed outdoor radio links or outdoor Line of Sight (LoS) communications, e.g., when high data transfer rates are required.
- Even more clearly than in the frequency range FR1, beamforming antennas in the frequency range FR2 can selectively and in a demand-oriented manner focus the available transmission power on certain areas. This means that an increase in exposure is to be expected especially where there is a large density of active user devices. In other local areas not covered by antenna beams, mean exposure will be lower compared to static illumination.
- As in the case of 5G in the FR1, the always-on signalling power continuously emitted from the 5G base station into the radio cell (i.e. the proportion of the total power continuously emitted for the purpose of signalling and synchronization of the user devices) is significantly lower than in the case of 2G/3G/4G. Especially in times of low utilization of the system, this implies that the ratio between actual and maximum exposure is lower than for precursor technologies.
- Due to the higher frequencies used in FR2, radiation absorption takes place on the surface of the body, so that the skin and the cornea of the eye are potential target tissues for harmful effects. The known metrological methods for demonstrating compliance with the limit values for protection against negative health consequences of radio transmitters operated in close proximity to the human body must be extended or adapted accordingly for devices transmitting in FR2 frequency range. International standardization bodies are currently working towards this.
- In principle, 5G base stations in FR2 frequency range in Germany are subject to the same legal and executive regulations that apply to radio transmitter sites in FR1 frequency range and that have been in operation for many years. This applies to both, systems with equal or more than 10 W EIRP and with less than 10 W EIRP.
- In principle there is also the option to operate private 5G campus networks in both FR1 and FR2 frequency ranges. It is foreseeable that the operators of such networks will require additional information regarding their obligation to ensure the protection of persons in the vicinity of base station antennas, since these operators are usually little experienced in the field of ensuring health protection from radio transmitter sites.

3.7 Open questions and domains requiring further research

- Due to the local concentration of radiation absorption in the skin and the cornea of the eye observed in FR2, detailed knowledge of the absorption processes is of particular importance. Although research results are already available on this set of questions, many specific questions still appear to remain open at present. Addressing these questions seems to be a very complex task, in particular because of the great biological variability of the skin along the human body and changes due to the aging process. Current limit value recommendations are based on numerical calculations using very simple planar layer models of the skin, exclusively with regard to thermal effects, taking safety factors of varying degrees of validity into account. Further systematic studies considering the anatomical and macroscopic fine structure of human skin – such as sweat glands or hair follicles (including their variability and age-related changes) – to establish anatomically sufficiently differentiated absorption models could contribute to a further development of the limit value recommendations.

- Since only a few 5G test installations in FR2 frequency range are currently available in Germany, the currently available exposure level data come from simulation-based estimates or from measurements in other countries. In the case of an operational network setup of 5G transmitters in the frequency range FR2 in Germany, it is recommended to accompany them in terms of exposure level measurement technology, taking into account, for example, the exposure-relevant characteristics of beam steering antennas.
- In order to evaluate – from a radiation protection point of view – radio transmitters operating in FR2 in close proximity to the body research activities striving to reliably determine S_{ab} and S_{inc} can be observed on an international level, and in parallel, corresponding international standards are currently being developed. According to the current assessment, it can therefore be assumed that the questions currently outstanding in this context can be answered within the next one to two years at least to the extent that nothing stands in the way of a reliable radiation protection assessment of future user devices in FR2 when it is introduced or distributed in Germany.
- Operators of 5G campus networks should be informed as part of the licensing process of their obligations to ensure the protection of people from electromagnetic fields (general public and occupationally exposed persons).

Currently, the definition of the 6th mobile phone generation 6G is being developed; the roll-out is expected at the beginning of the 2030s. According to the current understanding, 6G will operate in the same frequency ranges, that are currently used by GSM, LTE and 5G. In addition, a so-called frequency range FR3 is in preparation, which will extend from about 7 GHz to 24 GHz and thus close the gap between FR1 and FR2. The development of the sub-THz ranges from 100 GHz to 300 GHz is also being discussed. This will present new challenges for the exposure assessment as well as the biological assessment.

On the basis of the information currently available, it is not possible to carry out a sound assessment of 6G from a radiation protection point of view, as important technical parameters have not yet been defined. If 6G will operate in the currently established frequency ranges, it can be assumed that the statements regarding biological effects made in the relevant publications of the SSK are in principle transferable.

4 Scientific background regarding biological and health effects

In the second part of this statement, the scientific knowledge regarding biological and health effects of RF-EMF in the frequency range FR2 is collected and discussed. In the EMF portal (https://www.emf-portal.org/en) a query from 8 May 2025 retrieved a total of 372 studies for the millimetre wave frequency range (MMW), which are to be assigned to the subject area medicine/biology. Since the MMW range includes frequencies from 30 GHz to 300 GHz, thirty additional studies have been identified for the 20 GHz to 30 GHz frequency range. Of the 402 medical/biological studies listed in the EMF portal for the 20 GHz to 300 GHz frequency range, 54% (n = 216) were not considered relevant in this context, as they (a) were published as conference, symposium or book contributions, (b) examined frequencies outside FR2, (c) examined effects on plants, bacteria, yeasts, fungi or vesicles, (d) examined biophysical or technical effects and/or (e) carried out simulations without measurements. Furthermore, therapy-relevant animal studies as well as studies in patients were classified as not relevant.

Overall, there are comparatively few studies on biological effects of exposure in FR2 frequency range compared to those of exposure in FR1frequency range. This is especially true for human epidemiological and experimental studies. The latter are therefore all briefly described in section 4.3. Only two epidemiological studies were identified in the EMF portal, but they did not carry out a separate evaluation for FR2. They therefore do not provide information that is relevant to this statement. For animal in vivo studies (hereinafter referred to as 'in vivo studies') and in vitro studies, the data situation is slightly different, and reviews are already available (see section 4.1.1). A further literature search on the EMF portal for reviews conducted until 12 May 2025 yielded 209 publications. The same criteria were applied to reviews as to the original literature. In addition, only reviews that were accessible, published in the last 25 years, in which the literature selection was comprehensibly described, and which have carried out a quality assessment of the studies were taken into account. Sections 4.4 and 4.5 present the original studies, which were published from 2019.

Like the technical part, the second section of this statement is limited exclusively to FR2 frequency range (i.e., 24.25 GHz to 71 GHz), which is not yet significantly used for mobile communications in Germany. The technical, biological, and health assessment of 5G applications in the already used frequency range up to around 7 GHz (FR1) was dealt with in a separate statement of the SSK (SSK 2021).

In order to assess the current state of research in the field of biological and health effects, the first step was to compile the results and conclusions of existing reviews (section 4.1.1). In a second step, statements from national advisory bodies and authorities concerning FR2 are - presented (Section 4.1.2). In sections 4.1 to 4.5 results from original studies are presented for the various research disciplines (epidemiology, human experimental studies, in vivo studies, and in vitro studies). Thus, the currently available scientific knowledge identified here has been incorporated into the overall view of the considerations.

4.1 Relevant statements and reviews

In total, two reviews, a meta-analysis and a literature study focussing on the effects of exposure to electromagnetic fields of FR2 frequency range (> about 24 GHz) were identified (see section 4.1.1).

In addition, national authorities from the Netherlands and France have published statements on the health effects of 5G, in which FR2 frequency range is discussed separately (see section 4.1.2).

4.1.1 Reviews on biological and health effects of exposures in FR2 frequency range

The following four reviews presented in more detail in this section meet the above selection criteria:

In a literature search in the PubMed database[3] and EMF portal[4] as well as relevant literature from other documents, such as ICNIRP, SCENIHR, WHO, IARC, IEEE, etc., Simko und Mattsson (2019) have identified publications written in English that were published by the end of 2018 and which examined health effects of exposure in the 6 GHz to 100 GHz frequency range. In the review, 94 studies were identified and analysed. 45 in vivo studies were included, mainly in mammals (mouse, rat, rabbit) and in a few cases in humans. In the 53 in vitro studies, primary cells (n = 24) or cell lines (n = 29) were used. In some studies which were not considered, bacteria, fungi, and other living material were used for the experiments.

In addition to the study type (in vivo, in vitro), each study was characterized by biological material (species, cell type, etc.), biological endpoint, exposure (frequency, exposure duration, power density), results, and certain quality criteria. Eighty percent of the in vivo studies showed responses to exposure, while 58 percent of the in vitro studies showed effects. The reactions affected all investigated biological endpoints. There was no consistent relationship between power density, exposure duration, or the frequency and effects of the exposure. The available studies do not provide adequate and sufficient information for a meaningful risk assessment or on the question of non-thermal effects. Further research is needed on the local heat development on small surfaces, such as the skin or eye, and on the possible effects on the environment. In this review, a systematic quality assessment of the studies was also carried out, taking into account the criteria of temperature control, blinding, dosimetry, sham exposure, and positive control. Of the 45 in vivo studies, 78% (35) showed biological reactions after exposure to MMW. Of all studies, 73% were carried out with sham exposure or controls, 76% used appropriate dosimetry, 44% used positive controls, and 67% were carried out under temperature-controlled conditions. Unfortunately, only 16% of the studies were conducted according to protocols that ensured blinding, and only three publications were identified that met all five criteria. If the blinding criterion was excluded, 13 studies could be identified that met the remaining four criteria. Taking into account only three criteria, namely sham exposure, dosimetry, and temperature control, 40% (20 studies) were identified, which means that the quality of the in vivo studies as a whole must be classified as insufficient. Of the 53 in vitro studies, only 13 (42%) met three of the five quality criteria (temperature control, dosimetry, and consideration of sham exposure or control group). Positive controls were considered in 47% of the studies, and only one study was conducted with a blinded protocol. The authors concludes that design and conduct of future studies need to be significantly improved if they are to be useful for safety assessment. Simkó and Mattsson also point out that no epidemiological studies on exposures in the 5G FR2 frequency range existed by the reference date under consideration.

Karipidis et al. (2021) conducted a review on biological and health effects of exposure to RF-EMF > 6 GHz, taking into account only publications with exposures below the occupational exposure limit recommended by ICNIRP. For this purpose, a literature search was carried out in the databases PubMed, EMF-Portal, Google Scholar, Embase and Web of Science, which included studies published in English until December 2019. In addition, the literature lists of all included studies were used. The review included 107 experimental studies (91 in vitro, 15 in vivo and one human study) examining various biological endpoints, including genotoxicity,

[3] https://pubmed.ncbi.nlm.nih.gov/

[4] https://www.emf-portal.org/de

cell proliferation, gene expression, cellular signal transduction, membrane function and other effects. In addition, 31 epidemiological studies were included in which subjects were exposed to radar signals > 6 GHz.

Since the MMW are mainly absorbed in the area of the skin, epithelial and skin cells were a common model for investigating possible genotoxic effects. Genotoxicity was investigated in 22 studies using different methods (mainly comet assay, micronucleus assay, chromosomal aberrations and spindle disorders) on exposed cells. The methods used for this were generally very accurate, but conflicting results were reported in the studies, especially when chromosomal aberration or spindle disorders were studied. Some assays (such as the comet assay) consistently showed no signs of DNA damage in skin cells. However, animal studies conducted by one research group found DNA strand breaks and changes in enzymes that control the build-up of ROS. These studies, however, included only a small number of animals (e.g. in one study only six exposed animals). Two studies by a Russian research group have reported indicators of DNA damage in bacteria, but these results have not been independently reproduced by other researchers. Overall, the main problem of these studies was the lack of adequate dosimetry, blinding and sufficient temperature control.

The studies on the effect of MMW on cell proliferation in 23 studies focussed primarily on bacteria, yeast cells, and tumour cells, with many of the studies showing insufficient dosimetry and temperature control. The studies reported conflicting results, possibly due to thermal effects in some of the studies. An Italian research group that conducted the most studies on tumour cells reported either a reduction or no change in the proliferation of the exposed cells. However, these studies also showed insufficient dosimetry and temperature control.

The 18 gene expression studies mainly looked at two different indicators: the expression of stress-sensitive genes and chaperone proteins as well as the appearance of a resonant effect in the cells to explain changes in the DNA conformation state. Most studies found no effects of weak MMW on the expression of stress-sensitive genes or chaperone proteins, using a number of experimental methods to confirm these results. In these studies, there was also no blinding, so a bias of the results cannot be ruled out.

The 10 studies on signal transmission in cells and on electric activity reported a number of different results, including increases or decreases in signal amplitude and changes in signal rhythm. In most studies, no uniform effects were found, and again, the studies were not blinded. Karipidis et al. (2021) concluded that overall, the reported effects on electric activity cannot be dismissed as being within normal variability. However, the studies suggest that even with prolonged exposure, normal function is restored after a short period of time. In this case, in the opinion of the team of authors, these studies do not provide any indication of an expected negative effect on health.

In the analyses of membrane effects, changes in membrane properties and permeability were investigated in 20 studies. In some studies, changes in the transition from the liquid phase to the gel phase or vice versa have been observed, and the authors suggest that MMW affect cell hydration. However, the statistical methods used in these studies have not been described, making it difficult to verify the validity of these results. Overall, a large number of bio-effects of the membranes were reported, but these were not reproduced independently, and the studies showed insufficient dosimetry and temperature control, as well as an insufficient statistical analysis.

The limited number of studies (20) on a number of so-called ‘other effects’ of exposure to MMW below the exposure limit recommended by ICNIRP generally showed few to no consistent effects. In the only in vivo study of cancer development, but without sham exposure, no effect of MMW was observed. The effects on reproduction were inconsistent, possibly influenced by the opposing aims of studying adverse health effects or infertility treatment. In addition, the only human sperm study found no effects of weak MMW.

Karipidis et al. (2021) note that although a number of bio-effects have been reported in many experimental studies, the results have generally not been independently reproduced. Again, as with Simko und Mattsson (2019), it was pointed out that about half of the studies came from only five laboratories and several studies were carried out in collaboration between one or more laboratories. Exposure characteristics varied significantly between the different studies, with the studies showing the greatest effect grouped around a power density of about 1 W m^{-2}.

As in the study of Simko und Mattsson (2019), the quality of the studies was assessed in the review of Karipidis et al. (2021) coming to similar results. Most studies have deficiencies in a number of quality criteria, including dosimetry, lack of inclusion of positive controls, blinding, and accurate measurement or control of the temperature of the biological system being tested. The associated meta-analysis (Wood et al. 2021) showed that the majority of the studies had a quality score of less than two out of five possible points, with only one study achieving the maximum quality score.

The meta-analysis of Wood et al. (2021), based on the experimental data described in Karipidis et al. (2021), also showed that there is no dose-response relationship between exposure (either power density based on 84 studies or SAR based on 31 studies) and the magnitude of the effect. Rather, studies with higher exposure tended to show a smaller effect size. A negative correlation could also be observed between the effect size and the quality assessment. Most studies that showed a large effect were conducted in the 40 GHz to 55 GHz frequency range and represent studies on the use of MMWs for therapeutic purposes.

Taking into account all outcomes examined from a total of 107 experimental studies, Karipidis et al. (2021) concluded that there is no confirmed evidence of a health hazard from exposure to radiofrequency fields in the frequency range > 6 GHz when complying with the occupational exposure limit recommended by ICNIRP.

In addition, Karipidis et al. (2021) point out that there are no epidemiological studies that have directly investigated a relationship between 5G signals and potential health effects. However, there are epidemiological studies that have looked at effects of occupational radar exposure, which could potentially span FR2 frequency range from approximately 24 GHz to 71 GHz and thus were included in the review since they address occupational exposure below the ICNIRP guidelines. However, information on the frequency of the radar signals was often missing. If frequencies were specified, it was usually well below FR2. This was to be expected, because most radar systems use frequencies below about 10 GHz. The review included 31 epidemiological studies (eight cohort studies, thirteen case-control studies, nine cross-sectional studies, and one meta-analysis) that examined radar exposure and various health effects including cancer at different sites, effects on reproduction and other diseases. In these epidemiological studies, exposure levels were below the exposure limit recommended by ICNIRP in most situations, according to the authors. They provided little evidence of a link with health impairments. Only a small number of studies reported associations, although various methodological problems need to be considered. For example, the main problem of the cohort studies was that the exposure levels were not determined and the analysis was based only on the job title as an exposure surrogate. On the one hand, this leads to considerable errors in the exposure assessment; on the other hand, different occupational groups are compared with each other, which also differ with regard to other risk factors. Several studies have compared radar-exposed military personnel with the general public. On average, military service providers are expected to be healthier than the general public ('healthy worker effect').

Karipidis et al. (2021) also discuss a number of case-control studies that have examined the relationship between exposure to radar and testicular cancer or tumours in the eyes. Partially increased risks have been observed, but since the exposure was retrospectively self-reported and not quantified, the results could be affected by recall bias. Case-control studies of other tumours, such as brain tumours, Hodgkin's lymphoma and cancer in general usually found no correlations.

In two out of three cross-sectional studies on sperm quality, differences between radar-exposed and non-exposed were detected. Further studies on male fertility and pregnancy-related effects were also inconsistent.

Epidemiological studies of other diseases were rare. A few observational studies have found differences in physiological parameters. However, these studies had a high risk of bias.

In a literature study commissioned by the Swiss Federal Office for the Environment (FOEN) and published in May 2025, Mevissen et al. (2025) summarized study results on biological effects of electromagnetic fields in the frequency range 5.8 GHz to 200 GHz and their consequences for health. The aim of the study was to systematically record and evaluate effects of such exposures on laboratory animals, humans and cell cultures. The relevant biological effects relate primarily to cancer development, neurological diseases and skin diseases. However, they also include other biological functions, such as reproduction and fertility, developmental, cognitive and physiological aspects, as well as mechanisms that play a role in various processes, such as oxidative stress and cell death. The methodology of the report essentially follows that of a systematic review. The studies were identified through systematic queries in the MEDLINE (PubMed), Science Citation Index Expanded and Emerging Sources Citation Index (Web of Science) databases and the EMF portal. Taking into account the PECO criteria (‘Population, Exposure, Comparison, Outcome’, see Chapter 7) for systematic reviews, articles from scientific journals and publicly available reports from government agencies were included, containing original data on animal and cell studies with exposure to RF-EMF in the frequency range of 5.8 GHz to 200 GHz. For the report, the authors took into account studies published from 2019 to August 2024. For the discussion of possible health effects, the results of studies published before 2019 were also included. The methods and results of the studies in question were presented in accordance with the PRISMA guidelines. The studies were evaluated according to the Risk of Bias (RoB) risk analysis developed by the Office of Health Assessment and Translation (OHAT) of the US National Institute of Environmental Health Sciences (NIEHS). The authors note (original in German language):

> “The final assessment of the confidence in the experimental evidence and thus the reliability of the risk assessment of the respective biological effect of RF-EMF exposure in the MMW area was carried out using the so-called GRADE approach (Grading of Recommendations Assessment, Development and Evaluation),[5] again according to OHAT, with corresponding considerations.”

The qualitative analysis included 56 studies (29 in vivo studies and 28 in vitro studies), most of which investigated the 5.8 GHz to 29 GHz frequency range (n = 16 in vivo, n = 10 in vitro), followed by 50 GHz to 100 GHz (n = 5 in vivo, n = 13 in vitro), 101 GHz to 200 GHz (n = 3 in vivo, n = 6 in vitro) and 30 GHz to 49 GHz (n = 3 in vivo, n = 3 in vitro). On closer inspection, nine out of the 29 in vivo studies exclusively examined frequencies outside FR2. Another six studies were not conducted on mammals. Of the 28 in vitro studies, 12 examined effects of exposure to frequencies outside FR2.

[5] https://www.gradeworkinggroup.org

The authors carry out the following RoB assessment (original in German language):

> “In 20 in vivo studies, significant limitations regarding exposure and dosimetry were identified; for 19 studies, the ‘RoB’ was classified as ‘probably high’ and even ‘definitely high’ in one study.”

Fourteen in vivo studies also have limitations in temperature assessment. In ten studies, exposure contrast, i.e. between RF-EMF-exposed and sham-exposed animals, was assessed as likely to be insufficient or insufficient. According to the authors, similar assessments with limitations in different domains were also found for the in vitro studies.

With regard to health-related effects, study results were discussed in the following eight areas:

- Carcinogenesis, neurodegenerative and other neurological diseases,
- Diseases/impacts on the most exposed organs, such as skin and eyes, including thermal effects;
- Cardiovascular and immunological diseases,
- Fertility, reproduction and developmental processes,
- Cellular vitality, proliferation and senescence,
- Stress response and (cellular) homeostasis,
- Genetic and epigenetic integrity (transcriptomics/proteomics),
- Studies in humans that focus not only on symptoms of health but also on perception.

In summary, taking into account all studies, including those that examined frequencies outside FR2, Mevissen et al. (2025, p. 45/46), came to the following assessment (original in German language):

> “The studies on thermal effects of MMW show an increase in temperature in laboratory animals depending on the frequency and the intensity. The data do not allow statements on possible thresholds, but there are indications that a local temperature increase of 1 °C can be detected by test subjects (humans). The data from some studies also show that pulsed RF-EMF exposure in particular could be an interesting tool for cancer therapy in superficial skin tumours.
>
> Some of the in vivo studies provide evidence of impaired learning behaviour as well as structural changes in the brain, some of which are also associated with oxidative stress, as has already been observed at lower frequencies (< 5.8 GHz). At higher frequencies in the MMW range (< 60 GHz), there was evidence of altered activity of neurons, which, however, went in both directions. Evidence from in vitro studies showed an increased permeability of cell membranes after exposure at > 60 GHz, which could be caused by oxidative stress. Gene analyses partly support the observed changes in the neuronal and metabolic functions of the cells.
>
> Effects of MMW on cancer development are unlikely on the basis of data from in vitro studies on genotoxicity, whereby only one animal study on subcutaneous tumours has been published, which significantly lacks in quality (in three RoB domains). There is initial evidence of impaired reproduction from a multigenerational study of nematodes, which is likely due to oxidative stress. However, there are no studies in mammals to corroborate these findings.
>
> A statement on dose dependence cannot be made because, on the one hand, there are no studies investigating this and comparable experimental endpoints have rarely been evaluated, on the other hand, the dosimetry and the exposure characterization of many

studies is insufficient to derive reliable dose-response correlations. Overall, many of the published studies are affected by significant shortcomings, 46 studies in particular regarding exposure and dosimetry, meaning that no causal conclusions can be drawn from the results."

4.1.2 Statements from expert panels with an official mandate and from public authorities on biological and health effects of exposures in FR2 frequency range

Expert panels with an official mandate and from authorities from the Netherlands and France have published statements on biological and health effects of exposures in FR2 frequency range.

The report on health effects of 5G of the Health Council of the Netherlands (2020a, 2020b) already discussed in detail in the statement of the SSK (SSK 2021) on the topic of *Electromagnetic fields related to the current rollout of 5G mobile networks– Technical aspects and biological effects in the lower frequency range (FR1, up to approx. 7 GHz)* also considered the frequency range 40 GHz to 60 GHz. For the report, the committee analysed data from studies on the relationship between health effects and exposure to electromagnetic fields in three frequency bands, including the 20 GHz to 40 GHz frequency range. Studies with exposures above the applicable limit, which may lead to heating of the body or parts of the body, have not been considered. This also applies to studies on therapeutic effects. The literature search revealed that no experimental data are available for the frequency of 26 GHz. Since some radar systems also use frequencies of around 26 GHz (e.g. 24 GHz is a frequency used by police radar speedometers), the committee analysed studies of people working with or near such radar systems. However, many of these studies cannot be used because the radar systems used frequencies outside the range of 20 GHz to 40 GHz or because the studies did not specify which radar systems or frequencies were used. Overall, the Health Council of the Netherlands (2020b) concludes that the effects of exposure to electromagnetic fields with frequencies around 26 GHz at levels below the exposure limit recommended by ICNIRP should be explored in experimental studies. Due to the low penetration depth, research should focus on the effects that originate in the skin, including the effects on components of the immune system and nervous system that are in the skin. Since virtually nothing is known about the effects of exposure at 26 GHz, the committee recommends postponing the use of this frequency band for 5G until the research results are available.

The French Food, Environmental and Occupational Safety Authority ANSES (Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail) submitted a comprehensive update of its assessment of the *exposition aux champs électromagnétiques liée au déploiement de la technologie "5G"* (exposure to fields of electromagnetic radiation related to the introduction of the "5G" technology) in February 2022 following a request from the Ministries of Health, Environment and Economy (ANSES Opinion Request No 2019-SA-0006) (ANSES 2022a). This report in French is based on a comprehensive analysis of original studies. A 25-page English summary of the statement is available (ANSES 2022b).

In addition to a description of the characteristics and type of signals emitted, an assessment of the public's exposure in the context of 5G mobile technology and a review of existing knowledge of the health effects associated with exposure to electromagnetic fields in the 3.5 GHz and 26 GHz frequency bands were commissioned. A number of documents have been published together with the French National Frequency Agency (ANFR) (ANSES 2019, ANSES 2021a, ANSES 2021b).

The literature review of studies for the frequency ranges covered the period between January 2012 and July 2020. A number of studies published between July 2020 and March 2021 were also included when they were relevant and of satisfactory quality. The search engines used for this expert review were Scopus and PubMed. Some interesting references later mentioned in the public consultation were also taken into account. The publications used for the evaluation by the experts were articles, which were published in English or French in peer-reviewed scientific journals. The two frequency bands considered for the literature review were 3 GHz to 4 GHz and 18 GHz to 100 GHz, whereby for this statement only the results for the higher frequency range were taken into account.

For the frequency range around 26 GHz, the working group has taken into account all the publications on frequencies between 18 GHz and 100 GHz identified. The data available in the literature is limited. Nevertheless, these were used to assess the potential health effects of exposure in the 26 GHz frequency band. They mainly refer to radar applications or devices used for therapeutic purposes. This information was supplemented with biophysical data on the specifics of the interactions of these frequency bands with the human body.

The scientific literature identified for the frequency range 18 GHz to 100 GHz mainly examines effects on the skin, eyes, membranes, central nervous system and cells of various human or animal tissues (skin, neurons, cornea, etc.). The results are briefly summarised by ANSES (2022b) as follows, with ANSES (2022a) as much as possible providing an additional number of studies, as well as, partly, information on the intensity of the exposure from ANSES (2022a):

> *Skin*
> Studies available for the frequency range 18 GHz to 100 GHz are methodologically diverse and very small in number. Overall, the conclusions are based on nine studies on human skin, with the majority of the studies coming from the same research group. In seven of these studies, power densities ranging from 1.8 mW cm^{-2} to 20 mW cm^{-2} were reported. No genotoxic effects have been reported, although aneuploidy was observed in one study. No general effect on the transcriptome was noted, apart from a temporary effect (which lasted about a few hours) on the amount of transcripts of some genes involved in the cellular stress response. From these results, no conclusions can be drawn as to whether or not exposure to electromagnetic fields at frequencies from 18 GHz to 100 GHz has adverse effects on human skin.
>
> *Eyes*
> Based on the results of a total of five publications, ANSES (2022b) the studies conducted on corneal and lens cell lines showed no health effects of exposure to RF-EMF at 40 GHz and 60 GHz. An in vivo study in rabbits showed thermal effects on the cornea with exposure at a very high power density (10 mW cm^{-2} to 600 mW cm^{-2}).
>
> *Central nervous system*
> A total of six studies focus primarily on the possible pain-relieving effects of RF-EMF (42 GHz, 60 GHz, and 94 GHz and power densities of 17 mW cm^{-2}) and their mechanisms. From the available data (only one study on humans; Partyla et al. (2017), see section 4.3.2), no conclusions can be drawn as to whether there is an effect on nociception, i.e. the perception of pain or analgesia, i.e. the suppression of the sensation of pain. In addition, in vitro data of neurons in cultures of different animal species cannot be used to draw conclusions about a specific mechanism. In ANSES (2022b) it was noted that the working group did not find any articles on the possible effects of millimetre waves on the activity of nerve endings in the skin, although it seems very useful to investigate this type of effect.

Genotoxic effects
Four ex vivo or in vitro studies on human cell lines (fibroblasts, i.e. special cells of connective tissue, as well as corneal and lens cells of the eye) and rat leukocytes did not detect a genotoxic effect of exposure to electromagnetic fields at frequencies between 25 GHz and 60 GHz and power densities between 100 μW cm^{-2} to 1 mW cm^{-2}. However, aneuploidy (i.e. deviation from a set of chromosomes) was found in exposed fibroblasts in a study already cited in the "Skin" section. It is not possible to infer a genotoxic effect from the knowledge available.

Effects on membranes
The number of studies on cell membranes is low, according to ANSES (2022b) and they are very diverse. Seventeen publications of sufficient quality were identified. One of these studies showed an increase in membrane permeability in a cell line. In addition, studies on artificial membranes have shown that exposure to electromagnetic fields at frequencies between 52 GHz and 78 GHz leads to both structural and functional changes (structural changes in phospholipids and the arrangement of the water molecules at the interface; shift in the phase transition temperature). Given the results of these studies, there is a limited level of evidence for the effects of electromagnetic fields on cell membranes.

ANSES (2022b) explicitly points out once again that *health* effects must be distinguished from *biological* effects. Biological effects are molecular, cellular, or physiological changes in response to a stimulus. A biological effect lies within the limits of an organism's ability to maintain the balance of its internal environment (homeostasis) in response to external stresses and is usually reversible. The presence of a biological effect, especially under experimental conditions, does not necessarily mean that damage will be caused, and even less that it leads to a health impairment.

Against this background, ANSES (ANSES 2022b, 2022a) summarises that the data currently available are not sufficient to draw robust conclusions on the existence of adverse health effects related to exposure to electromagnetic fields in the 26 GHz frequency band (10 GHz to 100 GHz).

Since there are few studies available for the frequency range around 26 GHz (18 GHz to 100 GHz), the penetration depth of the fields into the body is very low and the energy deposition takes place on the surface, the following recommendations are made for further investigations- (ANSES 2022b, 2022a):

- carrying out further studies in the 26 GHz frequency band in chronic or acute exposure situations;
- analysis of biological effects and health risks in animals, examining the most exposed organs, in particular the skin and eyes;
- promotion of studies on the effects of millimetre waves on the skin flora: microorganisms that are part of the immune system and contribute to the health of the skin and body by forming a protective barrier against pathogenic germs; examination of the adaptive immune response; study of effects on the cellular microenvironment;
- carrying out in-depth studies to link the observations made on artificial membranes with those on natural membranes of whole cells;
- promotion of studies on in vitro models (skin, cornea, conjunctiva, etc.) to measure parameters such as cell viability and genotoxicity. It would be useful to implement global 'omics' approaches without targeted assumptions (Transcriptomics, Proteomics, Metabolomics, Lipidomics, Epigenomics); and finally

– analysis of the long-term effects of RF-EMF on the nervous system (behaviour, neurophysiology, nociception) in humans and/or in animal models.

ANSES (ANSES 2022b, 2022a) points out that further studies should follow strict quality criteria (e.g., including a thermal effect control group) to investigate possible biological effects of the intermittent signals of some wireless technologies. In addition, it is recommended to conduct studies that take into account simultaneous exposure to electromagnetic fields and other physical or chemical hazards.

4.2 Epidemiology

After the review of the epidemiological studies in the millimetre wave range by Karipidis et al. (2021) only two further studies in the relevant frequency range have been published. They were identified by means of a search for epidemiological studies in the EMF portal using the keyword search.[6] Both investigated cancer rates among those serving in the military in Israel, which were exposed to radar installations. Shapira et al. (2023) conducted a retrospective cohort study using data from 2009 to 2018. Cancer incidence due to all causes as well as for different types of tumours were compared between members of the antiaircraft defence with a similar sociodemographic group of soldiers without exposure. With regard to millimetre wave exposure, it was only described that antiaircraft personnel had been exposed by radar systems below 25 W m^{-2} (50% of the ICNIRP Recommendation for Occupational Exposure). According to the authors, all other information is subject to military secrecy. During a mean follow-up period of 4.8 years, 13 tumours were identified in the 3 825 exposed persons and 28 tumours in the 11 049 non-exposed persons. This resulted in an odds ratio (OR) of 1.34 (95% CI: 0.70-2.60), which is not statistically significant (p-value = 0.38). Adjustment of analyses for gender, age at enrolment, length of service, socioeconomic status and military occupation yielded virtually the same results. Younger age at start of service was associated with a higher incidence of cancer regardless of exposure (OR=1.13 [95% CI: 1.04-1.23]), while a longer duration of follow-up was negatively associated (OR = 0.87 [95% CI: 0.77-0.99]). Tumour specific analyses showed a trend towards higher incidences of haematological tumours and testicular cancer for the exposed group (OR = 2.76 [95% CI: 0.62-12.19 for four cases in both groups] and OR = 7.2 [95% CI: 0.71-73.8] based on three exposed cases and one non-exposed case), which were not significant due to the low number of cases.

Peleg et al. (2023) published a report on 46 patients who received a cancer diagnosis between 2002 and 2021, who served in the Israeli army and reported that they were working on radar or other wireless communication facilities or were on duty in the vicinity of these. They were identified because they approached a volunteer NGO whose mission is to help cancer patients with administrative, legal and social matters. Of the 46 patients, 19 had a hematologic tumour. This corresponds to 41.3%, 95% CI (27% to 57 %) compared to an expected 22.7% for a collective with this age and gender distribution. The relative incidence of Hodgkin's lymphoma (21.7% observed vs. 11.6%) and sarcoma (15.2% observed vs. 7.0% expected) was statistically significantly increased. In addition, a separate analysis was carried out on a group of 250 soldiers who were recruited in 2011. By 2014, there were five cancer cases in this group compared to 0.22 expected cases, which is statistically significantly increased. There were no measurements on exposure and no information on how millimetre waves played a role in the

[6] Search term: topic=epidemiological AND frequencyRange=radio_frequency AND year=2020-2024 AND (radar OR millimeter)

self-reported exposures. This study with a self-selected collective has a high risk of selection bias, which can plausibly explain the deviations from the expected numbers.

In both Israeli studies, the data on exposure in the millimetre wave range are so poor that the studies on the potential risk in this regard are not informative. In addition, high-performance or older radar devices generate non-ionizing radiation as well as X-rays (Radarkommission 2003), which could be an unconsidered confounder in both studies.

4.3 Experimental human studies

Since there are so far very few experimental human studies on biological effects of exposure in FR2 frequency range compared to FR1 frequency range, their results are presented in detail below. Clinical studies in patients in which millimetre waves have been used for therapeutic purposes are not taken into account. Due to the low penetration depth of electromagnetic fields of the FR2 frequency range, effects that are mediated via the skin or the eyes are of primary interest. However, experimental human studies in which the human eye is exposed are not acceptable for ethical reasons. The present studies are concerned with the perception of relevant fields (section 4.3.1), threshold values for thermal pain (section 4.3.2) and cardiovascular effects (section 4.3.3).

A table of experimental human studies can be found in Appendix A-1.

4.3.1 Studies on the perception of fields

A total of three human experimental studies are available for the perception of FR2 fields (Pakhomov et al. 1998, Blick et al. 1997 and Yuasa et al. 2024). Pakhomov et al. (1998) summarise the results of three studies published in Russian (Lebedeva 1993, Lebedeva 1995, Kotrovskaia 1994) on the perception of weak millimetre waves under double-blind experimental conditions as follows. The test person was located in an isolated room without contact with the experimenter. The surface of the hand was exposed 20 times for one minute each, with exposures performed at one-minute intervals and randomly mixed with sham exposures. The beginning and end of each verum and sham irradiation were signalled by tones. The subject had to press a button when they felt the field. Neither the subject nor the experimenter knew the order of the verum and sham exposures. Correct and incorrect reactions were automatically recorded. Field perception was characterized by reaction reliability (the percentage of correctly detected verum exposures) and false alarm level (the percentage of exposures falsely detected as verum exposures). One subject was classified as capable of detecting the field when the response reliability was constant and statistically significant above the false alarm value. At different frequencies (37.7 GHz, 42.25 GHz and 53.57 GHz), intensities (from 5 mW cm^{-2} to 15 mW cm^{-2}) and bandwidths, the radiation was detected by 30% to 80% of the subjects. The 37.7 GHz radiation at 15 mW cm^{-2} was detected by far fewer people than that at 42.25 GHz and 5 mW cm^{-2}. Reaction latency was usually between 40 s and 50 s. Some types of mechanoreceptors and nociceptors were thought to be involved in the perception of the fields.

In the study of Blick et al. (1997) the intensities at which exposure was perceived at 2.45 GHz, 7.5 GHz, 10.0 GHz, 35 GHz and 94 GHz, were investigated in 15 healthy participants (no gender information) at the mean age of (45.2 ± 6.0) years. A modified staircase procedure was used to determine the threshold for perception: For each frequency, 20 evenly distributed stimulus intensity levels were selected so that the lowest intensity for the most sensitive subject was below the threshold and the highest intensity for the least sensitive subject was above the threshold. Stimulation was performed in the middle of the back from a distance of 20 cm to 70 cm. For comparison, stimulation with infrared radiation was performed. For FR2 (here 35 GHz) the following threshold of perception could be observed: 8.8 mW cm^{-2} (±

1.3 mW cm^{-2}; standard error). For lower frequencies (2.45 GHz, 7.5 GHz and 10 GHz), the perception threshold varied from 63.1 mW cm^{-2} ± 6.7 mW cm^{-2} (2.45 GHz) over 19.5 mW cm^{-2} ± 2.9 mW cm^{-2} (7.5 GHz) to 19.6 mW cm^{-2} ± 2.9 mW cm^{-2} (10 GHz). At 94 GHz exposure, the perception threshold decreased to 4.5 mW cm^{-2} ± 1.1 mW cm^{-2} and was comparable to that of infrared radiation (5.34 mW cm^{-2} ± 1.1 mW cm^{-2}). The results showed that the sensitivity over the tested frequency range increased monotonously. The threshold at 94 GHz was more than an order of magnitude lower than at 2.45 GHz.

A study of Yuasa et al. (2024) examined the reliability of determining the threshold for thermal sensation. For this purpose, 20 healthy subjects (16 men and 4 women) aged (35.2 ± 3.0) years (mean ± standard deviation) were subjected to electromagnetic fields (28 GHz) at varying exposure (power density: 27 mW cm^{-2}, 126 mW cm^{-2}, 191 mW cm^{-2}, 252 mW cm^{-2} and 399 mW cm^{-2}) at the fingertip of the left index finger. Before the experimental runs, the fingertip of the left index finger was exposed to a power density of 191 mW cm^{-2} as part of a familiarization. If no heat sensation was detected, the test was repeated with a power density of 252 mW cm$^{-2.}$ One minute before exposure, the skin temperature was measured as a baseline. By pressing a computer mouse with the right hand, a sensation was logged by the subject, which led to the termination of exposure. After three minutes without perception at the latest, the passage was terminated by the experimenter. After the cessation of the exposure, the temperature at the fingertip was measured at intervals of one minute. The next test was started when the skin temperature had returned to the baseline (± 1 °C). One test consisted of five trials in which the power density was randomly assigned. After a short break of 60 seconds, the entire test was repeated. To assess the reliability of the heat perception, the intraclass correlation coefficient (ICC) was calculated for the two runs for each exposure. For exposures at 126 mW cm^{-2} to 399 mW cm^{-2}, the mean threshold for perception was almost consistently at 0.9 °C to 1.0 °C, while for the 27 mW cm^{-2} exposure condition it was 0.2 °C. The rate of temperature increase increased with increasing exposure levels, also, the higher the exposure level, the shorter was the response time. The ICCs for the threshold at 27 mW cm^{-2} and 126 mW cm^{-2} were interpreted as poor to sufficient, while the values at higher exposure levels were mediocre to considerable. These results suggest that the threshold for heat sensation is around 1.0 °C and is consistent across all exposure levels, while its reliability increases with higher exposure levels.

4.3.2 Studies on the thresholds for thermal pain

Overall, this effect of exposure to electromagnetic fields of the frequency range FR2 was investigated in three studies, all three also investigated effects on the cardiovascular system.

Radzievsky et al. (1999) conducted a prospective double-blind, randomized cross-over study to evaluate the pain-relieving effect of millimetre waves (42.25 GHz, 25.5 mW cm^{-2}) under experimental conditions. The Cold Pressure Test (CPT) was used as a model for tonic pain. After initial measurement of blood pressure and heart rate, the non-dominant hand was immersed in warm water ((37.0 ± 1.0) °C) for two minutes to compensate for the initial hand temperature. Afterwards, the participants dipped their open hand up to the wrist in a water bath ((1.0 ± 0.5) °C) with ice.

Participants were instructed to evaluate their sensations on a scale in front of them that was electronically time-stamped by the lead investigator. The time of immersion of the hand in the cold water was registered as the starting point (0). After that, the times of the appearance of the following sensations were recorded: chilly, cold, very cold, pain 1 (the onset of pain) and pain 2 to pain 10 (unbearable pain, hand withdrawal). The time to reach the stages pain 1 (pain threshold) and pain 10 (pain tolerance) were evaluated. Pain sensitivity was defined as the difference between the values of pain tolerance and pain threshold. After withdrawing the hand from the water, a digital thermoelement thermometer was used to determine the lowest temperature of the palm (usually displayed within 5-7 seconds) and the temperature of the palm 30 seconds after removal. At the same time, arterial blood pressure and heart rate were measured again. The experiment involved 12 healthy male volunteers. They were exposed for 30 minutes using an active medical millimetre wave generator or a deactivated dummy generator and tested six times at intervals of at least 24 hours between exposures. Initially, three baseline tests were performed without exposure, the first of which was to train the subjects. The results obtained in this test were not included in the data analysis. After the three baseline tests, the experiments were conducted with sham or millimetre wave exposure, with exposures randomly assigned. The last test was performed to determine whether the subjects had developed a lower sensitivity to the cold stimulus as a result of the multiple tests.

Exposure to millimetre waves resulted in a statistically significant ($p< 0.05$) suppression of pain sensation. On average, pain tolerance increased by 37.7% and pain sensitivity range by 49.3%. Of the 12 subjects, seven (58.3%) showed an increase in pain tolerance under verum exposure, two a reduction and three no significant change.

In the additionally investigated parameters blood pressure, heart rate and temperature of the palm after withdrawal of the hand from the water, no exposure-related differences were found. The authors conclude from their findings that MMW therapy may be used as a complementary or alternative treatment for pain relief.

Partyla et al. (2017) also studied the reduced sensation of pain (hypoalgesia) during a 30-minute exposure to millimetre waves in the frequency range 50 GHz to 75 GHz. In a similar way as Radzievsky et al. (1999), they used the CPT to analyse the effect of millimetre waves of different frequency ranges on pain perception. The test was carried out in accordance with the guidelines for test procedures for children (von Baeyer et al. 2005). For the study, 23 healthy right-handed men aged 20 to 40 years were recruited, three of whom had to be excluded due to their too long response time in the CPT (> 2 min). Six test runs were carried out at 24-hour intervals. Experiments one, two and six were without exposure. In passages three, four and five, the skin of the lower part of the sternum was exposed in a randomized way to either an MMW with a fixed frequency of 42.25 GHz (active generator), to a signal in the frequency range from 50 GHz to 75 GHz (noise generator) or an inactive device (placebo generator) in a crossover double-blind study. The generators were placed in a metal box for blinding and positioned at a distance of 1 cm to the skin surface for optimal skin exposure at < 17.2 mW cm^{-2}. The times until the levels of pain already mentioned above were reached (excluding the category: cool) were recorded using the verbal reports of the participants with a stopwatch. The pain threshold was used as the primary endpoint. Other measured parameters included CPT values, heart rate, blood pressure, the occurrence of subjective sensations (paraesthesias) during exposure, and the quality of the blinding of the subjects. The results under exposure at 42.25 GHz were compared with the baseline values, the results under exposure at 50 GHz to 75 GHz and those under placebo exposure. During exposure to the 42.25 GHz generator, the pain threshold increased compared to the baseline, with a median difference of 1.97 seconds (95% confidence interval [CI] = [0.35-3.73], $p = 0.064$). For the noise generator, the corresponding median difference was 1.27 seconds (95% CI = [0.05-2.33], $p = 0.092$). The results for the placebo generator showed no deviation from the baseline. The time until the onset of cold and increasing pain sensations was prolonged under exposure by the 42.25 GHz generator compared to the baseline and the noise generator. Diastolic blood pressure increased under exposure. Other outcomes were comparable between study conditions. The authors conclude that their experiments were able to confirm the increase in the threshold for pain perception when exposed to low-intensity millimetre waves. However, the effect was statistically indistinguishable from the placebo condition.

Another human experimental study on the effect of electromagnetic fields in the millimetre wave range on the perception of pain was carried out by Minier et al. (2023) examining ten healthy subjects (seven men and three women) aged 21 to 54 years (mean ± standard deviation: (35.2 ± 12.9) years). They were exposed on the palmar side of the right wrist at a frequency of 61.25 GHz (17 mW cm^{-2}) for 30, 60 and 90 minutes, and in addition to a 30-minute sham exposure. The study was conducted in a cross-over design. The four experiments were carried out in a randomized way at intervals of at least 24 hours. Since the sham exposure lasted 30 minutes, blinding was not completely guaranteed. Pain threshold and pain tolerance were determined using the Cold Pressor Test (CPT), as described by Radzievsky et al. (1999) and Partyla et al. (2017). The subjects used their right hand to continuously record the extent of the pain on a computerized visual analogue scale. The subjects' heart rate, blood pressure and skin temperature were measured before and after exposure. For evaluation, the pain threshold (time to reach a value different from zero on the visual analogue scale) and the pain tolerance (time to reach a value of 100/withdrawal of the hand) were considered. When comparing verum exposures in pairs with sham exposure, a statistically significant increase in the pain threshold and a reduction in heart rate were observed exclusively for the 30-minute exposure. Pain, blood pressure and skin temperature were not significantly altered by any of the verum exposures compared to sham exposure.

In conclusion, in two out of three studies, a statistically significant increase in the pain threshold at 30-minute exposures to electromagnetic fields in the millimetre wave range (42.25 GHz, 25.5 mW cm^{-2}; 61.25 GHz, 17 mW cm^{-2}) could be observed. Overall, only very small samples (n = 10 to n = 21) with varying exposures have been analysed so far. Further studies (Nelson et al. 2003, Walters et al. 2004, Alekseev et al. 2005) also showed a dependence of the resulting increase in temperature in the skin on the local blood circulation.

4.3.3 (Further) Studies on Cardiovascular Effects

Effects of exposure to radiofrequency electromagnetic fields of FR2 frequency range on the cardiovascular system have been investigated not only by Radzievsky et al. (1999), Partyla et al. (2017) and Minier et al. (2023) (see section 4.3.2), but also in two other studies from the same working groups (Müller et al. 2004 and Kantz et al. 2005).

In both studies, the effects of a 15-minute exposure to RF-EMF (Müller et al. 2004: 77 GHz, 3 μW cm^{-2}, Kantz et al. 2005: 5.8 GHz to 110 GHz, 59.7 μW cm^{-2}) on the cardiovascular system were studied in 50 subjects each: (Müller et al. 2004: 12 women and 38 men aged 18 to 36 years who did not have a cardiovascular disease; Kantz et al. 2005: 18 women and 32 men aged 15 to 78). The study provided for a 30-minute lead time to allow equilibrium to be established followed by a 15-minute exposure phase, a 15-minute recovery phase without any exposure, and another 15-minute exposure phase followed by a further recovery phase. As the exposures took place on the same day, a carry-over effect (i.e. the influence of the previous intervention on the results of an experimental intervention – especially for sham exposure after actual exposure) cannot be excluded. The sample was divided into two groups, one group started with verum exposure, the other with sham exposure.

Over the entire duration of the experiment, an electrocardiogram (ECG) was recorded to determine the heart rate and various parameters derived from the ECG. Breathing activity was recorded using a conductive stretch band around the chest and logged as a change in the electric conductivity of the stretch band. The skin temperature was measured with a thermoelement on the right hand. To measure skin conductivity, Ag/AgCl electrodes were used, which were attached to two fingertips of the left hand. Systolic and diastolic blood pressure was measured with an automatic cuff on the left upper arm. All measurements were performed continuously throughout the experiment and automatically transferred to a PC for further analysis. All experiments were conducted in a room with controlled temperature and humidity. Exposure was carried out by a commercial automotive radar system. Kantz et al. (2005) used an exposure protocol where with six frequencies (5.8 GHz, 12 GHz, 24 GHz, 60 GHz, 77 GHz and 110 GHz) were applied sequentially, with each frequency being active for 5 ms. The whole sequence was repeated 35 times.

To verify whether there was a statistically significant exposure effect, a multivariate analysis of variance (MANOVA) was performed. While the factor time (first and second half of the test) had a significant impact on the results, statistically significant differences between the exposure conditions were not observed in any of the cardiovascular parameters examined (heart rate, electrocardiographic parameters, breathing rate, skin temperature and skin conductivity, as well as for systolic and diastolic blood pressure). In both studies, the authors concluded from their findings that the millimetre waves used in the experiment do not cause physiologically relevant changes in autonomic nerve activity and cardiovascular function.

In summary, in two of the four studies on cardiovascular effects mentioned above, isolated effects were observed that could not be reproduced in the other studies. Overall, the studies vary in terms of exposure (42.25 GHz, 25.5 mW $cm^{-2;}$ 42.25 GHz, 17.2 mW cm^{-2}; 61.25 GHz, 17 mW cm^{-2}; 77 GHz, 3 µW cm^{-2}), exposure duration (15 min to 90 min) and sample size (n = 10 to n = 50). It should be noted that the observed biological effects do not necessarily imply health effects.

4.4 In vivo studies

In vivo studies are useful for obtaining information about the possible mechanisms of action, biological plausibility, dose response, and the effect of exposure. Many in vivo studies have been conducted on the effects of RF-EMF exposures, with a very limited number of studies in the frequency range relevant for 5G FR2. The existing studies deal with effects on the body and skin temperature, on the eye status, behaviour, and the function of the immune system.

A table of the in vivo studies mentioned below can be found in Annex A-2.

4.4.1 Thermal effects, especially on the skin and eye

One study by Ijima et al. (2023a) was designed to investigate the relationship between the absorbed power density and the increase in skin temperature in vivo. For this purpose, the dorsal skin of rats (male Sprague-Dawley rats; n = 6-15 for each condition) was exposed for 18 minutes to a continuous 26 GHz wave of 0 W m^{-2} to 500 W m^{-2} (0 W m^{-2}, 125 W m^{-2}, 250 W m^{-2}, 370 W m^{-2}, 500 W m^{-2}). The skin (at three points) and rectal temperature were measured with a fibre-optic thermometer. Temperature data were collected for a total of 30 minutes (6 minutes before, 18 minutes during, and 6 minutes after exposure). The skin temperature increased dose-dependently right at the beginning of the exposure, with a maximum increase of 11.3 °C at 500 W m^{-2}. The relationship was investigated using a linear regression model, which showed an estimated temperature increase of less than 5 °C at a 200 W m^{-2} exposure. The temperature rise stopped immediately when the exposure ended. The rectal temperature increased by 0.6 °C after 4 minutes of exposure only at 370 W m^{-2} and 500 W $m^{-2.}$

A second study by the same group (Ijima et al. 2023b) determined the relationship between exposure intensity and elevated body temperature in rats and also examined whether thermos-regulation, including changes in blood flow in the skin, is reduced during whole-body exposure to MMW. A total of 31 male Sprague-Dawley rats were used in the study, with temperature measured using fibre optic thermometers and blood flow measured using Doppler blood flow meters. The backs of the unanaesthetised rats were individually irradiated in an acrylic holder 50 cm below a lens antenna for 40 minutes with a continuous 28 GHz wave at 0 W m^{-2}, 8.5 W m^{-}

^{2}, 122 W m^{-2}, and 237 W m$^{-2.}$ The corresponding calculated whole-body SAR values were 0.26 W kg^{-1}, 3.7 W kg^{-1}, and 7.2 W kg^{-1}, respectively. Both temperature and blood flow measurements were performed on the dorsal and tail skin, with additional temperature measurements in the rectum.

The exposure caused an immediate rise in temperature in the skin at all intensities, while rectal temperature began to rise after 46 s of exposure. The temperature increase persisted throughout the entire exposure period. Blood flow in the dorsal skin remained at the same level during exposure, but increased linearly in the tail skin, with a factor of three at 237 W m^{-2}. The temperature rise in the dorsal skin was 2.7 °C and 3.9 °C at 122 W m^{-2} and 237 W m^{-2}, respecttively. The corresponding increases were 4.4 °C and 7.4 °C for the tail skin and 0.9 °C and 1.3 °C in the rectum.

The authors concluded that exposure caused an initial rise in temperature in the dorsal skin, followed by increased blood flow in the tail skin, which activated further thermoregulatory systems.

A number of studies by Foroughimehr et al. have investigated the temperature effects of RF-EMF radiation in various biological models. Foroughimehr et al. (2023) developed a mathematical simulation for the absorption of MMW by the cornea, both under normal and pathological conditions. For the simulations, they used a 3D model of the human eye, assuming a tear film on the cornea with a thickness of 8 μm as the normal condition, and a 2 μm thick film for the dry eye condition and the pathological condition. In addition, the water content of the normal cornea was set at 80% and that of the dry eye at 40%. In the study, the temperature change in the two corneal models was calculated in the frequency range from 30 GHz to 0.5 THz (continuous wave; 20 W m^{-2} and 100 W m^{-2}). The 30 GHz exposure caused a temperature increase of 0.02557 °C at 20 W m^{-2} and an increase of 0.1278 °C at 100 W m^{-2} in the normal eye, according to the authors. For the dry eye, the corresponding increases were 0.02575 °C and 0.1288 °C, respectively. The modelling also showed an E-field distribution in the cornea with 'radiation hotspots', especially in the dry eye.

In another study by the same group (Foroughimehr et al. 2024), fluorescence lifetime imaging microscopy (FLIM) was used to uncover potential damage to cellular respiratory processes to investigate the effects of 26 GHz exposure (5.1 kW m^{-2}) on the skin of pigs for 5 minutes, 10 minutes, 20 minutes, and 30 minutes. The investigated endpoints were changes in tissue temperature and autofluorescence of flavin adenine dinucleotide (FAD). Fresh ex vivo skin samples (n = 6) were collected, stored at 21° C, and exposed in an absorber chamber. In addition to FLIM, the temperature level was measured with an infrared thermal imaging camera (3 measurements/minute). The temperature rise was strongest in the first 5 minutes, then slowed and reached a plateau after 30 minutes. The maximum temperature increase measured was 7 °C. The lifetime of FAD, as an indicator of an intact metabolism, decreased over time (statistically not significant), both in the control and exposed samples.

Parker et al. (2024) conducted a study on burn thresholds in pigs' skin through superficially penetrating high-frequency fields at 8.2 GHz and 95 GHz. The study determined the threshold values for superficial, partial, and full-surface burns after 5 seconds of exposure at power densities of 4-30 W cm^{-2} and 2-15 W cm^{-2} at 8.2 GHz and 95 GHz, respectively. Female pigs (n = 8 for each frequency) were exposed in an absorber chamber at four sites on each flank of the animal at 8 W cm^{-2}, 20 W cm^{-2}, 25 W cm$^{-2,}$ and 30 W cm$^{-2.}$ Thermal images were taken with an infrared camera and digital colour photographs were taken from the sites before the exposure as well as 1 h, 24 h, 72 h and 7 days after the exposure. In addition, biopsies were taken 1 h, 24 h, 72 h, and 168 h after the exposure for histological examinations of the degree of burning (20 histological factors).

The results showed that burn damage occurs dose-dependently, with the degree of burning increasing with increasing energy input. Threshold values have been found at which the transition from superficial burns to more severe burns occur in parts or throughout the entire skin layer. The effects at 8.2 GHz showed significant changes and burns in parts of the skin layers from about 10 W cm^{-2}. Burns of the entire skin were observed from about 20 W $cm^{-2.}$ At 95 GHz, burns were found in parts of the skin layer from about 4 W cm^{-2} and burns of the entire skin from about 15 W $cm^{-2.}$

The skin of male Sprague-Dawley rats was studied for the analysis of steady-state temperature increases due to exposures in the 6 GHz to 100 GHz frequency range (Li et al. 2023a). The authors analysed the skin thickness of the scalp and dorsal skin at four sites in four animals with the help of histological examinations and CT measurements. Subsequently, a model was constructed with a flat wave, which is radiated from the air to the skin surface. The stationary temperature, which is due to the power absorption of the injected EMF, was calculated by solving Pennes' bioheat transfer equation. The results showed a linear relationship between the absorbed power density at the skin surface and the power density outside the body at frequencies of 6 GHz, 30 GHz, 60 GHz, and 100 GHz. The warming factor for the rat's scalp varied between power densities of 0.0083 °C and 0.0118 °C per W $cm2^{-}$ over the range of 6 GHz to 100 GHz. For the rat dorsal skin, the warming factor ranged from 0.0172 °C per W cm^{-2} to 0.0186 °C per W cm^{-2} between 30 GHz and 100 GHz. The results show that above 30 GHz, the equivalent absorbed power density could cause a 70% higher temperature in the dorsal skin of the rat compared to the scalp of the rat. Between 6 GHz and 100 GHz, the increase in surface temperature in the scalp and dorsal skin of the rat varied in a frequency depending manner from 55.6% to 32.2% and from 83.3% to 58.8%, respectively, compared to average human models from other studies. The larger percentage increases occurred at the lower frequencies. The team of authors concluded that the temperature change at the skin surface of the rat could be influenced by thermal parameters, tissue thickness, and blood flow rate in the deeper tissue layers.

Kojima et al. (2024) published a study in which they examined the damage to the rabbit's eye with continuous 60 GHz exposure (200 mW cm^{-2} or 300 mW cm^{-2} for 6 min) under different environmental conditions (temperature and relative humidity). The same authors had previously published several studies on the same topic using different frequencies (40 GHz, 60 GHz, 75 GHz, 95 GHz, 162 GHz). The aim of the present study was to investigate the influence of ambient temperature and humidity as environmental factors on the threshold values for the development of MMW-induced eye damage. ‘Eye damage’ was defined as abnormal findings and is based on previous studies, including corneal epithelial damage, corneal oedema, and corneal opacity.

The 60 GHz wave was transmitted by a conical horn antenna aimed at the rabbit's eye. The animals were anesthetized male pigmented rabbits (Dutch-belted, Kbl Dutch), irradiated on the left eye, while the right eye served as a control. Slit lamp microscopy with fluorescein staining was used to study the initial health of the eye, including the state of the epithelium and corneal and lens transparency. Optical coherence tomography of the anterior part of the eye was used to measure corneal thickness. Prior to exposure, (pre-warmed) physiological saline drops were applied to the eyes to counteract eye drying. The ambient conditions were either the ‘standard’ condition (25 °C, 50% relative humidity) or 45 °C with 20%, 50% or 80% relative humidity. The animals were acclimatized to the respective conditions for 10 minutes prior to exposure. Eye damage was observed immediately before exposure, and then 10 minutes and one day after exposure. Tissue temperature measurements were performed using a fluoroptic thermometer placed on the corneal stroma, front cortical lens and subcutaneous tissue on the back of the animal.

Previous studies have identified power density thresholds above which eye damage occurs. Under standard conditions, the range of these thresholds was given as 200 mW cm^{-2} to 300 mW cm^{-2}. In the present study, under conditions of high temperature and high humidity (45 °C, 80% relative humidity), corneal opacities, corneal oedema, and damage to the corneal epithelium occurred in all animals examined (n = 5) when exposed at 200 mW cm^{-2}. At the same temperature, but with 50% relative humidity, the corresponding incidence was 67% (two out of three animals). At 20% relative humidity, the incidence was 0 (n = 5). The occurrence of damage was also investigated at an exposure at 300 mW cm^{-2}, but only at 25 °C. At a relative humidity of 50%, damage was found in 85.7% of the animals (six out of seven animals), at a relative humidity of 20%, it was 100% (n = 5). The authors observed that the power density is most closely related to the development of eye damage, and also that a relative humidity of 80% significantly promotes eye damage. The team also pointed out that only a few animals were examined and that in many cases the statistical significance was low.

Regarding temperature changes, a pattern of a gradual temperature rise in the eye, and subcutaneous tissue was observed after a transition from 24 °C and 50% relative humidity to 45 °C and 20% or 80% relative humidity. The increase occurred at all three sites (corneal, lens, subcutaneous) at the same speed. During exposure to 200 mW cm^{-2} at 45 °C and 80% relative humidity, an immediate increase in temperature in the cornea was observed, followed by an increase in the lens. Exposure to 200 mW cm^{-2} at 45 °C and 20% relative humidity caused a rapid increase in the cornea, followed by an increase in the lens, but to a lesser extent.

In conclusion, the authors found that the threshold for eye damage is directly affected by power density and that high ambient temperature and humidity exert a secondary, exacerbating effect on eye damage. In addition, it was concluded that a low-humidity environment does not necessarily prevent the development of eye diseases due to MMW exposure.

The most recent study by this group (Kojima et al. 2025) examined the effects of RF field eye exposure at 28 GHz and compared the results with those previously published for other frequencies, applying the same exposures and using the same protocols for animal handling, temperature control and tissue testing. Exposure lasted for 6 minutes at different incident power densities (200-750 mW cm^{-2}) at a distance of 135 mm from the antenna opening of the lens to the corneal apex. At 400 mW cm^{-2}, damage to the corneal epithelium, corneal oedema and lens opacity (cataract) were observed. The authors also determined the power density threshold (using the Probit analysis), which indicates a 10 per cent, 50 per cent and 90 per cent probability (DD_{10}, DD_{50} and DD_{90}, respectively) of eye damage from the 6-minute exposure. These values were 327 mW cm^{-2}, 359 mW cm^{-2} and 394 mW cm^{-2}, which are higher than the values found by the authors for MMW exposure at higher frequencies (40 GHz, 60 GHz, 75 GHz, 95 GHz and 162 GHz) in their previous studies.

In conclusion, the majority of available in vivo studies dealing with skin and eye warming have shown biological reactions. However, since the studies are very heterogeneous and do not provide adequate and sufficient information, no meaningful and reliable hazard assessment can be derived from them.

4.4.2 Other endpoints

In a study of male Wistar rats by Perov et al. (2022), chronic multi-frequency exposure was used in various 5G frequency bands. The animals were chronically exposed in four groups for 1, 2, 3 or 4 months, 24 hours a day, 7 days a week. In addition, the fifth group was examined after a 4-month exposure period and then a month without exposure. Each exposed group was accompanied by a sham-exposed control group. The sham exposure was mentioned, but its conditions were not described. Exposure occurred simultaneously at 3.6 GHz, 28 GHz and 37 GHz (5G/IMT-2020 base station), at 250 μW cm^{-2}. The endpoints investigated included the exploration and orientation activity (open field test, but the details are not explained) and the serum concentrations of the hormones ACTH (adrenocorticotropic hormone) and corticosterone (ELISA assays). All parameters were examined at the end of each month and one month after the 4-month exposure. Twelve rats were included in each exposure and control group.

Orientation and exploration activity decreased in the exposed animals compared to the control animals, with a maximum effect after three months, although this was usually not statistically significant. Only one behavioural parameter (‘hole reflex’) showed a statistically significant decrease after two months of exposure. The values one month after exposure, were the same as for the controls. As for hormone levels, ACTH levels were significantly elevated after three months compared to the control, while corticosterone levels were statistically significantly elevated only in the two groups analysed after one and two months, respectively.

The authors conclude that the results indicate a moderate stress effect of exposure to the hypothalamic-pituitary-adrenal axis. However, this is based on the fact that only a few time points during the exposure show statistically significant effects, and that the data from the behavioural test were only mentioned, but the results were not shown. In addition, the publication lacks information on dosimetry and the conditions of the control animals.

Yao et al. (2022) investigated the response of the immune system of rats to combined single and multifrequency exposures at 2.8 GHz and 9.3 GHz. The team of authors used adult male Wistar rats and exposed them under sham conditions or at the two frequencies alone or in combination (sequentially) at a power density of 10 mW $cm^{-2.}$ Exposure duration was 6 min or 6 plus 6 min (combined exposure). Organ pathology (thymus, spleen) was studied 6 h and 7 days, 14 days, and 28 days after exposure. Cellular ultrastructure was studied using transmission electron microscopy, and a number of cellular and molecular endpoints were analysed using assays such as hemogram, flow cytometry, immunoassays, transcriptomics, proteomics, and mass spectrometry.

The team of authors reports that pathological changes occurred in both the thymus and spleen, starting on day 7 after exposure, with stronger effects under conditions of multifrequency exposure. In particular, the lymphocytes in these two organs showed congestion and nuclear fragmentation, which were no longer present on the 28th day after exposure. The single-frequency exposures did not affect the number of white blood cells. By contrast, multifrequency exposures altered the number and proportion of both T and B lymphocytes, with the number of B cells increasing. It is not discernible whether the effect was caused by the longer duration of exposure or the combination of frequencies. These effects were no longer present on day 28 after exposure. Several serum cytokines (IL-1alpha, IL-1beta, IL-4, TNF-alpha, IL-12) increased at 6 h and 7 days, but returned to normal by day 28. IFN gamma levels (interferon gamma, also a cytokine) remained unchanged at all times. Effects on gene expression were found at the mRNA level (through transcriptomics), which showed that 373 of the genes studied were upregulated and 254 genes were downregulated, more pronouncedly under the condition of multifrequency exposure. The genes represent immune regulation and cell metabolism. A different expression of proteins was also found, with 16 proteins up-regulated and 80 down-regulated, especially in animals exposed to only 9.3 GHz. In addition to these studies of whole blood and serum, the team of authors conducted Omics studies on the spleen. In this organ, more genes were found to be differently expressed than in the blood, with 475 genes being upregulated and 477 genes downregulated. Many of these genes play a role in immune activity. The proteome analysis of the spleen also showed different expressions of proteins (79 increased, 65 decreased) related to metabolism and immune-associated processes.

Overall, studies on other endpoints are very heterogeneous and do not show a consistent relationship between power density, exposure duration, or frequency, and the effects of exposure.

4.5 In vitro studies

In vitro tests investigate toxicological, mechanistic and other relevant effects by detecting the development of diseases or cellular changes using a variety of biological endpoints and potentially contributing to their understanding. In vitro tests can be used to identify hazardous substances, but their usefulness for assessing a biological effect is limited (SCENIHR 2009). However, in 2019, the IARC revised its procedures for defining hazard classifications in order to assign more significance to the findings on mechanisms from in vitro studies that can help predict carcinogenicity in humans (IARC 2019). This change in the classification of substances could be relevant for the assessment of the carcinogenicity of exposure to RF-EMF, especially since it was classified as '2B – potentially carcinogenic' by the IARC using its methodology, which was strongly focussed on epidemiological and in vivo studies (IARC 2013).

A table of the in vitro studies mentioned below can be found in Annex A-3.

4.5.1 Gene expression

Rampazzo et al. (2024) investigated the effects of 30.5-GHz exposure (continuous millimetre waves) on glioblastoma organoids. Despite the therapeutic approach of the study, the results on the thermal effect of the fields used are relevant for this statement. The experimental part was preceded by a comprehensive dosimetric approach combined with numerical and experimental methods to limit temperature rise during exposure. In the biological part, a global transcription profile analysis, the analysis of cell morphological changes and the phenotypic characterization of cells were performed. The team of authors used two exposure conditions: one with twice as much power over half the time as the other (i.e. 0.2 W average power for 10 minutes or 0.1 W average power for 20 minutes). In both cases, statistically significant effects of EMF exposure on cell proliferation and apoptosis were observed compared to the non-exposed control group, but without affecting the differentiation status of the glioblastoma cells. In combination with the chemotherapeutic drug temozolomide, even a statistically significant therapeutic effect was observed at a mean power of 0.1 W, which led to an increased death of glioblastoma cells. However, information is lacking on the number of independent experiments carried out and whether the examinations were blinded.

In one study (Martin et al. 2024), cellular responses were studied at the molecular level (transcription of certain genes), with two primary keratinocyte cultures (HEK and NHEK) and one keratinocyte-derived cell line (HaCaT) exposed at 60 GHz (for 3 h or 14 h). Three conditions were used: Sham-exposed cells, MMW-exposed cells and heat shock control. The authors only detected changes caused by the thermal effect of the MMW with high power density (above 10 mW cm^{-2}).

A dose effect was investigated by increasing the power density from 5 mW cm^{-2} to 20 mW cm^{-2}. The latter power density corresponds to the previously recommended maximum level for the general public for a skin surface area of 1 cm^2 (ICNIRP 1998) However, the new exposure limit recommended by ICNIRP (10 mW cm^{-2}) has also been tested (ICNIRP 2020). The authors summarize its results in such a way that apart from a heat effect associated with the acute 60 GHz exposure with high power density, there appears to be no further effect.

In a previous study, the authors (Martin et al. 2020) investigated the expression changes of three genes (ADAMTS6, IL7R and NOG) in primary cultures of human keratinocytes and in a cell line (HaKaT), using the same exposure conditions. Although statistically significant changes were recorded, the authors considered the fluctuations as random and did not associate them with the exposure.

Lawler et al. (2022) examined the effects of MMW exposure on primary human skin fibroblasts and found that high doses of MMW simultaneously cause non-thermal changes in the transcriptome as well as in the dynamics of the DNA structure, but do not cause DNA damage. The authors used a repeated 60 GHz exposure (2.6 mW cm^{-2}, 46.8 J cm^{-2} d^{-1}) (energy emitted by the MMW beam per area unit per day) and found a unique physiological response after exposure. For the exposure, a grid scan setup was used to avoid focussed warming effects. The fibroblasts were exposed 5 hours per day at 60 GHz for 4 days at 46.8 J cm^{-2} $d^{-1.}$ The controls were exposed to the same conditions but without MMW. For fibroblast exposure, 6-well plates were placed less than 2 mm above the WR12 waveguide and exposed with the 100 mW MMW beam, with the beam passing through the plastic bottom of the well, resulting in an average power density of 2.6 mW cm^{-2}.

The quantification of extracellular collagen was immunocytochemically investigated, which is a common marker for the stimulation of fibroblasts. After exposure, a statistically significant increase in collagen deposition was observed microscopically ($n = 3$). No positive control was used, and the experiments were not conducted in a blinded manner.

The analysis of gene expression revealed 255 genes (DEGs) expressed significantly differently between control and MMW-exposed samples with a false detection rate (FDR) of < 0.05 in both biological replicates. Of these DEGs, 126 genes were upregulated and 129 genes were downregulated. Most genes are affected differently by MMW and TGF-β treatments, suggesting, according to the authors, that the observed MMW-induced changes differ from the traditional cytokine-induced response (TGF-ß).

Furthermore, the authors conclude that the characteristic transcriptomic and genomic changes are not associated with a typical cellular thermal reaction, but could rather be associated with changes in DNA structural dynamics. These changes indicate a unique interaction of MMWs with biological material and underline the relevance of both power density and total duration for the setting of safety limits for longer exposure periods.

4.5.2 Other endpoints

Kim et al. (2022) investigated the effects of 28-GHz exposure on skin pigmentation in a mouse melanoma cell line (B16F10) and a 3D model of the pigmented epidermis (MelanoDerm). Exposure was for 4 h d^{-1} for 4 days (B16 cells) or every other day for 14 days (MelanoDerm), in the presence or absence of the hormone alpha-MSH (positive control that activates melanocytes). The temperature was monitored with an infrared camera. Cell morphology was monitored with Fontana-Masson staining, which allowed an investigation of the activated cells as well as the shape and length of the melanocyte dendrites. The generation of ROS was investigated with DCF-DA, and the melanin content by measuring absorption at 405 nm and cytotoxicity with the MTT assay. In addition, gene expression of the main melanin synthesis enzymes (tyrosinase, TRP-1, TRP-2, Rab27a, Mlph, MyoVa) was measured using the qRT-PCR method. The observations were made 4 h, 18 h and 24 h after exposure.

The mRNA level in the alpha-MSH-activated B16F10 cells was only reduced in samples taken 24 hours after exposure, similar to the reduction in ROS and melanin levels. Microscopic observations confirmed the lower melanin levels. No effects on cytotoxicity and dendrite lengths have been observed. Some of the observed effects were not found consistently at all the time points studied.

The MelanoDerm models were exposed every other day for 14 days. On the last days of the experiment, the tissue was prepared for the morphology and immunohistochemistry of melanin.

The results showed, in accordance with experiments on B16F12 cells, that 28-GHz exposure reduced the melanocyte phenotype, with less melanoma accumulation and melanocyte dendrite formation.

The article does not contain a sufficient description of the exposure protocol and the dosimetry and contains contradictory information in the main body of the text as well as in the figures illustrating the results.

Zhao et al. (2020) investigated the potential apoptosis-promoting effect of MMW on human A375 melanoma tumour cells in vitro. The exposure was at 35.2 GHz (0.16 mW cm^{-2}) for 15 minutes, 30 minutes, 60 minutes and 90 minutes for both exposed and sham exposed cell samples. The viability and apoptosis of the cells were determined after exposure. In addition, the changes in the expression of apoptosis-related proteins, such as caspase-3 and -8, were investigated. The study showed that the viability of the cells was statically significantly inhibited, while the number of apoptotic cells increased with increasing exposure duration. In parallel, it was found that the expression of caspase-3 and -8 was statistically significantly upregulated. In summary, it was noted that exposure at 35.2 GHz has an apoptosis-promoting effect on the A375 cells mediated by the activation of caspase-8 and -3.

There is no information on the number of independent experiments and whether they were conducted blinded in this study, either. There is also a lack of positive controls.

The aim of the study by Ploskonos et al. (2022) was to investigate the influence of MMW on normal and pathological human sperm by detecting polyamines (PA) in vitro. The stability of the sperm membranes, the number of apoptotic gametes and the content of PA in the semen plasma in the ejaculations of fertile and infertile men were compared before and after short-term exposure in vitro. The ejaculate samples were taken from healthy donors [n = 25, age 22-38 years, average age (30.6 ± 1.1) years (mean ± SEM)] and from subfertile men (n = 78, age 25-48 years, average age (34.1 ± 0.8) years) and exposed to MMW (42.194 GHz) for 20 minutes. The fragility of the sperm membranes, apoptotic cells and the PA content were determined. The results show that no changes in morphology and virtually no effects on sperm motility were observed in healthy samples. Rather, the authors identified the increase in the resistance of sperm membranes, the decrease in acrosine activity (the determination of the enzymatic activity of acrosine is used as a diagnostic test to evaluate the fertility of spermatozoa in vitro), the decrease in the number of apoptotic gametes, and the decrease in PA concentrations in sperm plasma in native human sperm after exposure. Positive reactions were observed in the subfertile samples, namely the increase in the motility of gametes of men with impaired fertility. This study shows an insufficient methodological quality, which significantly limits the informative value (lack of controls, no blinding, unclear dosimetry).

Microtubules are highly polar and can reach a length of several micrometres. They were thought to be sensitive to non-ionizing radiation. Therefore, Hammarin et al. (Hammarin et al. 2024a, Hammarin et al. 2024b) studied the growth behaviour of microtubules of eukaryotic cells after exposure to 3.5 GHz, 20 GHz and 29 GHz. The exact parameters of the exposure cannot be found in the publication. The authors found a strong influence on the kinetics of microtubule growth and could clearly link this effect to an increase in temperature. The very complex temperature control experiments, such as the comparison of the growth curves of microtubules at different temperatures, produced by MMW with different frequencies, exposure with infrared lasers or air flow heating, confirm these results, which were summarized in such a way that no measurable effects on the growth of microtubules could be detected that could not be explained as purely thermally induced.

4.6 Summary assessment of the biological and health effects of 5G technology in the FR2 frequency range

The results of the biological part of this statement can be summarised as follows:

- Compared to the frequency range FR1, the number of experimental studies for the frequency range FR2 is low. This is especially true for human experimental studies.
- Epidemiological studies in FR2 have mainly examined occupational radar exposure in the military or in the police. Most studies, that addressed EMF exposure, have not found any increased risks for diseases such as cancer. However, the studies are methodologically not robust. For example, exposure levels have been insufficiently quantified in most studies, or possible confounders have not or only rudimentarily been considered.
- Human experimental studies show that the perceptual threshold for temperature rise at the surface of the skin caused by the high-frequency electromagnetic fields (RF-EMF) in the frequency range FR2 is about 1 °C.
- In two out of three available studies on the threshold for thermal pain, a statistically significantly increased pain threshold was observed during a 30-minute exposure to millimetre waves at field strengths partly above the limit values. Overall, only very small samples with exposure parameters varying within a study and from study to study have been investigated so far.
- The majority of in vitro and in vivo animal studies with millimetre wave exposures have shown biological reactions (usually as a result of thermal exposure). However, no conclusions can be drawn with regard to the biological and health effects of exposures in the frequency range FR2, as the studies are very heterogeneous and low in number. There was no consistent relationship between power density, exposure duration or frequency, and the effects of exposure. The available in vivo studies, which were mostly concerned with warming the skin and eye, do not provide adequate and sufficient information for a meaningful, reliable risk assessment. In addition, the studies (in vivo and in vitro) do not provide sufficient information to answer the question of the presence of health-related non-thermal effects.

Currently available data is insufficient and therefore does not yet allow any conclusions to be drawn regarding possible health-related effects of exposure to radiofrequency electromagnetic fields in FR2 below the limit values applicable in Germany. In summary, however, it can be stated that the data currently available does not indicate that there are potentially negative biological effects from FR2 other than those based on thermal effects in body tissue, which are generally already known from FR1.

In view of the potential future use of FR2 in Germany (see section 3.1.2) and the currently insufficient data, it is necessary to further investigate potential health risks.

4.7 Open questions and research needs

Since there are few studies available for the frequency range FR2, since the penetration depth of the fields into the body is very low, and since the energy deposition takes place on the surface, the following recommendations are given for further investigations:

- Further studies on biological effects should primarily concern those frequencies of the FR2 which are intended for use.

- Since many studies are qualitatively insufficient in terms of scientific methodology or at least have significant weaknesses, the design and conduct of future studies need to be significantly improved. This applies to epidemiological studies and human experiments, and in particular to in vivo and in vitro studies.
- Human experimental studies on biological and health effects: These should focus on the effects mediated in particular through the skin, including the effects on components of the nervous and immune systems.
- In humans and/or in animal models: Analysis of possible long-term effects of exposure to frequencies of FR2 on the entire nervous system, in particular those mediated through the skin (e.g., behaviour, cognitive performance, neurophysiology, pain perception).
- Animal experimental studies: These should examine the most exposed organs, especially the skin and eyes.
- In vivo/in vitro studies: Effects of FR2 exposure on the skin flora, in particular on the microorganisms that are part of the immune system, should be investigated. In addition, in this context, it is recommended to investigate the immune response.
- Studies on in vitro models (skin, cornea, and conjunctiva of the eye, etc.) on thermal effects should be encouraged. It would be useful to implement global “omics” approaches without specific presumptions (Transcriptomics, Proteomics, Metabolomics, Lipidomics, Epigenomics).
- To improve the data situation, there is a need for research into possible non-thermal mechanisms of action.

Four EU projects are currently underway (ETAIN, GOLIAT, NextGEM, and SEAWave, see AnnexA-4), from which answers to some outstanding questions are expected.

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Unger 2022	Unger P. Fachvortrag mit Diskussion zum Thema "Mobilfunkausbau der Telekom: Stand und Perspektiven" in der Sitzung der Arbeitsgruppe „EMF und 5G-Mobilfunknetze“ des Ausschusses „Nichtionisierende Strahlen“ der Strahlenschutzkommission vom 05.12.2022.
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Walters et al. 2004	Walters TJ, Ryan KL, Nelson DA, Blick DW, Mason PA. Effects of blood flow on skin heating induced by millimeter wave irradiation in humans. Health Phys. 2004 Feb;86(2):115-20, doi: 10.1097/00004032-200402000-00001
Walther 2022	Walther L. Fachvortrag mit Diskussion zum Thema „5G im FR2: Grundlagen, Unterschiede zu FR1, Anwendungsbeispiele“ in der Sitzung der Arbeitsgruppe „EMF und 5G-Mobilfunknetze“ des Ausschusses „Nichtionisierende Strahlen“ der Strahlenschutzkommission vom 14.09.2022.
Wood 2023	Wood M. Fachvortrag mit Diskussion zum Thema „Addressing Public Concerns around Telecommunications Facilities - Telstra’s EMF Testing and Communications“ in der Sitzung der Arbeitsgruppe „EMF und 5G-Mobilfunknetze“ des Ausschusses „Nichtionisierende Strahlen“ der Strahlenschutzkommission vom 19.09.2023.
Wood et al. 2021	Wood A, Mate R, Karipidis K. Meta-analysis of in vitro and in vivo studies of the biological effects of low-level millimetre waves. J Expo Sci Environ Epidemiol. 2021 Jul;31(4):606-13, doi: 10.1038/s41370-021-00307-7, Epub 2021/03/18
Yao et al. 2022	Yao C, Wang H, Sun L, Ren K, Dong J, Wang H, Zhang J, Xu X, Yao B, Zhou H, Zhao L, Peng R. The Biological Effects of Compound Microwave Exposure with 2.8 GHz and 9.3 GHz on Immune System: Transcriptomic and Proteomic Analysis. Cells-Basel. 2022 Nov 30;11(23), doi: 10.3390/cells11233849, Epub 20221130
Yuasa et al. 2024	Yuasa A, Uehara S, Ushizawa K, Kodera S, Arai N, Hirata A, Otaka Y. The thermal sensation threshold and its reliability induced by the exposure to 28 GHz millimeter-wave. Front Neurosci. 2024;18:1331416, doi: 10.3389/fnins.2024.1331416, Epub 20240227
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Zilberti et al. 2015	Zilberti L, Voyer D, Bottauscio O, Chiampi M, Scorretti R. Effect of Tissue Parameters on Skin Heating Due to Millimeter EM Waves. IEEE Transactions on Magnetics. 2015;51(3):9400904, doi: 10.1109/tmag.2014.2363898

6 List of abbreviations

ACTH	Adrenocorticotropic hormone
Alpha-MSH	alpha-melanocyte stimulating hormone
ANFR	Agence Nationale des Fréquences (France) (National Frequency *Agency)*
ANSES	Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail (France) (The French Agency for Food, Environmental and Occupational Health & Safety)
CD spectroscopy	circular dichroism spectroscopy
CI	Confidence Interval
CLUE-H	Cluster on Electromagnetic fields Exposure and Health
CPT	Cold pressor test
DCF-DA	dichlorodihydrofluorescein diacetate
DNA	Deoxyribonucleic acid
EEG	Electroencephalography
ECG	Electrocardiogram
ELISA	Enzyme-linked immunosorbent assay
ETAIN	Enhancing the investigation of RF-EMF and its possible effects on human health and biodiversity
fad	Flavin adenine dinucleotide
FAIR	Findability, Accessibility, Interoperability, *and Reusability*
FLIM	Fluorescence Lifetime Imaging Microscopy
FR1	Frequency range 1
FR2	Frequency range 2
GHz	Gigahertz
GOLiAT	5G exposure, casual effects and risk perception through citizen engagement
GSMA	GSM Association
HaCaT	spontaneously transformed human keratinocyte *cell culture*

HAS	Human serum albumin
HEK	Human Embryonic Kidney Cells
HF	High frequency
RF-EMF	Radio/High-frequency electromagnetic field(s)
HSC	heat shock control
IARC	International Agency for Research on Cancer
ICC	Intraclass Correlation Coefficient
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IL	interleukin
MANOVA	Multivariate Analysis of Variance
Mlph	melanophilin
MMW	millimetre wave
MyoVa	Myosin VA Gene
NextGEM	Next Generation Integrated Sensing and Analytical System for Monitoring and Assessing RF-EMF Exposure and Health
NHEK	normal human epidermal keratinocytes
NIKH	NextGEM Innovation and Knowledge Hub
OFDMA	Orthogonal Frequency-Division Multiple Access
OR	Odds ratio
PA	polyamines
qRT-PCR	Quantitative reverse transcriptase polymerase chain reaction
Rab27a	Ras-related protein Rab-27A
ROS	Reactive oxygen species
SAR	Specific absorption rate
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks (European Union)
SEAWave	Scientific-Based Exposure and Risk Assessment of Radiofrequency and mm-Wave Systems from children to elderly (5G and Beyond)

TDD	Time Division Duplex
THz	Terahertz
TNF	Tumour necrosis factor
TRP-1	tyrosinase related protein-1
TRP-2	tyrosinase related protein-2
WHO	World Health Organization
Wi-Fi	Wireless Fidelity

7 Explanation of terms

3G	Third generation of mobile communications (3G): The third generation of mobile communications is the UMTS (Universal Mobile Telecommunications System) mobile communication standard. UMTS used the 2100 MHz frequency band. In Germany, UMTS is now switched off. Downlink data rates of up to a few 100 kBit s^{-1} (with the extension HSPA+ up to several 10 MBit s^{-1}) could be achieved.
4G	Fourth generation of mobile communication (4G): The fourth generation of mobile communications includes the Long Term Evolution (LTE) and Long Term Evolution - Advanced (LTE-A) mobile communication standards with downlink data rates of up to a few 100 $Mbps^{-1}$. LTE and LTE-A currently use the 700 MHz, 800 MHz, 900 MHz, 1.5 GHz, 1.8 GHz, 2.1 GHz and 2.6 GHz frequency bands in Germany.
5G	Fifth generation of mobile communications (5G): The fifth generation of mobile communications is referred to as the 5G mobile communication standard. In Germany, 5G currently uses the frequency bands 700 MHz, 1.8 GHz, 2.1 GHz and 3.6 GHz with theoretically achievable downlink data rates of just over 1 GBit s^{-1} in Frequency Range 1 (FR1). In Frequency Range 2 (FR2), the 26 GHz band with theoretically achievable downlink data rates of up to a few GBit s^{-1} is used (as of 07/2025).
Absorption (radiation)	Absorption refers to the attenuation of radiation when passing-through matter by converting radiant energy into another form of energy (e.g. thermal energy).
Antenna array	An antenna array consists of individual antenna elements that can be combined to form a group antenna with a high directivity by phase control and thus enable beamforming.
Antenna gain	The antenna gain is the ratio of the power density generated by a real antenna in its main beam direction in the far field at a certain distance to the power density of a reference antenna (typically an ideal isotropic radiator) at identical input power at the same distance in the main beam direction.

Basic restrictions (electromagnetic fields)	The basic restriction is a benchmark value for physical quantities caused (induced) inside the body as a result of external exposure to electric, magnetic or electromagnetic fields that are directly related to the biophysical effect to be limited. For the assessment of electromagnetic fields, depending on the frequency, the recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) set basic restrictions for the intracorporeal electric field strength (> 0 Hz to 10 MHz), the intracorporeal electric current density (> 0 Hz to 10 MHz), local and body averaged specific absorption rate (100 kHz to 6 GHz), specific absorption (400 MHz to 6 GHz), absorbed power density (100 kHz to 300 GHz), and absorbed energy density (6 GHz to 300 GHz). Verifying compliance with the basic restrictions generally requires a lot of effort, which is why in practice it typically only takes place when reference levels (see there) are exceeded. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends a concept of basic restrictions and reference levels to limit electric, magnetic and electromagnetic fields. Basic restrictions are set for electric quantities induced in the body and address biological effects of the fields. Reference levels are derived from the basic restrictions assuming conservative (unfavourable) exposure conditions.
Beamforming	Beamforming refers to the possibility of selectively changing the shape and orientation of the beam or transmission beam of an intelligent (adaptive) antenna. For modern adaptive antennas, which are partly used in the course of the 5G expansion, this is done in a software-controlled manner in order to steer the transmission beam in a specific direction (e.g. in an area with high user density).
Blood perfusion	Blood flow through the body or an organ.
Broadcast Beam(s)	Radiation beam(s) of a 5G antenna over which the signalling information is radiated.
Diffraction (radio transmission)	The diffraction is the deflection of electromagnetic waves in one or more new direction(s) at an obstacle, e.g. at a building edge. By diffraction, a wave can spread into areas of space that would be blocked by the obstacle on a straight path.
EIRP	Equivalent Isotropically Radiated Power is the active power that would have to be fed to an ideal lossless, isotropic emitter instead of a real antenna, so that it would provide the same electromagnetic power density at a certain distance (in the far field) as the real antenna in its main beam direction (far field).

Fading (radio transmission)	Fading in radio transmissions is defined as local variations in field strength caused by interference, shadowing, multi-path propagation and by the Doppler effect.
FR1	The abbreviation FR1 refers to the frequency range 1. This includes the frequencies from 410 MHz to 7.125 GHz (see also "5G" for the frequency ranges currently used for 5G applications in Germany)
FR2	The abbreviation FR2 refers to the frequency range 2. This includes the frequencies from 24.25 GHz to 71 GHz (see also “5G” for the frequency ranges currently used for 5G applications in Germany)
Handover	A process in a mobile communication network in which the radio connection to the mobile device is seamlessly transferred from one radio cell to another during a call or data connection.
Horn layer	The corneal layer (Stratum Corneum) is a part of the epidermis
Hydrometeor	The term hydrometeor is the generic term used in meteorological terminology for all forms of condensed water that can be observed on the earth's surface or in the atmosphere.
ICNIRP	The International Commission on Non-Ionizing Radiation Protection is an international association of scientists that contributes to the protection of humans from non-ionizing radiation by analysing and evaluating the state of knowledge on the health effects of electric, magnetic and electromagnetic fields, optical radiation and infra- and ultrasound. Important results of its work are the publication of limit value recommendations, which are taken into account, inter alia, by the EU in the preparation of recommenddations and legal acts.
Latency	In telecommunications technology, the delay time between the occurrence of an event and the occurrence of an expected subsequent event.
Loss of penetration	Attenuation of an electromagnetic wave when penetrating an object.
Massive MIMO	See ‘MIMO’

Matching layer	A matching layer is a material layer that is inserted at the boundary between two media A and B of different dielectric tissue or wave propagation properties. Due to the special dielectric properties of the matching layer (relative to the dielectric properties of the two media A and B), its presence leads to the resultant reflection coefficient for electromagnetic waves during wave propagation from medium A to medium B being smaller than at the direct transition from medium A to medium B (without matching layer). The presence of the matching layer therefore leads to more electromagnetic radiation power being transferred from medium A to medium B than would be the case without the matching layer.
Maxwell equations	The Maxwell equations are the four basic equations for all electromagnetic phenomena and electrodynamics. They describe how electric and magnetic fields are generated and how they are related to each other and to electric charges and electric current.
MIMO	Multiple Input Multiple Output is a multi-antenna technology in which multiple antennas are used in parallel on the side of the transmitter and receiver in order to optimise data transmission. This allows for multiple data streams to be sent and received at the same time. If dozens or even hundreds of antennas are used, this is also referred to as massive MIMO.
Multi-carrier method	A multi-carrier modulation method (OFDMA, see abbreviation directory) in which the data is distributed over several carriers. These subcarriers are orthogonal to each other, i.e. the maximum of one subcarrier in the amplitude spectrum coincides with the zero passages of all other subcarriers. Therefore, there is no cross-talk between the subcarriers and therefore no large safety distance between them is required. This results in relatively low bandwidth requirements.
Multi-path propagation	Multipath propagation occurs when electromagnetic waves from a transmitter are deflected by reflectors (e.g. buildings, vehicles, water-surface areas, etc.) and arrive at the receiver in various ways.
PECO	Patient/population, exposure, comparison, outcome is a scheme used in evidence-based medicine to formulate and answer research questions. PECO criteria help to structure research questions and evaluate the relevance of studies.
Penetration depth (electromagnetic fields)	In the case of electromagnetic fields, the penetration depth denotes the distance in matter after which the field strength has dropped to 1 e^{-1} or 37% of its initial value.

Pennes' bioheat equation — The Pennes’ bioheat equation describes the development of temperature T inside the human body as a result of an energy input through absorption of electromagnetic waves (taken into account by the volumetric power density Q_{abs}). The equation takes into account the mass density ρ, the specific heat capacity c, the thermal conductivity k, the metabolic heat generation Q_m and the blood perfusion rate w_b of the tissue under consideration as well as the specific heat capacity of the blood c_b and the temperature of the arterial blood T_a.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T - w_b c_b (T - T_a) + Q_m + Q_{abs}$$

Polyamines — Polyamines (PA), such as spermine and spermidine, are the most important PA found in all living organisms. PA are formed by the decarboxylation of amino acids and facilitate cell growth and development through various cellular reactions. PA are an integral part of the cellular and genetic metabolism and contribute to transcription, translation, signal transmission and posttranslational modifications.

Poynting vector — The Poynting vector is the vector that describes the electromagnetic power flow by size and direction. It is the vectorial product of the vectors of electric and magnetic field strength.

Radiation power — See ‘EIRP’

Radio cell — A radio cell is an area that is supplied by a transmitter. Depending on the size, a distinction is made between femtocells, picocells, microcells and macrocells. Especially in mobile communications, the term radio cell refers to the area within a mobile network that is supplied with high-frequency electromagnetic fields by a base station. The size of a radio cell in the network depends, among other things, on data throughput and topographic conditions.

Reference level (electromagnetic fields)	The reference level is a conservative benchmark for a physical quantity that is accessible to routine measurement and that can be used for a simplified exposure assessment. The recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) specify the reference levels for the assessment of electromagnetic fields, depending on frequency, for the incident field variables electric field strength (> 0 Hz to 300 GHz), magnetic field strength or flux density (> 0 Hz to 300 GHz), power density (30 MHz to 300 GHz), energy density (400 MHz to 300 GHz) as well as for contact currents (> 0 Hz to 10 MHz) and high-frequency currents in limbs (100 kHz to 110 MHz). If the reference levels are not exceeded, it can be assumed without further examination that there is no danger to persons from direct effects of the electric, magnetic or electromagnetic fields. If the reference levels are exceeded, it may be possible to show compliance with the biologically relevant basic restrictions (see there) by more complex evaluation procedures. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends a concept using both basic restrictions and reference levels to limit electric, magnetic and electromagnetic fields. Basic restrictions are set for the electric quantities induced in the body and address biological effects of the fields. Reference levels are derived from the basic restrictions assuming conservative (unfavourable) conditions.
Reflection loss	Attenuation of an electromagnetic wave during reflection.
Shadowing	Reception level variation in signal transmission due to the interaction of electromagnetic waves with objects, for example by shading.
Spectrum analyser	A spectrum analyser is a measuring instrument used in electric measurement technology for the detection and representation of a signal in the frequency range.
Speed of light	Speed at which electromagnetic waves propagate. In vacuum, the speed of light is 299 792 458 m s^{-1}. In ground-level air, the propagation speed of electromagnetic waves at approximately 299 710 km s^{-1} is slightly lower than in vacuum.

Site certificate	According to Section 4 of the BEMFV 2002, a site certificate is a certificate of harmlessness from a radiation protection point of view and must be available for the operation of stationary radio equipment with an EIRP (see 'EIRP') of 10 watts or more. The same applies to stationary radio equipment with an EIRP of more than 0.1 W but less than 10 W installed at a site with a total EIRP of 10 W or more, or if the added radio equipment reaches or exceeds the total EIRP of 10 W. Site certificates are issued on request by the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railways (BNetzA). Exceptions apply, for example, to certain amateur radio equipment.
Scattering	Diffuse deflection of an electromagnetic wave into many directions due to interaction with an object.
Traffic Beam(s)	Radiation beam(s) of a 5G antenna through which the communication of the base station with the individual user devices takes place.
Transmission loss	Additional attenuation of an electromagnetic wave when passing through matter.
Voxel	The smallest cube-like part in a three-dimensional space. A voxel is defined by the x, y, and z coordinates of one of the eight vertices or by its centre. The term voxel is used in the three-dimensional representation of tissue in medical imaging procedures.

Appendix

A-1 Tabular compilation of experimental human studies

Tab. A-1.1: Tabular compilation of the publications mentioned in section 4.3 'Experimental human studies'

study	n	gender	age (years)	frequency(s)	power density	duration of exposure	result
perception							
Pakhomov et al. 1998 [1)]	no information	no information	no information	37.7 GHz 42.25 GHz 53.57 GHz	5 - 15 mW cm^{-2}	20 times 1 min, 1-min intervals between exposures	• Frequency of perception across all frequencies and power densities: 30% to 80%; • Combination 37.7 GHz and 15 mW cm^{-2}: Frequency of perception significantly lower than at 42.25 GHz and 5 mW cm^{-2}. Reaction latency: 40 s - 50 s.
See also et al. 1997	15	no information	45.2 ± 6.0	2.45 GHz 7.5 GHz 10.0 GHz 35 GHz 94 GHz	20 intensities	no information	• Perception thresholds: 2.45 GHz: 63.1 mW cm^{-2}; 7.5 GHz: 19.5 mW cm^{-2}; 10 GHz: 19.6 mW cm^{-2}; 35 GHz: 8.8 mW cm^{-2}; 94 GHz: 4.5 mW cm^{-2} (comparable to infrared: 5.34 mW cm^{-2})
Yuasa et al. 2024	20	16 men, 4 women	35.2 ± 3.0	28 GHz	27 mW cm^{-2} 126 mW cm^{-2} 191 mW cm^{-2} 252 mW cm^{-2} 399 mW cm^{-2}	no information	• Perception thresholds: 27 mW cm^{-2}: 0.2 °C 126 mW cm^{-2} to 399 mW cm^{-2}: 0.9 °C to 1.0 °C; • Reliability of perception threshold determination increases with exposure level
Threshold for thermal pain							
Radzievsky et al 1999	12	12 men	37.3 ± 4.9 18 – 65	42.25 GHz	25.5 mW cm^{-2}	30 min	• Significant ($p < 0.05$) suppression of pain sensation; • Increase in pain tolerance: 37.7%; • Increase in pain sensitivity range: 49.3%
Partyla et al. 2017	23	23 men	20 - 40	42.25 GHz, 50 - 70 GHz noise signal	17.2 mW cm^{-2}	30 min	• Increase in pain threshold: 42.25 GHz: 1.97 seconds; 50 - 70 GHz noise generator: 1.27 seconds; Sham exposure: No deviation from baseline

study	n	gender	age (years)	frequency(s)	power density	duration of exposure	result
Minier et al. 2023	10	7 men, 3 women	35.2 ± 12.9 21 - 54	61.25 GHz	17.2 mW cm^{-2}	30, 60 and 90 min	• Pain threshold: 30 min: statistically significant increase in pain threshold; 60 and 90 min: no change in pain threshold; • Pain tolerance: no change
Cardiovascular effects							
Radzievsky et al 1999	12	12 men	37.3 ± 4.9 18 - 65	42.25 GHz	25.5 mW cm^{-2}	30 min	No exposure-related differences
Müller et al. 2004	50	38 men, 12 women	18 - 36	77 GHz	3 μW cm^{-2}	15 min	• Heart rate, electrocardiographic parameters, respiratory rate, skin temperature and skin conductivity as well as systolic and diastolic blood pressure: No statistically significant differences between exposure conditions
Kantz et al. 2005	50	32 men, 18 women	15 - 78	5.8 GHz, 12 GHz,24 GHz, 60 GHz, 77 GHz, 110 GHz	59.7 μW cm^{-2}	15 min	• Heart rate, electrocardiographic parameters, respiratory rate, skin temperature and skin conductivity as well as systolic and diastolic blood pressure: No statistically significant differences between exposure conditions
Partyla et al. 2017	23	23 men	20 - 40	42.25 GHz	< 17.2 mW cm^{-2}	30 min	• Diastolic blood pressure: increase under exposure; • Other outcome variables (systolic blood pressure, heart rate and paraesthesia): No change.
Minier et al. 2023	10	7 men, 3 women	35.2 ± 12.9 21 - 54	61.25 GHz	17.2 mW cm^{-2}	30, 60 and 90 min	• Heart rate: 30 min: statistically significant reduction; 60 and 90 min: no change; • Blood pressure and skin temperature: No significant differences
[1)] Summary of three original studies published in Russian (Lebedeva 1993, Lebedeva 1995, Kotrovskaia 1994)							

A-2 Tabular compilation of in vivo studies

Tab. A-2.1: A tabular compilation of the publications mentioned in section 4.4 "In vivo studies" (author: Mats-Olof Mattsson)

study	exposed system	biological endpoint	frequency	power density/SAR	exposure time (min to d)	sham exposed/control	positive control	temperature control	blinded	dosimetry	number (n)	results
Thermal effects, especially on the skin and eye												
Ijima et al. (2023a)	male Sprague-Dawley rats	dorsal skin	26 GHz	0 W m^{-2} 125 W m^{-2} 250 W m^{-2} 370 W m^{-2} 500 W m^{-2}	18 min	yes	no	yes	no	yes	6-15	• The skin temperature increased dose-dependently right at the beginning of exposure, with a maximum increase of 11.3 °C at 500 W m^{-2}. • The temperature rise stopped immediately when the exposure ended. • Rectal temperature increased by 0.6 °C after 4 minutes of exposure only at 370 W m^{-2} and at 500 W m^{-2} (rectal temperature data were collected for a total of 30 minutes, 6 minutes before, 18 minutes during and 6 minutes after exposure).
Ijima et al. (2023b)	male Sprague-Dawley rats	thermoregulation, including changes in blood flow in the skin, during whole body exposition	26 GHz	0 W m^{-2} 8.5 W m^{-2} 122 W m^{-2} 237 W m^{-2}; Correspondingly 0 W kg^{-1} 0.26 W kg^{-1} 3.7 Wkg^{-1} 7.2 Wkg^{-1}	40 min	yes	no	yes	no	yes	31	• Exposure caused an immediate rise in temperature in the skin at all intensities, while rectal temperature began to rise after 46 s exposure. • The temperature increase persisted throughout the exposure period. • Blood flow in the dorsal skin remained at the same level during exposure, but increased linearly in the tail skin, with a factor of three at 237 W m^{-2}. • The temperature rise in the dorsal skin was 2.7 °C and 3.9 °C at 122 W m^{-2} and 237 W m^{-2}, respectively. • The corresponding elevations were 4.4 °C and 7.4 °C for the tail skin and 0.9 °C and 1.3 °C in the rectum.
Foroughimehr et al. (2023)	human eye, 3D models for normal and dry eye	temperature levels in the two corneal models	0.5 GHz to 30 GHz	20 W m^{-2} 100 W m^{-2}	model study, therefore not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	not relevant	• The 30 GHz exposure caused a temperature increase of approximately 0.03 °C at 20 W m^{-2}in the normal eye and an increase of approximately 0.13 °C at 100 W m^{-2} in the normal eye. • For the dry eye, the corresponding increases were 0.03 °C and 0.13 °C, respectively.

study	exposed system	biological endpoint	frequency	power density/SAR	exposure time (min to d)	sham exposed/control	positive control	temperature control	blinded	dosimetry	number (n)	results
Foroughimehr et al. 2024	pigs' skin	changes in the tissue temperature and autofluorescence of flavin adenine dinucleotide (FAD).	26 GHz	5.1 kW m^{-2}	1-30 min	no	no	no	no	yes	6	• The temperature rise was strongest in the first 5 minutes, slowed, and reached a plateau after 30 minutes. • The maximum temperature increase was 7 °C. • The lifetime of FAD, as an indicator of intact metabolism, decreased over time (statistically not significant), both in the control and exposed samples.
Parker et al. (2024)	female pigs' skin	burn thresholds	8.2 GHz 95 GHz	8 W cm^{-2} 20 W cm^{-2} 25 W cm^{-2} 30 W cm^{-2}	5 sec	yes	no	falls off	no	yes	8	• Burn damage occurred in a dose-dependent manner • Severity of burns increased with increasing energy input
Li et al. (2023a)	skin of male Sprague-Dawley rats	local temperature increases	6 GHz 30 GHz 60 GHz 100 GHz	0-500 W m^{-2}	no information	no	no	yes	no	yes	n/a	• Linear relationship between the absorbed power density at the skin surface and the power density outside the body at 6 GHz, 30 GHz, 60 GHz and 100 GHz. • The warming factor for the rat's scalp varied from 0.0083 °C to 0.0118 °C per W cm^{-2} over the 6 GHz to 100 GHz range. • Above 30 GHz, the equivalent absorbed power density could cause a 70% higher temperature in the rat dorsal skin compared to the rat scalp. • The temperature change on the skin surface of the rat could be affected by thermal parameters, tissue thickness and blood flow rate in the deeper tissue layers.
Kojima et al. (2024)	rabbit's eye	damage to the rabbit's eye	60 GHz	200 mW cm^{-2} 300 mW cm^{-2}	6 min	yes	no	yes	no	yes	5	• Under conditions of high temperature and high humidity (45 °C, 80% relative humidity), corneal opacity, corneal oedema, and damage to the corneal epithelium (at 200 mW cm^{-2}) were induced in all animals examined. • A relative humidity of 80% significantly promoted eye damage. • The threshold for eye damage depended directly on the power density. • A high ambient temperature and humidity played a secondary role and caused an exacerbating effect on eye damage. • A low-humidity environment did not necessarily prevent the development of eye damage from MMW exposure.

study	exposed system	biological endpoint	frequency	power density/SAR	exposure time (min to d)	sham exposed/control	positive control	temperature control	blinded	dosimetry	number (n)	results
Kojima et al. (2025)	rabbit's eye	damage to the rabbit's eye	28 GHz	200 mW cm^{-2} until 750 mW cm^{-2}	6 min	yes	no	yes	no	yes	35	• At 400 mW cm^{-2}, damage to the corneal epithelium, corneal oedema, and lens opacity (cataract) were observed. • Power density thresholds that resulted in a 10%, 50%, and 90% probability (DD10, DD50 and DD90, respectively) of eye damage due to the 6-minute exposure: • 327 mW cm^{-2}, 359 mW cm^{-2} or 394 mW cm^{-2}. • These values are higher than at the higher frequencies (40 GHz, 60 GHz, 75 GHz, 95 GHz, and 162 GHz) applied in previous studies by the same team of authors.
Other endpoints												
Perov et al. (2022)	male Wistar rats	exploration and orientation activity, serum concentrations of the hormones ACTH and corticosterone	3.6 GHz 28 GHz 37 GHz	250 µW cm^{-2}	1, 2, 3 or 4 months, 24 h/d, 7 days per week; additional group after four months exposure time and then one month without exposure.	yes	no	no	no	n/a	12 for each group	• Orientation and exploration activity decreased in the exposed animals compared to the control animals, with a maximum effect after three months (mostly not statistically significant). • Only one behavioural parameter ('hole reflex') showed a statistically significant decrease after two months of exposure.
Yao et al. (2022)	male Wistar rats	immune system, organ pathology (thymus, spleen), examined 6 h as well as 7 days, 14 days and 28 days after exposure	2.8 GHz 9.3 GHz (alone or in combination)	10 mW cm^{-2}	6 min 6 plus 6 min	yes	no	no	no	no	5	• Pathological changes in both thymus and spleen, starting on day 7 after exposure, with stronger effects under conditions of multi-frequency exposure. • In particular, the lymphocytes in these two organs showed congestion and nuclear fragmentation, which were no longer present on the 28th day after exposure. • The single-frequency exposures did not affect the number of white blood cells. • By contrast, multifrequency exposures altered the number and proportion of both T and B lymphocytes, with the number of B cells increasing. • It is unclear whether the longer duration of exposure or the combination of frequencies caused the effects. These effects were no longer present on day 28 after exposure. Several serum cytokines (IL-1alpha, IL-1beta, IL-4, TNF-alpha, IL-12) increased at 6 h and 7 days but returned to normal by day 28. The interferon gamma levels remained unchanged at all times. • At the genome and protein level, metabolism and immune-associated processes were altered.

A-3 Tabular compilation of in vitro studies

Tab. A-3.1: Tabular compilation of the publications mentioned in section 4.5 "In vitro studies"

study	exposed system	biological endpoint	frequency	power/ power density/SAR	exposure time (min to d)	sham exposed/control	positive control	temperature control	blinded	dosimetry	number (n)	results
Gene expression												
Rampazzo et al. (2024)	glioblastoma organoids	gene expression	30.5 GHz	0.2 W 0.1 W	2 W mean power for 10 minutes 0.1 W mean power for 20 minutes	yes	yes	yes	no	yes	n/a	• In both cases, compared to the unexposed control group, statistically significant effects from EMF exposure on cell proliferation and apoptosis without affecting the differentiation status of glioblastoma cells. • In combination with the chemotherapeutic agent temozolomide, a statistically significant therapeutic effect was observed at a mean power of 0.1 W, which led to an increased apoptosis of glioblastoma cells.
Martin et al. (2024)	keratinocyte cultures (HEK and NHEK) HaCaT cells	gene expression	60 GHz	2 mW cm^{-2} 5 mW cm^{-2} 10 mW cm^{-2} 20 mW cm^{-2}	3 h 14 h	yes	no	yes	yes	yes	3-5	Apart from a heat effect associated with acute 60 GHz exposure with high power density, no further effects.
Martin et al. (2020)	primary cultures of human keratinocytes HaKaT cells	gene expression	61 GHz	5 mW cm^{-2} 10 mW cm^{-2} 20 mW cm^{-2}	3 h 14 h	yes	no	yes	yes	yes	3-6	Statistically significant changes; the author team considers the fluctuations as random.
Lawler et al. (2022)	primary human skin fibroblasts	gene expression	60 GHz	2.6 mW cm^{-2} 46.8 J cm^{-2} d^{-1}	4 days 5 h/d	yes	no	yes	no	in-adequate	3	Exposure to high-energy MMW, which simultaneously causes non-thermal changes in the transcriptome as well as in the dynamics of the DNA structure, but does not cause DNA damage.

study	exposed system	biological endpoint	frequency	power/ power density/SAR	exposure time (min to d)	sham exposed/control	positive control	temperature control	blinded	dosimetry	number (n)	results
Other endpoints												
Kim et al. (2022)	mouse melanoma cell line (B16F10) 3D model of the pigmented epidermis (MelanoDerm)	ROS gene expression of melanin synthesizing enzymes dendrite formation in B16F10 cells	28 GHz	10 W m^{-2}	4 h/d for 4 d (B16 cells) or every other day for 14 d (MelanoDerm)	yes	yes	yes	no	unclear	3	Tests 4 h, 18 h and 24 h after exposure: 24 h after exposure, ROS and melanin as well as mRNA levels in alpha-MSH-activated B16F10 cells were reduced.
Zhao et al. (2020)	human A375 melanoma tumour cells	apoptosis	35.2 GHz	0.16 mW cm^{-2}	15 min 30 min 60 min 90 min	yes	yes	yes	no	yes	n/a	• Statistically significant upregulation of Caspase-3 and Caspase-8 • Inhibition of cell viability • Induction of apoptosis
Ploskonos et al. (2022)	normal and pathological human sperm	stability of sperm apoptosis	42.194 GHz	no information	20 min	yes	no	no	no	no	healthy donors (n = 25) subfertile donors (n = 78)	• Increased resistance of sperm membranes • Reduction of acrosine activity • Reduction in the number of apoptotic gametes • Reduction of PA concentrations in sperm plasma
Hammarin et al. (2024a), (2024b)	samples of extracted purified tubulin from pig brain tissue	growth behaviour of the microtubules of eukaryotic cells	3.5 GHz 20 GHz 29 GHz	no information	no information	yes	no	yes	no	no	n/a	Effects were clearly associated with temperature rise

A-4 EU studies under Horizon Europe (CLUE-H)

In the context of its various research frameworks, the European Commission has funded several projects dealing with the potential health effects of exposure to different types of EMF, including RF-EMF. The “Horizon Europe” program is currently underway, with EU funding for the period from 2021 to 2027. As part of this program, the Cluster on Electromagnetic fields Exposure and Health (CLUE-H; https://research-and-innovation.ec.europa.eu/research-area/health/environment-climate-and-health/clue-h_en) was founded (total funding: EUR 29 million). For this purpose, four projects were selected for funding on the basis of a request for proposals: ETAIN, GOLIAT, NextGEM, and SEAWave.

The aim of the CLUE-H research program is to answer the following questions (CLUE-H 2025a):

- To what extent are we exposed to RF-EMF?
- How is our electromagnetic environment changing with the introduction of new wireless technologies, especially 5G?
- Is there any impact on our health and the environment?

In order to coordinate and harmonise the work between the four projects, five working groups have been set up:

- Working Group 1 (WG1) Scientific Translation for Politics and Practice
- Working Group 2 (WG2) Data Management and Exchange
- Working Group 3 (WG3) Communication and Information Dissemination
- Working Group 4 (WG4) Experimental Studies
- Working Group 5 (WG5) Exposure Assessment

As part of CLUE-H, newsletters, brochures, and policy briefs are created, which are available on the website (CLUE-H 2025b). Several focus workshops/training sessions on specific topics of common interest will also be organised. Links to all the publications of the four projects can be found on the same website.

The projects within the cluster started their investigations in 2022 and are expected to continue until 2027. They intend to provide results that can contribute to an evidence-based policy strategy in dealing with RF-EMF. The four projects are briefly described below.

Improving the study of RF-EMF and its potential impact on human health and biodiversity (ETAIN)

The aim of ETAIN (Exposure To electromAgnetic fIelds and plaNetary health) is to develop and validate approaches to assess the effects of RF-EMF from a human and planetary health point of view, as well as to explore options for reducing exposure.

For this purpose, a mobile phone app is developed and validated as part of a citizen science approach, which informs the users about their current RF-EMF exposure. In addition, the app collects data that is used to model the spatial distribution of RF-EMF exposure in Europe. On the one hand, calibration measurements are carried out in order to estimate the relationship between the signal quality in the mobile and Wi-Fi network and the associated exposure due to the infrastructure and one’s own device (Sandoval-Diez et al. 2025). In addition, an exposure model is developed that allows laypersons to estimate their cumulative exposure to RF-EMF in

FR1. In addition, new dosimetric models for new technologies and applications with a focus on the millimetre wave range (FR2) are being developed.

It also evaluates how networks can be designed to minimise public exposure and develops appropriate network planning tools. Biological effects of RF-EMF are studied in honeybees (*Apis mellifica*), wild bees (*Osmia bicornis*), and blue flies (*Calliphora vomitoria*). On the one hand, 3-dimensional models characterize RF-EMF absorption in the range of 0.1 to 120 GHz. In laboratory experiments, effects of 1.8 GHz, 3.5 GHz and 26 GHz exposure on the various stages of development of these insects are investigated. In a field experiment, the influence of 3.5 GHz and 24-26 GHz exposure on biodiversity in general and bees in particular is investigated. Furthermore, the effects of 26 GHz exposure on the behaviour of fruit flies over several generations are experimentally investigated in the laboratory. In addition, analyses of transcriptomics and metabolomics are carried out on the fruit flies.
In terms of human health, experimental studies are carried out on the skin and the eye. Effects on oxidative stress are in the foreground. By means of transcriptomics, the biological effects at the level of gene expression are investigated in order to investigate the potential effects of a 26 GHz signal in the human 3D skin model. It is also being tested whether exposure at 26 GHz could affect the metabolome of the endo- and extracellular extracts of the reconstructed human skin and fruit fly and, among other things, produce oxidative derivatives. The project results are evaluated together with literature findings with regard to planetary health.

5G exposure, causal effects and risk perception through civic engagement (GOLIAT)

The main objective of the five-year project GOLIAT (5G expOsure, causaL effects, and rIsk perception through citizen engAgemenT) is to characterize RF-EMF exposure in the population more precisely and to record possible changes over time. In addition, new insights into potential causal neuropsychological and biological effects will be gained and the understanding of the risk perception and risk communication of the public in a Europe-wide approach will be examined in an interdisciplinary and transdisciplinary way.

On the one hand, measurement campaigns are carried out in ten European countries in order to record the exposure from mobile base stations and mobile phones. The data are combined with dosimetric modelling and population surveys to estimate potential risks for the population. In addition, measurements are carried out in professional situations where 5G may be relevant.

GOLIAT also conducts a series of cohort studies in children and adolescents. Primarily, effects on cognition and sleep are investigated. Other health-related effects include behaviour, nonspecific symptoms, and mental health. In human studies, the effects of exposure at 3 GHz, 5 GHz and 26 GHz on EEG, cognition and thermoregulation are evaluated. In young mice and rats, in vivo exposure to 5G mobile radio fields is studied for behaviour, cognition, and thermoregulation. In vitro, the effects of 5G fields (0.7 GHz to 26 GHz) on neocortical neurons and brain cells are investigated. In addition, thermoregulation in human thermoreceptors and radical stress in different skin cells are investigated in vitro. By means of molecular modelling, the understanding of the biophysical interaction mechanisms is to be improved. The synthesis includes a health risk assessment. In addition to the biological-medical evidence assessment, this also includes the characterization of the risk perception of the public using mental models and case studies for efficient RF-EMF exposure reduction in everyday life. In order for the findings to be communicated efficiently, there is continuous exchange with the members of the public.

Next Generation Integrated Sensor and Analysis System to Monitor and Evaluate Exposure to RF-EMF and Health (NextGEM)

NextGEM is designed to provide a framework for obtaining health-relevant scientific knowledge and data based on new scenarios for exposure to RF-EMF in multiple frequency bands and to develop and validate tools for evidence-based risk assessment. NextGEM will also establish a NextGEM Innovation and Knowledge Hub (NIKH) for EMF and health, providing a standardized way for European regulators and the scientific community to store and evaluate project results. Most of NextGEM's activities take into account 5G FR1 and FR2.

The objectives of the project are:

- Measurement and modelling of single and multiple RF-EMF sources as EMF exposure patterns change based on innovative monitoring technologies (5G FR1, FR2)
- Assessment of the health effects and elucidation of the effects of different and combined RF-EMF exposure patterns through in vitro, in vivo and human studies (5G FR1, FR2)
- Identification of causal relationships and conduct of risk assessments with regard to EMF exposure and selected health consequences with the provision of FAIR data (Findable, Accessible, Interoperable, Reusable), (5G FR1, FR2)
- Development of the NextGEM Innovation Knowledge Hub (NIKH) and its validation in practice
- Maximizing the importance of NextGEM through comprehensive dissemination, communication, standardization, utilisation, capacity building, and clustering activities.

Scientific-Based Exposure and Risk Assessment of Radiofrequency and mm-Wave Systems from children to elderly (5G and Beyond) (SEAWave).

This project is co-financed by Horizon Europe and SERI (Switzerland). The aim is to contribute to the scientific basis for assessing the health risks of 5G and to provide the means to effectively communicate the health risks and disseminate the results to all stakeholders, from citizens, and national regulatory authorities to standardisation bodies and industry.

The objectives are:

- Identifying differences in exposure patterns between the 2G to 4G mobile standards and the 5G mobile standard for the entire public, including children and workers;
- providing tools and instruments for reliable exposure assessment;
- contributing to the scientific basis for assessing the health risks of 5G;
- providing measures for effective communication on health risks and dissemination of the results to the stakeholders.

Tab. A-4.1: Current projects in the Horizon Europe Research Cluster CLUE-H (Status: June 2025, author: Mats-Olof Mattsson)

project	**acronym**	**coordinator**	**runtime**	**site**
Exploring the impact of RF-EMF exposure on planetary health	ETAIN	Utrecht University, The Netherlands	5 years	https://www.etainproject.eu/
5G exposure, causal effects and risk perception through citizens engagement	GOLIAT	Barcelona Institute for Global Health (ISGlobal), Spain	5 years	https://projectgoliat.eu/
Next Generation Integrated Sensing and Analytical System for Monitoring and Assessing Radiofrequency Electromagnetic Field Exposure and Health	NextGEM	Foundation for Research and Technology – HELLAS (FORTH), Greece	4 years	https://www.nextgem.eu/
Scientific-Based Exposure and Risk Assessment of Radiofrequency and mm-Wave Systems from children to elderly (5G and Beyond)	SEAWave	Aristotle University of Thessaloniki, Greece	3.5 years	https://seawave-project.eu/