Power lines and health: neurodegenerative diseases

To: the State Secretary of Infrastructure and Water Management,
the Minister of Economic Affairs and Climate Policy and
the Minister of Social Affairs and Employment

No. 2022/13e, The Hague, 29 June 2022

Health Council of the Netherlands

contents

summary

In the Netherlands, a precautionary policy is in place with regard to overhead power lines. The purpose of this policy is to avoid, as much as possible, creating new situations in which children are subjected to long-term exposure to magnetic fields with an annual average field strength above 0.4 microtesla that are generated by overhead power lines.
This precautionary policy is partly based on an earlier advisory report issued by the Health Council of the Netherlands. In 2000, the Council concluded that there are indications that children who live near such power lines are at a greater risk of developing leukaemia than other children. The cause is unclear, although the magnetic fields generated by the power lines may play a role.

Three advisory reports

The State Secretary for Infrastructure and the Environment (now Infrastructure and Water Management) asked the Health Council of the Netherlands to update the advisory report issued in 2000 and to focus not only on childhood leukaemia, but also on Alzheimer's disease and cancer in adults. The report on childhood leukaemia was published in 2018. In that report, the Health Council suggested considering an expansion of the precautionary policy to other sources of long-term exposure to magnetic fields generated by the electrical grid, such as underground power cables, transformer stations and transformer substations.
This current report relates to neurodegenerative diseases in adults, namely amyotrophic lateral sclerosis (ALS), Alzheimer's disease, Parkinson's disease and multiple sclerosis (MS). Cancer in adults is addressed in a separate report.

Working method

The Electromagnetic Fields Committee of the Health Council has analysed the scientific data on a possible relationship between exposure to magnetic fields generated by power lines and other sources, such as transformers, and the occurrence of neurodegenerative diseases.
IIt has mainly focused on epidemiological studies, taking into account studies on exposure in both residential areas and the workplace.
In some occupational groups, the average level of exposure to magnetic fields is substantially higher than in residential areas. If magnetic fields can affect health, this will be more evident among such occupational groups. However, it should be noted that workers are a more homogeneous group than the general population, as the latter includes potentially more vulnerable groups such as children, the elderly and chronically ill people.

In most epidemiological studies, the level of exposure to magnetic fields is approximated. In residential studies, the assessment of the magnetic field strength in the home is usually based on calculations or measurements. Sometimes, the distance between the home and an overhead power line is used as a proxy for the level of exposure. In occupational studies, the level of exposure is usually reconstructed based on the employees' job history.

Epidemiological studies can show that, at certain levels of exposure, a certain illness occurs more frequently than would otherwise be expected. Such an association does not necessarily mean that exposure causes the illness, although it can be an indication for possible causation. For more clarity on this matter, additional data from experimental research (including animal studies) and investigations into working mechanisms are required. To the extent that it was available, information from this kind of research has also been incorporated in this advisory report.

Conclusions

With regard to Parkinson's disease, the Committee considers a causal link between exposure to magnetic fields and the development of the disease to be unlikely. Residential studies did not show an association between the proximity of power lines and the risk of developing Parkinson's disease. The scale and the quality of the research may well be limited, but more extensive studies into substantially higher levels of exposures to magnetic fields in the workplace also found no associations.

For the other diseases, the picture is less clear. With regard to ALS and Alzheimer's disease, limited research into residential exposure did not shows associations between the proximity of power lines and the risk of developing the diseases. However, for occupational groups with substantially higher levels of exposure to magnetic fields than in residential areas, the research did reveal associations between exposure and the risk of developing both illnesses, although these are less clear for Alzheimer's disease than for ALS. For this reason, the Committee considers the results for the residential areas to be inadequate to infer a causal relationship between the proximity of power lines and the risk of developing either disease. The Committee considers the associations identified by the occupational studies to be suggestive of a causal relationship. The few data available from experimental studies do not provide further support for a causal link.

For MS, no association was found in either the residential or occupational studies. However, in both environments, the number of studies was too limited to make definitive statements about whether or not there is a causal link between exposure to magnetic fields and development of the disease.

Recommendations

Based on the current state of knowledge, the Committee does not consider it possible to

provide an unambiguous answer to the question of whether exposure to magnetic fields can cause neurodegenerative illnesses. At least, the residential studies did not give any indication that ALS, Alzheimer's disease, Parkinson's disease or MS are more prevalent in people who live closer to overhead power lines.
Therefore, the Committee does not believe that precautionary measures to limit exposure are currently necessary. Moreover, the current policy concerning overhead power lines is already based on precaution due to indications of a possible causal relationship between proximity to power lines and the risk of childhood leukaemia. Previously, the Committee recommended considering an expansion of this policy to underground power cables and other sources of long-term exposure to ma
gnetic fields generated by the electrical grid, such as transformer stations and transformer substations.

Within the occupational groups under investigation – which are subjected to significantly higher levels of exposure than found in the residential environment – the Committee has found indications suggesting an increased risk of ALS and Alzheimer's disease. As a precaution, it therefore recommends restricting occupational exposure to magnetic fields to as low a level as reasonably possible.

The Committee does not expect that more epidemiological research will provide greater certainty in the short term regarding the effect of exposure to magnetic fields on the risk of neurodegenerative diseases. The Committee believes more research into possible underlying biological mechanisms to be more effective.
Due to the energy transition, there has been a substantial increase in the use of wind turbines and solar panels as a primary source of energy. The use of electric cars and heat pumps is also on the rise. As a result of these changes in production and consumption, more electricity will need to be transported. Consequently, levels of exposure to magnetic fields in the vicinity of components of the electrical grid and in some workplaces may increase. For this reason, the Committee recommends monitoring of the level of exposure to magnetic fields in residential areas and in the workplace.

01 introduction

The State Secretary for Infrastructure and the Environment (now Infrastructure and Water Management) asked the Health Council to update its 2000 advisory report on the health effects of living near overhead power lines.[1] In that report, the Council noted that there is a reasonably consistent association between living in the vicinity of overhead power lines and an increased incidence of leukaemia in children. This would mean that one case of childhood leukaemia every two years may be linked to the presence of overhead power lines. The State Secretary asked the Health Council the following questions:

1. Is there a link between living within a certain distance from overhead power lines and the occurrence of health risks such as childhood leukaemia, other types of cancer in children and adults, and Alzheimer's disease, and does the voltage on the lines play a role?
2. Is there a link between exposure to extremely low frequency magnetic fields and the occurrence of health risks?
3. If there is an increased risk associated with spending long periods in the vicinity of overhead power lines, are there indications of factors other than the magnetic field that are associated with the presence of overhead power lines that could explain this risk?

The standing Committee on Electromagnetic Fields has divided its response to the request for advice into three parts:

- an advisory report on leukaemia and other types of cancer in children, published on 18 April 2018;[2]
- an advisory report on neurodegenerative diseases, this report, submitted to the Minister of Infrastructure and Water Management (IenW), the Minister of Economic Affairs and Climate Policy (EKZ) and the Minister of Social Affairs and Employment (SZW) on 29 June 2022;
- an advisory report on cancer in adults, submitted to the same ministers at the same time as this report.

A list of the Committee's members can be found at the end of this advisory report. The request for advice and the accompanying letter can be found at www.gezondheidsraad.nl.

1.1 Background

In 1979, US researchers discovered that the incidence of childhood leukaemia was higher in the vicinity of overhead power lines (the distribution lines that often run in between houses in the United States) than further away.[3] Power lines generate extremely low frequency (ELF) electric and magnetic fields (see Chapter 2; for the sake of brevity, the term 'magnetic fields' is used in the rest of this report to refer to ELF magnetic fields). The question arose as to whether exposure to these fields could potentially cause childhood leukaemia. This led to further research focusing not only on childhood leukaemia, but also on other types of cancer in children and adults and on other diseases, including neurodegenerative conditions such as amyotrophic lateral sclerosis (ALS) and Alzheimer's disease.

The occurrence of ALS was already linked to electric shocks early in the previous century. In recent decades, research has mainly focused on a possible association with exposure to magnetic fields, however a number of recent studies have also looked at exposure to electric shocks.
In addition to studies in the residential environment, studies have mainly been carried out on exposure to magnetic fields at work, where exposure levels can be much higher than in the residential environment.

Some studies found associations between exposure to the magnetic fields generated by power lines or electrical equipment and a higher incidence of certain diseases. For more information on what this means, see the box below.

Association or causal relationship

When talking about relationships between exposure to a specific factor, such as magnetic fields, and the risk of a specific disease, a distinction is made between an *association* and a *causal relationship*. An association between exposure and the risk of disease means that these two things occur together more often than might be expected by chance. A causal relationship means that the disease is a direct result of the exposure. An association between exposure and disease, resulting from a statistical analysis, is not in itself conclusive evidence of the cause. The cause cannot be determined based on statistics alone. Additional information is needed, for example from experimental research or based on a plausible biological mechanism of action.

Methodology

In this section, the Committee sets out its approach to the literature analysis for this advisory report. A detailed description of the Committee's methodology can be found in the background document to this report.
The background document contains an overview of the studies used, the detailed results of the meta-analyses, the results of subanalyses and explanatory notes on the classifications of evidential value for a causal relationship between exposure and disease.

Four neurodegenerative diseases

Neurodegenerative diseases is a collective term for various diseases that attack the nerve cells (neurons) in the brain or elsewhere in the body. For the purpose of this advisory report, the Committee has looked at four of these diseases, namely ALS, Alzheimer's disease, Parkinson's disease and multiple sclerosis (MS).

Residential and occupational exposure

With regard to residential exposure to magnetic fields, the primary focus of the request for advice, the Committee looked at whether the risk of the listed diseases is related to the distance from home to high-voltage power lines (as a measure of exposure) or to the measured or calculated residential exposure to magnetic fields.

The Committee considered not only residential exposure, but also occupational exposure. In some occupations, exposure to magnetic fields can be considerably higher than in the residential environment. If the magnetic field can cause health problems, this is more likely to be evident in people who are exposed to relatively high magnetic field strengths in their profession, such as electric welders or people who work at a power plant. A substantially larger amount of research has therefore been carried out into possible effects of occupational exposure. The Committee notes, however, that the general population varies more widely in composition than the working population, and includes groups that are potentially more vulnerable, such as children, the elderly and people with chronic diseases.

For occupational exposure, the Committee compared the risk of the diseases considered in workers who had spent a long time (one or more years) working in a profession where exposure is higher than the background level to the risk in workers exposed at the background level. In the analysis, the Committee makes a distinction between epidemiological studies of occupational exposure in the general population and research in specific industrial populations, such as electricity company employees. Generally speaking, exposure can be better characterised in the latter populations.

Both residential and occupational studies use different measures of exposure: average exposure over a specific period, expressed in microtesla (μT), or cumulative exposure, expressed in μT-years. Both are typically divided into different categories. For these studies, the Committee has calculated an average risk estimate for all exposure categories and regarded this as a measure for ‘ever exposed above the background level’. The meta-analyses were then carried out using these average risk estimates.

Epidemiological and experimental research

The Committee has primarily focused on epidemiological research. These studies have been systematically selected and analysed according to a pre-established protocol. The analysis included papers up to April/May 2021. The Committee also looked for relevant data from experimental research, including in animals, to support indications of a possible causal relationship. It searched for this data up to June 2021.

Meta-analyses

Where three or more suitable epidemiological studies are available on a specific question, the Committee has carried out meta-analyses.
A meta-analysis involves combining the results of various studies to produce a single risk estimate. Alongside each risk estimate, the Committee also gives the 95% confidence interval, which is a measure of the uncertainty of the estimate (see box). The Committee also states whether there was a high level of heterogeneity in the risk estimates for the studies included in the meta-analysis. The meta-analyses provide two

measures of heterogeneity: I^2 and tau^2. The Committee has only used I^2. A high level of heterogeneity (defined in this report as $I^2 > 60\%$) means that the results of the individual studies are ambiguous. This means that less value can be assigned to the risk estimate from the meta-analysis.

For the meta-analyses of studies on occupational exposure, in addition to the main analysis of exposure above the background level versus exposure at the background level, the Committee has also carried out a number of subanalyses to obtain a better understanding of how completeness of the occupational history and reliability of the disease diagnosis affect the risk estimates and heterogeneity. Where possible, the Committee has also carried out subanalyses of the data on highest level of exposure and longest duration of exposure. The results of both the main analyses and the subanalyses can be found in the background document. The Committee discusses the conclusions in this advisory report.

Where possible, the Committee bases its conclusions on the subanalysis of the studies that took into account the complete occupational history of the workers, in other words studies where the exposure has been determined for all occupations an individual has had, making it possible to calculate an average or cumulative exposure over their entire working life. The Committee feels that this data provides the most reliable reflection of occupational exposure. If not enough data is available for this subanalysis, the Committee bases its conclusions on the main analysis, in other words on all studies regardless of completeness of the occupational history. The data used in the advisory report is marked in the background document. Not enough data is available on residential exposure to carry out comparative subanalyses.

The Committee also considered the possibility of selective publication, in other words that studies that did not find a link are less likely to be published. This publication bias could distort the results of the meta-analyses. Results of cohort studies in the general population and in industrial populations are usually published regardless of outcome, due to their scale and the amount of funding involved. The Committee therefore expects a negligible level of bias in its findings due to selective publication.

Risk estimate and confidence interval

The risk estimate shows the estimated risk of a specific effect in a specific situation relative to the control situation, in other words the relative risk. For example, a risk estimate of 1.3 means that the estimated risk of a disease occurring is 1.3 times as great, or 30% higher, in people who have been exposed than the risk in people with no or less exposure. A risk estimate of 0.9 means that the risk is 0.9 times as great, or 10% lower. A risk estimate of 1 means that the risk of the disease is similar in both situations.

Most studies report relative risks, rate ratios (RR) or odds ratios (OR) as a risk estimate. Some studies also use other measures of risk: the SMR (standardised mortality ratio), SIR (standardised incidence ratio) and SRR (standardised rate ratio). A ratio of 1 or 100% means that there is no difference in risk between the exposed group and the population as a whole.

The 95% confidence interval shows the uncertainty of the risk estimate and the limits within which we expect the actual effect to lie. It means that if we were to repeat the study 100 times in the same population with different random samples, the actual effect would lie within the confidence interval in 95 cases. If the 95% confidence interval contains the value 1, we refer to the relationship found as not statistically significantly increased or decreased. If the lower limit of the 95% confidence interval is greater than 1, we refer to a statistically significantly increased risk. If the upper limit of the 95% confidence interval is less than 1, we refer to a statistically significantly decreased risk.

Strength of evidence for a causal relationship

Finally, the Committee checks whether, based on the available epidemiological research data, its meta-analyses of this data and data from experimental studies, it can draw a conclusion as to a possible causal relationship between exposure and the disease investigated. To this end, it uses the US Environmental Protection Agency (EPA) methodology, which it has used in previous advisory reports[2,4] and which distinguishes between the following classifications based on the quality, nature and scale of the research data (see table 1).[5]

Table 1 EPA classification of the strength of evidence for a causal relationship between exposure and disease

Classification
Causal relationship proven
Causal relationship likely
Indications of a causal relationship
No statements can be made regarding a causal relationship
Causal relationship unlikely

A more detailed description of the criteria for these classifications of the strength of evidence for a causal relationship can be found in the background document.

The Committee applies this methodology as follows. It regards a statistically significant association in a meta-analysis of epidemiological

studies as an indication of a causal relationship. If the association is not statistically significant, but the risk estimate is relatively high (1.25 or higher), the Committee also regards this as an indication of a causal relationship. This is because if few studies are available, the statistical power of the meta-analysis is low. The Committee only assigns higher classifications (causal relationship likely or proven) where there is additional evidence from experimental or mechanistic research. If little or too little high-quality research has been carried out or various studies contradict each other, the Committee feels that no statements can be made regarding a causal relationship. Where sufficient epidemiological research of high quality has been carried out and there is absolutely no indication of a causal relationship, the Committee opts for the classification ‘causal relationship unlikely’. Where the Committee reaches the conclusion that a causal relationship is unlikely in the case of occupational exposure, then it deems the same conclusion to apply in principle to residential exposure, as this type of exposure is lower. Where the Committee believes that there are indications of a causal relationship in the case of occupational exposure, it will in principle not reach the conclusion of ‘causal relationship unlikely’ for residential exposure.

1.2 Reading guide

The advisory report starts with an explanation in Chapter 2 of a number of technical terms and exposure characteristics. In Chapters 3 to 6, the Committee discusses the results of the meta-analyses of the studies on the relationship to residential and occupational exposure to magnetic fields for ALS, Alzheimer’s disease, Parkinson’s disease and MS in that order. For each condition, the data from the relevant scientific research is subdivided into:

- epidemiological studies on residential exposure;
- epidemiological studies on occupational exposure to magnetic fields;
- experimental studies in laboratory animals and cultured cells.

The Committee sets out its recommendations in Chapter 7.

02
power lines and magnetic fields

This chapter gives a brief explanation of magnetic fields, plus a description of a number of technical terms and exposure characteristics.

2.1 Voltage, current and fields

The voltage on a power line causes an electric field. When current is passing through the line, a magnetic field is also generated. Electric fields and magnetic fields spread in different ways. Figure 1 demonstrates this in a simple diagram.

The current on the power grid switches from positive to negative and back again 50 times per second (alternating current), or at a frequency of 50 hertz (Hz). This is an extremely low frequency (ELF). By way of comparison, mobile phones operate at much higher frequencies of around 900 and 2000 megahertz (one megahertz is a million hertz).

Electric fields and magnetic fields propagate in different ways

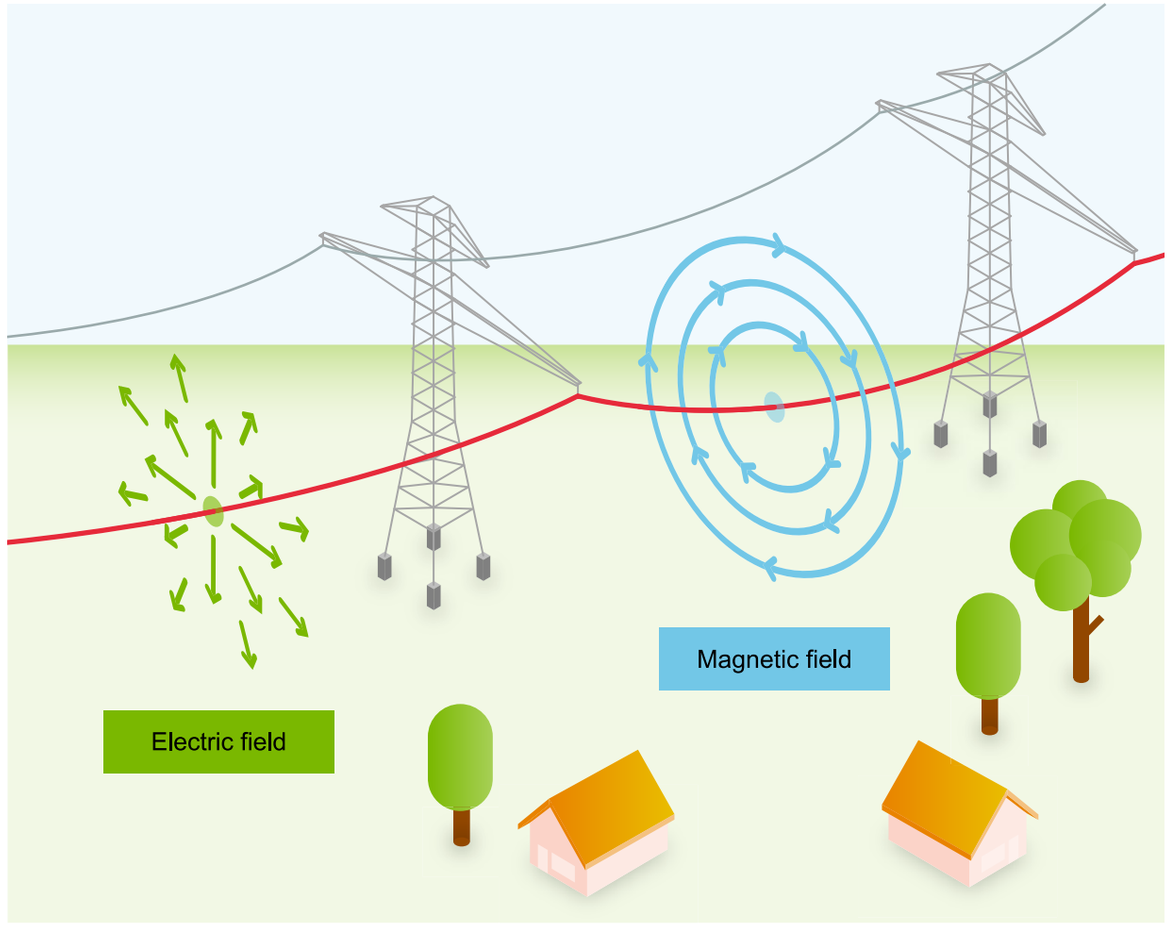

Figure 1 Diagram showing the electric and magnetic field around a high-voltage power line

The power grid

The power grid between power stations and homes is made up of transport and distribution lines and cables. Lines are overhead connections, while cables lie underground.

Transport connections in the Netherlands are high-voltage power lines or cables with a voltage of 380 or 220 kilovolts (kV: 1 kV is 1000 V). They transport the current from the station to a substation. They are the motorways of power transmission. High-voltage power lines and cables also run between substations and transformer stations, but with a lower voltage of 150, 110 or 50 kV. Transport from the transformer stations to the transformer boxes in residential and business premises takes place by means of distribution cables with a medium voltage of 25, 20, 12.5, 10, 6, 5 or 3 kV. In the transformer boxes, the voltage is reduced further to 400 and 230 V and carried to the final destination through low-voltage distribution cables.

In the Netherlands, overhead power lines are almost exclusively high-voltage power lines. In other countries, distribution lines sometimes also run above ground.

2.2 Field strength

At extremely low frequencies, a distinction is made between electric and magnetic fields, which have different properties. The electric field is considerably weakened by trees, plants and buildings (see figure 2). Its ability to penetrate materials is negligible, resulting in a surface charge that is discharged to the ground. Inside a home, the electric field generated by a nearby power line is easily 10 to 100 times weaker than outside the home. By contrast, the magnetic field is only weakened by obstacles to a very small extent. It easily penetrates homes and the human body (see figure 2). Studies on the relationship between overhead power lines and possible health effects therefore focus on exposure to magnetic fields rather than exposure to electric fields.

A magnetic field is invasive, an electric field is not

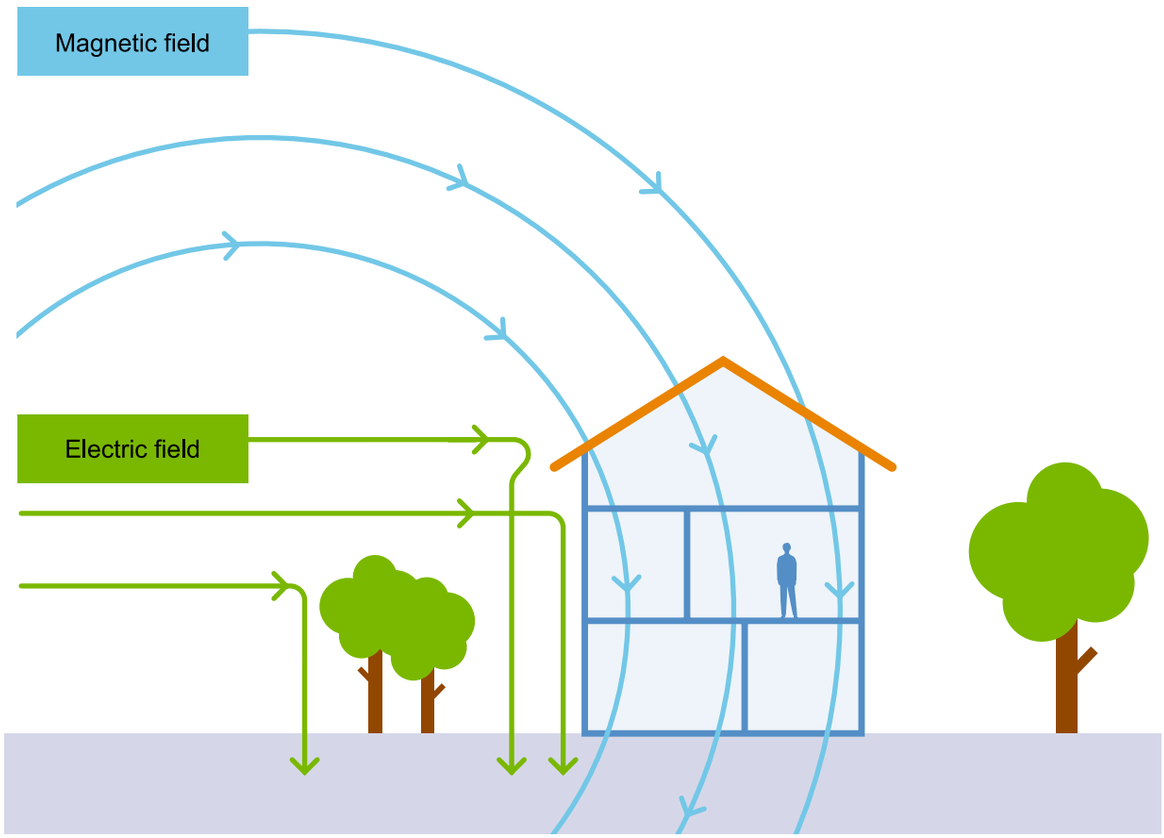

Figure 2 Diagram showing the extent to which electric and magnetic fields penetrate materials

The strength of a magnetic field is expressed in tesla (T). In practice, the strength of magnetic fields generated by the power system is always expressed in microtesla (μT = 1 millionth T). The more current passes through a line, the stronger the magnetic field. The strength of the magnetic field falls rapidly as the distance to the line increases (see figure 3). Broadly speaking, field strength is four times lower when the distance is doubled. The distance to an overhead high-voltage power line also depends on the extent to which the line droops between two masts (the 'sag'). The hotter conductors (the actual lines) become, the more they sag. The heat depends on a number of factors, such as the strength of the current through the conductor and the ambient temperature. In practice, the situation is more complex as there are several conductors and a number of electric circuits in a high-voltage power line, which can cause partial local 'cancellation' or weakening of magnetic fields. Where new connections are installed, efforts are made to ensure that the magnetic fields of the different conductors cancel each other out as much as possible to minimise the total strength of the magnetic field generated at ground level by a high-voltage power line.

The larger the distance to the electricity lines, the weaker the magnetic field

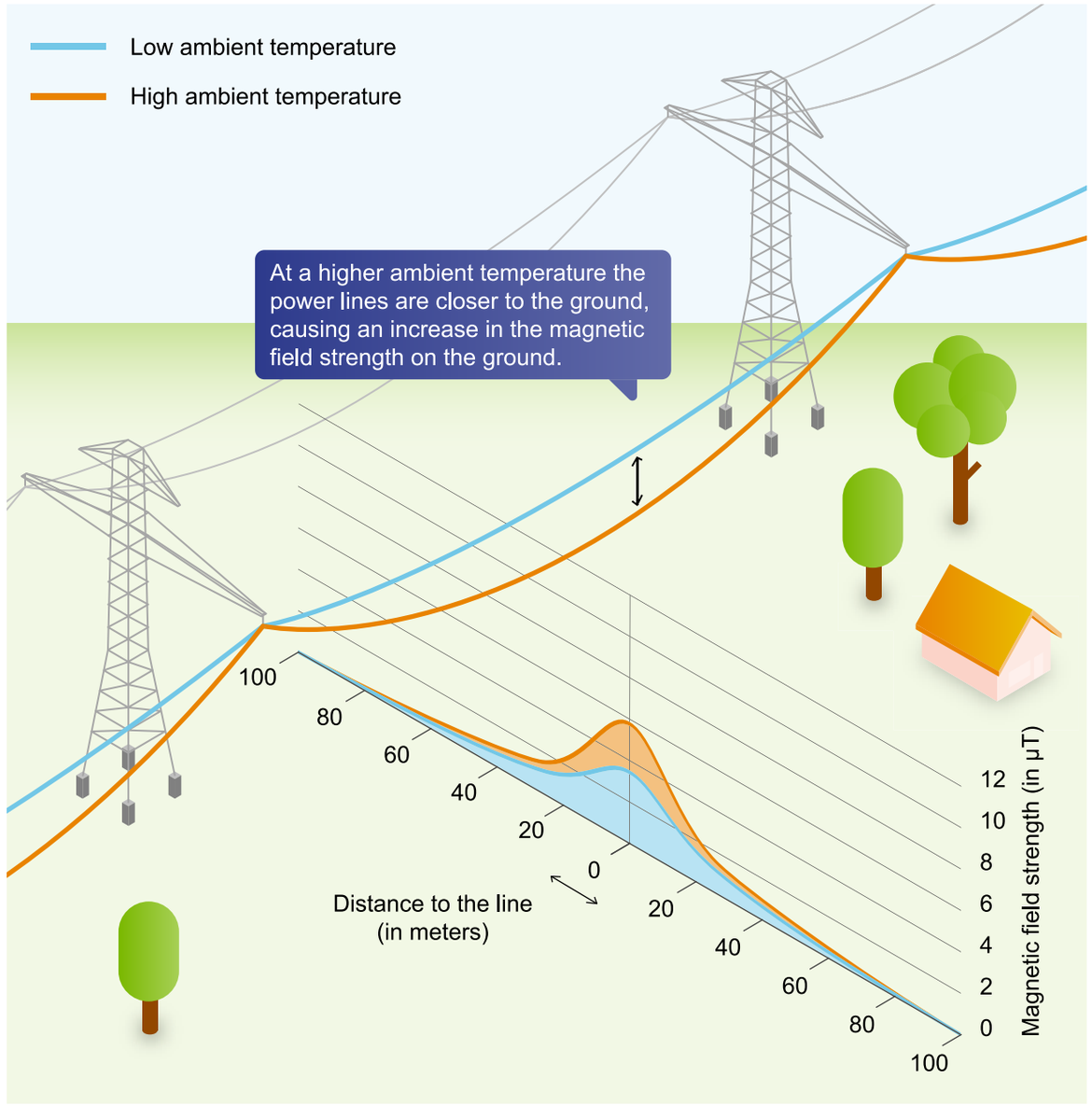

Figure 3 Relationship between distance to the line and magnetic field strength on the ground

On average, field strengths in the residential environment do not exceed 0.1-0.2 μT in a 24-hour period.[6-10] This exposure comes from the power system in the home and from the use of electrical equipment.
The presence of a high-voltage power line can increase average exposure to over 1 μT (see figure 3). This also applies to residing in the vicinity of other power grid components, such as underground high-voltage cables, high-voltage stations and indoor or outdoor transformers. Short-lasting peak exposures during the use of household appliances can rise to several dozen μT if the distance between the device and the user is only a few centimetres.[10] In the case of electric bed warmers, such as electric blankets and heating elements in waterbeds, which are often used close to the body for long periods of time, exposure can rise to more than 2 μT for electric blankets and up to 0.04 μT for waterbeds.[10]

Occupational exposure can be considerably higher than residential exposure, for instance in the case of electricians (peak exposure of up to more than 50 μT) and people employed in the electricity industry (peak exposure of up to 500 μT), welders (up to 5 μT) and train drivers (peak exposure of up to more than 50 μT).[11-13] Such peak exposures can occur more frequently than peak exposures in the home, depending on the nature of the work. For the previously mentioned occupations, the average exposure over a working day in the workplace can rise to 26 μT.[13,14]

2.3 Determining exposure

The exposure of individual people to magnetic fields can only be determined accurately by means of long-term measurements on the body. Such measurements are rarely carried out in epidemiological studies, and where they are carried out, it is mainly in industrial populations.
Most studies use methods that yield a rough estimate of actual exposure.

Determining residential exposure

A rough estimate of residential exposure can be made based on the distance of the home to a high-voltage power line (usually measured as the distance to the centre of the line at ground level). The voltage on the line may or may not be taken into account. Exposure can also be estimated by measuring or calculating the magnetic field strength in or next to the home over a shorter or longer period. In order to calculate cumulative exposure, or average exposure over a longer period, information on residential history is also needed: at what addresses have the people in question resided?

The advantage of distance as a measure of exposure is that it is easy to determine to a reasonable level of accuracy. The disadvantage is that it is a very rough measure of actual exposure to the magnetic fields generated by power lines, because actual exposure also depends on other factors such as height of the line above the ground (see figure 3), configuration of the lines and, most importantly, the amount of current being transported

through the line. Current can fluctuate significantly over time. However, this information is generally not available.

The measured or modelled exposure to the magnetic field is a more relevant measure of exposure than distance, but its calculation also has limitations. Measurements are not necessarily more accurate than modelled exposure. For residential measurements, researchers are dependent on the cooperation of residents. Refusal to cooperate can lead to selective participation and therefore potential bias of the results. This problem does not exist in the case of modelled exposure. In addition, measurements of magnetic field strength in the home are carried out over a maximum period of a few days, whereas modelled exposure is determined over a longer period that in some cases covers many years. For a longer period, this means that measurements can give a less accurate picture of the exposure than modelled exposure. On the other hand, modelled exposure as a result of the presence of a high-voltage power line does not generally take into account exposure from other sources near to or inside the home, such as indoor transformers in apartment buildings, the electricity system in the house and the use of electrical appliances. The latter usually only results in short-lasting peak exposures on top of the more long-term exposure from the electricity system in the home and nearby high-voltage power lines. One exception to this rule is bed warmers (electric blankets and heating elements for waterbeds), which usually do result in long-term exposure.

Another factor that plays a role in studies of residential exposure is the fact that people often spend a not inconsiderable part of the day outside of the home, for example at work or school. The exposure to magnetic fields at these other locations can be lower or higher than at home.

Determining occupational exposure

Occupational exposure is determined in a variety of ways.[15] Some estimates that use extensive measurements of exposure in specific occupations are reasonably accurate. Others are less accurate, such as those simply based on the fact that exposure is higher for a specific job. In some cases, a job-exposure matrix (JEM) is also used. The matrix links an occupation to an intensity of exposure, which can be measured or estimated by experts such as an occupational hygienist.

Some studies verify an individual's complete occupational history, which can provide an insight into the total or average exposure throughout a person's working life. Other studies only take into account a person's main occupation or most recent occupation when determining exposure. Examples include studies that retrieve information about a person's occupation from registers of deaths, or that are based on information from one or more population censuses. This gives a less accurate picture of total exposure.

Studies of occupational exposure assume a 40-hour working week. In certain jobs, occupational exposure is so high that exposure from other sources in the environment is more or less insignificant.[16] The exposure pattern in the residential and occupational environment can substantially differ.

03 amyotrophic lateral sclerosis (ALS)

Research in the residential environment does not show an association between the proximity of high-voltage power lines and the risk of ALS. An association has been found, however, between occupational exposure to magnetic fields above the background level and the risk of ALS. The Committee sees this as an indication of a causal relationship. The risk of ALS also shows an association with occupational exposure to electric shocks, however this association is less clear than that with exposure to magnetic fields.

This chapter summarises the results of the meta-analyses carried out by the Committee. Details of all studies and the analyses can be found in the background document.

3.1 About ALS and other motor neurone diseases

Motor neurone disease or neuromuscular disorders are diseases of the motor neurones: the nerve cells that control muscle movement. ALS is the most common motor neurone disease, accounting for around 80% of motor neurone diseases.[17] ALS affects both the central and peripheral motor neurones. The disease leads fairly rapidly, usually within a few years, to death due to paralysis of the respiratory muscles or the heart muscle.

ALS is a relatively rare condition. On average, the incidence (the number of new cases per year) in the Netherlands over the period 2006–2017 was around 1 per 100,000 population,[17] while the prevalence (the total number of cases at any time) was around 1400.[18]

ALS can occur in adults at any age, but most ALS patients are aged between 50 and 90.[19] On average, patients survive for a further three years after developing the first symptoms.

3.2 Residential exposure

The Committee found six studies that investigated the relationship between residential exposure to magnetic fields and the occurrence of ALS. Five of these studies used the distance between home and overhead power lines as a measure of exposure.[20-24] Four of these five studies applied the same distance categories and these four studies were used to carry out a meta-analysis.[21-24]

Two of these four studies also calculated exposure to magnetic fields.[20,23] As the protocol required at least three studies to be available, no meta-analysis was carried out using this data. In one of these studies it was not possible to calculate a risk estimate as only one patient lived close to a high-voltage power line.[20] In the other study, a non-significantly increased risk was only found for the exposure category 0.2–0.4 μT, but not for the lower and higher categories.[23]

Three distance categories are used in the studies from the meta-analysis. The Committee used data on the shortest distance (0 to 50 metres between home and high-voltage power line) to calculate a risk estimate compared to the reference distance (more than 400 or more than 600 metres). This showed that people living at a distance of less than 50 metres from a high-voltage power line do not have an increased risk of ALS. The risk estimate is calculated as 0.99 (0.65-1.52).

For these meta-analyses, it should be noted that the number of people who live within a range of 50 metres from a high-voltage power line is small and that ALS is a rare disease. As a result, the number of ALS patients in this distance category was very low in the studies analysed (between 1 and 12 per study), leading to greater uncertainty in the risk estimates.

There is not enough data to also perform an analysis according to line voltage (a question raised in the request for advice). Only one study makes a distinction according to line voltage (50-150 kV or 220-380 kV).[22] The risk estimates are the same for both line voltages.

3.3 Occupational exposure

3.3.1 Magnetic fields

The Committee found 34 studies that investigated the relationship between occupational exposure to magnetic fields and the occurrence of ALS. Of these, 14 studies were not included in the analyses for various reasons (see the background document). The Committee used the data from the 20 remaining studies of occupational exposure to carry out meta-analyses.[25-44]

Both studies of occupational exposure in the general population and those on exposure in industrial populations indicate an increased risk of ALS. From studies of occupational exposure in the general population in which the complete occupational history was determined, the Committee calculated a risk estimate of 1.56 (0.83-2.93). This association is also demonstrated by the studies in industrial populations with a risk estimate of 1.55 (1.17-2.06). Although the risk estimates are lower if all studies, including those with an incomplete occupational history, are taken into account, the confidence intervals fully overlap (see the background document). Heterogeneity of the results within the five studies of exposure in the general population is high.

3.3.2 Electric shocks

A number of studies also investigate occupational exposure to electric shocks. These studies are based on reports of serious electrical accidents.

The Committee identified nine studies in the scientific literature that look at the relationship between electric shocks at work and the risk of ALS. In

one of the studies it was not certain whether all of the shocks had occurred at work. The Committee used the data from the remaining eight studies to carry out a meta-analysis.[25,27,34-36,38,39,44] The analysis reveals an association between electric shocks at work and the risk of ALS.
For occupational exposure to electric shocks in the general population and studies with a complete occupational history, the Committee has calculated a risk estimate of 1.23 (1.07-1.42). However, the characterisation of exposure, in this case undergoing electric shocks, is less reliable than that of exposure to magnetic fields. No studies have been carried out in industrial populations.

3.4 Experimental research

The Committee found three experimental studies that investigated the relationship between exposure to magnetic fields and ALS. Two are animal studies of a rare familial form of ALS.[45,46] There is also one study involving cultured cells.[47] None of these studies showed statistically significant effects at exposures up to 1 mT (around 1000 times higher than residential exposures).

3.5 Conclusions

The epidemiological studies analysed show no association between residential exposure to magnetic fields and the risk of ALS. It should be noted that the studies included few ALS patients with high exposure levels, as the disease is rare and few people live within 50 metres of a high-voltage power line. The low numbers mean that the risk estimate is uncertain.

Due to the low number of high-quality studies carried out in the residential environment, the Committee considers the EPA classification ‘no statements can be made regarding a causal relationship’ to apply.

Epidemiological studies of occupational exposure to magnetic fields do show an association with the risk of ALS. The risk estimates are an estimated 1.6 times higher compared to exposure at the background level.

It is not possible to determine an exposure-effect relationship on the basis of the studies. As a result, it is impossible to establish whether there is a level of exposure above the background level at which the risk of ALS is not increased.

Experiencing electric shocks at work is also a potentially harmful factor, as this exposure is also associated with the risk of ALS, albeit less clearly. The risk estimate is an estimated 1.2 times higher compared to not experiencing electric shocks.

From the epidemiological studies alone it cannot be deduced with certainty whether the associations found between occupational exposure to magnetic fields or electric shocks and the risk of ALS are based on a

causal relationship. The limited additional information available from animal studies and mechanistic research does not substantiate such a relationship. Based on the association observed, the Committee considers the EPA classification ‘indications of a causal relationship’ to apply to occupational exposure to magnetic fields.

04
alzheimer’s disease

Research in the residential environment does not show an association between the proximity of high-voltage power lines and the risk of Alzheimer's disease. An association has been found, however, between occupational exposure to magnetic fields above the background level and the risk of Alzheimer's disease. This association may indicate a causal relationship. The association found is less clear than in the case of ALS. This chapter summarises the results of the meta-analyses carried out by the Committee. Details of all studies and the analyses can be found in the background document.

4.1 About Alzheimer's disease

Dementia is a collective term for diseases in which the brain is no longer able to process information properly. Dementia is characterised by a combination of symptoms, such as memory loss and other cognitive abnormalities and changing behaviour. Alzheimer's disease is a form of dementia in which nerve cells in the brain no longer function and die off in response to processes including the accumulation of the protein amyloid β and changes in the tau protein.[48]

Dementia mainly occurs in old age: the number of cases per age category rises rapidly from around 70 years. In 2021, an estimated 290,000 people in the Netherlands had dementia.[49] It is assumed that approximately 65% of cases involve Alzheimer's disease: around 188,500 people. Based on the number of new cases of dementia in 2019[50], it is possible to calculate that around 5200 men (61 per 100,000) and 8060 women (93 per 100,000) developed Alzheimer's disease that year. Not broken down by gender, this is an incidence of 77 per 100,000 population.

4.2 Residential exposure

The Committee found three studies that investigated the relationship between residential exposure to magnetic fields and the occurrence of Alzheimer's disease.[21,51,52] These studies investigated the association between distance from the residential address to overhead power lines and the occurrence of Alzheimer's disease. The Committee used the data from these studies to carry out a meta-analysis. None of the studies determined the residential exposure to magnetic fields in the study population.

The same distance categories were used in the three available studies. The Committee carried out an analysis for the distance category of less than 50 metres, compared to more than 600 metres. The analysis gives a risk estimate of 1.11 (0.97-1.28).

4.3 Occupational exposure

The Committee found 28 studies that investigated the relationship between occupational exposure to magnetic fields and the occurrence of Alzheimer's disease. Of these, 10 studies were not included in the analyses for various reasons (see the background document).

The Committee used the data from the remaining 18 studies to carry out meta-analyses.[29-31,33,37,40-43,53-61]

The Committee again made a distinction between studies of occupational exposure in the general population and occupational exposure in specific industrial populations, such as employees of electricity companies. In both groups, the Committee's meta-analyses show an increased risk of the occurrence of Alzheimer's disease with occupational exposure to magnetic fields above the background level. For occupational exposure in the general population with complete determination of the occupational history, the risk estimate is 1.15 (1.01-1.30) and for industrial populations it is 1.24 (0.87-1.78). Heterogeneity is high for the studies on exposure of workers in industrial populations. Particularly in the older studies, the quality of diagnosis of Alzheimer's disease is uncertain.

4.4 Experimental research

Five studies in laboratory animals with Alzheimer's disease found that exposure to magnetic fields had health benefits in the form of improved cognitive ability.[45,62-65] Two other studies found no adverse health effects in healthy laboratory animals.[66,67] Exposure levels varied from 100 µT to 10 mT and were therefore considerably higher than residential levels.

Six studies were also found on cellular models for Alzheimer's disease (in other words studies on cultured cells). Two found no effects of exposure to magnetic fields[68,69], three found effects that may indicate the occurrence of disease[70-72] and one study found a potentially health-promoting effect.[73] Exposure levels varied from 50 µT to 3.1 mT: much higher than levels in the residential environment.

4.5 Conclusion

The analysed epidemiological studies of residential exposure to magnetic fields show no association with the risk of Alzheimer's disease. Due to the low number of high-quality studies, the Committee considers the EPA classification 'no statements can be made regarding a causal relationship' to apply to residential exposure.

Research into occupational exposure reveals a different picture. The meta-analyses show that people who are exposed to magnetic fields above the background level as part of their job have an increased risk of Alzheimer's disease. The risk is an estimated 1.2 times higher compared to exposure at the background level.

It is not possible to determine an exposure-effect relationship on the basis of the studies. As a result, it is impossible to establish whether there is a level of exposure at which the risk of Alzheimer's disease is not increased.

The associations found in epidemiological research between occupational exposure to magnetic fields and risk of Alzheimer's disease may indicate

a causal relationship. However, the available information from animal studies and mechanistic research does not substantiate such a relationship. The Committee therefore considers the EPA classification ‘indications of a causal relationship’ to apply to occupational exposure.

05
parkinson’s disease

Research in the residential environment does not show an association between the proximity of high-voltage power lines and the risk of Parkinson’s disease. The research is limited in terms of scale and quality, but because no associations were found in occupational groups who experience work-related exposure to magnetic fields above the background level, the Committee considers a causal relationship between the risk of Parkinson’s disease and residential or occupational exposure to magnetic fields to be unlikely.

This chapter summarises the results of the meta-analyses carried out by the Committee. Details of all studies and the analyses can be found in the background document.

5.1 About Parkinson’s disease

Like Alzheimer’s disease, Parkinson’s disease is caused by the dying off of nerve cells in the brain but for a different reason, namely the accumulation of the protein alpha-synuclein. This is accompanied by motor and cognitive symptoms such as stiffness, shaking, sluggishness, and loss of concentration and memory. There are also other diseases with similar symptoms such as multiple system atrophy and progressive supranuclear palsy, which are summarised together with Parkinson’s disease under the term ‘parkinsonism’.

In 2019, around 52,900 people in the Netherlands had parkinsonism.[74] Another approximately 6090 new cases were diagnosed in that year. The incidence in 2019 was around 4000 men (47 per 100,000) and 2090 women (24 per 100,000). Parkinson’s disease also mainly occurs in old age: the number of cases per age category rises rapidly from around 60 years. There is no data specifically relating to Parkinson’s disease available.

5.2 Residential exposure

The Committee found four studies that investigated the relationship between residential exposure to magnetic fields and the occurrence of Parkinson’s disease.

Three studies used distance to high-voltage power lines as a measure of exposure.[21,51,52] The same distance categories were used in all three studies. The Committee has calculated the risk of the disease for the distance category of 0 to 50 metres compared to the distance category of more than 600 metres. The analysis shows no clear association between distance to high-voltage power lines and risk of Parkinson’s disease. The Committee has calculated a risk estimate of 1.08 (0.93-1.26).

The fourth study investigates cumulative exposure resulting from the use of household appliances, expressed in microtesla-year.[75] The risk estimates did not vary significantly from 1.0.

5.3 Occupational exposure

The Committee found 26 studies that investigated the relationship between occupational exposure to magnetic fields and the occurrence of Parkinson’s disease or parkinsonism. Of these, 14 studies were not included in the analyses for various reasons (see the background document). The Committee used the data from the remaining 12 studies to carry out meta-analyses.[29-31,33,37,40-43,75-77]

The Committee again made a distinction between studies of occupational exposure in the general population and occupational exposure in industrial populations, such as employees of electricity companies.
The Committee’s meta-analyses reveal that neither of the two types of study show an increased risk of the occurrence of Parkinson’s disease in the event of exposure above the background level. For the studies of occupational exposure in the general population, the Committee has calculated a risk estimate of 1.03 (0.95-1.11). This risk estimate applies to all studies regardless of completeness of occupational history, as only two studies that involved a complete occupational history were available.
The risk estimate for the studies in industrial populations is 0.97 (0.75-1.26). The heterogeneity in the risk estimates is high and some studies indicate an increased risk, while others indicate a reduced risk. There is a lack of uniformity in the results of the individual studies in the meta-analyses, which reduces their significance.

5.4 Experimental research

Two publications were found on animal research on the relationship between exposure to magnetic fields and Parkinson’s disease.[78,79] Both investigated the effect of implantation of mesenchymal stem cells exposed in culture to 0.4-1 mT fields in experimental animals in which Parkinson’s-like symptoms had been induced. These symptoms were reduced in both studies.

Five studies were found on cellular models for Parkinson’s disease, in other words studies on cultured cells. In two of these, no effects were found of exposure to magnetic fields[68,80] and in three studies effects were found on oxidative stress, which could potentially cause harm to health.[71,81,82] At 1 or 2 mT, exposure levels were high compared to residential or occupational exposure.

5.5 Conclusion

The analysed epidemiological studies of residential exposure to magnetic fields show no association with the risk of Parkinson’s disease.
The studies of occupational exposure in the general population and in industrial populations also show no association. Additional information from animal studies and mechanistic research gives no indication of a causal relationship.

As the studies of occupational exposure involving exposures above the background level show no association between exposure and Parkinson’s disease, the Committee considers it unlikely that people in the residential environment, where exposure is lower, may develop Parkinson’s disease as a result of living in the vicinity of high-voltage power lines.
The Committee notes, however, that the general population has a broader composition than the working population and includes groups that are potentially more vulnerable, such as children, the elderly and those with chronic diseases. However, no information is available on any differences in vulnerability. For the time being, the Committee therefore considers the EPA classification ‘causal relationship unlikely’ to apply to the relationship between both residential and occupational exposure to magnetic fields and the risk of Parkinson’s disease.

06 multiple sclerosis (MS)

Both studies in the residential environment and studies in occupational groups that are exposed to magnetic fields above the background level show no association between exposure to magnetic fields (or proximity to high-voltage power lines) and the risk of MS. The number of studies is too limited to draw any conclusions regarding a possible causal relationship between exposure and disease.

This chapter summarises the results of the analyses carried out by the Committee. Details of all studies and the analyses can be found in the background document.

6.1 About multiple sclerosis (MS)

MS is a disease of the central nervous system, in which inflammation and scarring occurs in the protective layer around nerves (myelin). This prevents the nerves from functioning properly or at all, accompanied by motor symptoms. The disease mainly occurs in young adults aged between 20 and 40, but also in younger and older people.

In 2018, around 34,700 people in the Netherlands had MS.[83] The number of new cases per year in the age group 20-64 (55% of the population) is around 1470, or around 15 per 100,000 population.[84,85]

6.2 Residential exposure

The Committee found two studies that investigated the association between the residential distance to high-voltage power lines and the occurrence of MS.[21,51] The data shows no increased risk of MS in people who live close to high-voltage power lines.

6.3 Occupational exposure

The Committee found three studies that investigated the association between occupational exposure to magnetic fields and the occurrence of MS.[30,31,37] Two of these are studies of occupational exposure in the general population, while one was carried out in an industrial population. The data shows no increased risk of MS due to occupational exposure above the background level.

6.4 Experimental research

No publications were found on experimental research into the relationship between exposure to magnetic fields and MS.

6.5 Conclusion

The little epidemiological data available on the relationship between risk of MS and residential or occupational exposure to magnetic fields shows no associations. There is no additional information from animal studies and mechanistic research. The Committee considers the available scientific data to be insufficient to conclude that a causal relationship between

exposure and disease is unlikely. It therefore considers the EPA classification ‘no statements can be made regarding a causal relationship’ to apply to the association between both residential and occupational exposure to magnetic fields and the risk of developing MS.

07 recommendations

The Committee concludes that, based on the available research, it is not possible to make any statements about whether residential exposure to magnetic fields can cause ALS, Alzheimer's disease and MS. It considers such a causal relationship to be unlikely in the case of Parkinson's disease.

Few studies are available on residential exposure and most of these studies use proximity to high-voltage power lines as a measure of exposure to the magnetic field, which is less accurate than determining exposure by means of measuring or modelling. In the limited available data, the Committee found no associations between living close to a high-voltage power line and an increased risk of the four neuro-degenerative diseases.

For occupational exposure to magnetic fields above the background level, the Committee has found associations with the risk of ALS and Alzheimer's disease. The Committee considers this to be an indication of a causal relationship. The Committee did not find any such associations for Parkinson's disease and considers a causal relationship to be unlikely. Not enough data is available for MS to make any statements in this regard.

The occupational exposures investigated are considerably higher than residential exposures. On the other hand, residential exposure can occur over a longer period and the exposed population also includes groups that are potentially more vulnerable, such as children, the elderly and those with chronic diseases. Nevertheless, the Committee does not see any reason at present to take measures to limit residential exposure further than is already the case under the current policy. When it comes to occupational exposure to magnetic fields, the Committee recommends precautionary measures in the form of application of the ALARA principle, which aims to keep exposure 'as low as reasonably achievable'.

7.1 Conclusions for each condition

Amyotrophic lateral sclerosis (ALS)

The available evidence provides no indication of an increased risk of ALS as a result of living close to high-voltage power lines or residential exposure to magnetic fields. It is unclear whether this is because residential exposure is lower than levels above which the disease may occur, or because of the imprecise determination of exposure, or because only a limited number of studies were carried out and these studies only include a small number of ALS patients who reside within 50 metres of a high-voltage power line, due to the rare nature of the disease.

Epidemiological research does indicate an increased risk of ALS due to occupational exposure to magnetic fields above the background level or to electric shocks. The risk is estimated to be 1.6 times higher for exposure to magnetic fields and 1.2 times higher for exposure to electric shocks.

Although these associations are indicative for a causal relationship, the limited data available from animal studies and mechanistic research does not further substantiate such a relationship. No exposure-effect relationships can be derived from the epidemiological research.

Alzheimer's disease

There are no indications that living close to high-voltage pow°r lines causes an increased risk of Alzheimer's disease. It is unclear whether this is because environmental exposure is lower than levels above which the disease may occur, or because of the imprecise determination of exposure, the limited number of studies, or uncertainty regarding diagnosis of the disease (particularly in older studies).

Epidemiological research does indicate an increased risk of Alzheimer's disease with occupational exposure to magnetic fields above the background level. The meta-analyses show that the risk is an estimated 1.2 times higher. The association is less clear than in the case of ALS, yet is still indicative for a causal relationship. Here too, the results of the scientific research are insufficient to determine the exposure level at which the risk is actually increased. No further support for a causal relationship was found in animal studies or mechanistic research.

Parkinson's disease

Epidemiological research did not show any association between exposure to magnetic fields and the risk of Parkinson's disease. This applies to both residential and occupational exposure. The small number of available animal and mechanistic studies yield no information that could help to determine whether a causal relationship exists.

Multiple sclerosis (MS)

Not enough data is available to draw any conclusions about a possible relationship between residential or occupational exposure to magnetic fields and the risk of MS.

EPA classification of the strength of evidence for a causal relationship

In table 2, the Committee states what it considers the study results to mean in terms of evidence of a causal relationship between exposure to magnetic fields and the four neurodegenerative diseases. It does this separately for residential exposure and occupational exposure.

Table 2 Strength of evidence for a causal relationship between exposure and disease

Disease	Residential	Occupational
Amyotrophic lateral sclerosis	No statements can be made regarding a causal relationship	Indications of a causal relationship
Alzheimer's disease	No statements can be made regarding a causal relationship	Indications of a causal relationship
Parkinson's disease	Causal relationship unlikely	Causal relationship unlikely
Multiple sclerosis	No statements can be made regarding a causal relationship	No statements can be made regarding a causal relationship

Little research is available on residential exposure. The studies suitable for meta-analyses all use proximity to high-voltage power lines as a measure of exposure to the magnetic field, which is less accurate than determining exposure by means of measuring or modelling. The Committee therefore concludes that it is not possible to make any statements about a causal relationship between residential exposure and the risk of three of the four neurodegenerative diseases. As the available data on both residential and occupational exposure in relation to Parkinson's disease provided no indication of a causal relationship between exposure and disease, the Committee considers it unlikely that people who live close to high-voltage power lines have an increased risk of Parkinson's disease.

The Committee sees the associations between occupational exposure to magnetic fields and the risk of ALS and Alzheimer's disease as an indication of a causal relationship. Too little research has been carried out into a relationship between occupational exposure to magnetic fields and risk of MS to make reliable statements about a causal relationship.

7.2 Recommendations

Further research

The Committee does not expect that further (retrospective) epidemiological research will provide greater certainty in the short term. The Committee does, however, recommend monitoring residential and occupational exposure to magnetic fields. The use of wind turbines and solar panels as a primary energy source has increased considerably in recent years. At the same time, we are witnessing a surge in the popularity of electric cars and heat pumps. Changes in the production and consumption of electricity are leading to an increase in the transport of electricity and thus, probably, to higher exposures to magnetic fields in the vicinity of power lines and in some workplaces. Further animal studies and mechanistic research may yield additional information on causal relationships.

Precaution

The current policy concerning overhead high-voltage power lines is based on the principle of precaution due to indications of a causal relationship between exposure to magnetic fields and the risk of childhood leukaemia. In its previous advisory report, the Committee recommended considering

broadening the precautionary policy to underground power cables and other sources of long-term exposure to magnetic fields generated by the electrical grid, such as transformer stations and transformer substations. The present analyses did not indicate that the general population is at higher risk of developing a neurodegenerative disease as a result of residential exposure to magnetic fields. The Committee therefore sees no need for further recommendations on measures to limit residential exposure.

Given the indications of an increased risk of ALS and Alzheimer's disease from occupational exposure to magnetic fields above the background level, the Committee recommends the precautionary measure of keeping occupational exposure as low as reasonably achievable (ALARA).

references

1 Health Council of the Netherlands. *Exposure to electromagnetic fields (0 Hz-10 MHz)*. Den Haag, 2000; publication nr. 2000/06E.

2 Health Council of the Netherlands. *Power lines and health, part 1: Childhood cancer*. Den Haag, 2018; publication nr. 2018/08E.

3 Wertheimer N, Leeper E. *Electrical wiring configurations and childhood cancer*. Am J Epidemiol 1979; 109(3): 273-284.

4 Health Council of the Netherlands. *5G and health*. Den Haag, 2020; publication nr. 2020/16E.

5 Owens EO, Patel MM, Kirrane E, Long TC, Brown J, Cote I, et al. *Framework for assessing causality of air pollution-related health effects for reviews of the National Ambient Air Quality Standards*. Regul Toxicol Pharmacol 2017; 88: 332-337.

6 Eliyahu I, Hareuveny R, Riven M, Kandel S, Kheifets L. *24-h personal monitoring of exposure to Power Frequency Magnetic Fields in adolescents - Results of a National Survey*. Environ Res 2017; 158: 295-300.

7 Magne I, Souques M, Bureau I, Duburcq A, Remy E, Lambrozo J. *Exposure of children to extremely low frequency magnetic fields in France: Results of the EXPERS study*. J Expo Sci Environ Epidemiol 2017; 27(5): 505-512.

8 Calvente I, Davila-Arias C, Ocon-Hernandez O, Perez-Lobato R, Ramos R, Artacho-Cordon F, et al. *Characterization of indoor extremely low frequency and low frequency electromagnetic fields in the INMA-Granada cohort*. PLoS One 2014; 9(9): e106666.

9 Bolte JF, Baliatsas C, Eikelboom T, van Kamp I. *Everyday exposure to power frequency magnetic fields and associations with non-specific physical symptoms*. Environ Pollut 2015; 196: 224-229.

10 Kelfkens G, Pruppers MJM. *Extreem-laagfrequente elektrische en magnetische velden van huishoudelijke apparatuur*. Bilthoven, 2005; RIVM Rapport 300010001/2005.

11 Gourzoulidis GA, Tsaprouni P, Skamnakis N, Tzoumanika C, Kalampaliki E, Karastergios E, et al. *Occupational exposure to electromagnetic fields. The situation in Greece*. Phys Med 2018; 49: 83-89.

12 Gobba F, Bravo G, Rossi P, Contessa GM, Scaringi M. *Occupational and environmental exposure to extremely low frequency-magnetic fields: a personal monitoring study in a large group of workers in Italy*. J Expo Sci Environ Epidemiol 2011; 21(6): 634-645.

13 van Tongeren M, Mee T, Whatmough P, Broad L, Maslanyj M, Allen S, et al. *Assessing occupational and domestic ELF magnetic field exposure in the uk adult brain tumour study: results of a feasibility study*. Radiat Prot Dosimetry 2004; 108(3): 227-236.

14 Kromhout H, Loomis DP, Mihlan GJ, Peipins LA, Kleckner RC, Iriye R, et al. *Assessment and grouping of occupational magnetic field exposure in five electric utility companies*. Scand J Work Environ Health 1995; 21(1): 43-50.

15 Bolte JFB, Pruppers MJM. *Elektromagnetische velden in arbeidssituaties*. Den Haag, 2006; RIVM-nr. 610015001.

16 The National Institute for Occupational Safety and Health (NIOSH). *EMFs in the workplace*. https://www.cdc.gov/niosh/docs/96-129/default.html. Accessed: 09-03-2022.

17 de Jongh AD, van Eijk RPA, Peters SM, van Es MA, Horemans AMC, van der Kooi AJ, et al. *Incidence, prevalence and geographical clustering of Motor Neuron Disease in the Netherlands*. Neurology 2021:

18 ALS Centrum Nederland. *Epidemiologie van ALS*. https://www.als-centrum.nl/kennisplatform/epidemiologie-van-als/. Accessed: 09-03-2022.

19 van Es MA, Hardiman O, Chio A, Al-Chalabi A, Pasterkamp RJ, Veldink JH, et al. *Amyotrophic lateral sclerosis*. Lancet 2017; 390(10107): 2084-2098.

20 Marcilio I, Gouveia N, Pereira Filho ML, Kheifets L. *Adult mortality from leukemia, brain cancer, amyotrophic lateral sclerosis and magnetic fields from power lines: a case-control study in Brazil*. Rev Bras Epidemiol 2011; 14(4): 580-588.

21 Frei P, Poulsen AH, Mezei G, Pedersen C, Cronberg Salem L, Johansen C, et al. *Residential distance to high-voltage power lines and risk of neurodegenerative diseases: a Danish population-based case-control study*. Am J Epidemiol 2013; 177(9): 970-978.

22 Seelen M, Vermeulen RC, van Dillen LS, van der Kooi AJ, Huss A, de Visser M, et al. *Residential exposure to extremely low frequency electromagnetic fields and the risk of ALS*. Neurology 2014; 83(19): 1767-1769.

23 Vinceti M, Malagoli C, Fabbi S, Kheifets L, Violi F, Poli M, et al. *Magnetic fields exposure from high-voltage power lines and risk of amyotrophic lateral sclerosis in two Italian populations*. Amyotroph Lateral Scler Frontotemporal Degener 2017; 18(7-8): 583-589.

24 Filippini T, Hatch EE, Vinceti M. *Residential exposure to electromagnetic fields and risk of amyotrophic lateral sclerosis: a dose-response meta-analysis*. Sci Rep 2021; 11(1): 11939.

25 Deapen DM, Henderson BE. *A case-control study of amyotrophic lateral sclerosis*. Am J Epidemiol 1986; 123(5): 790-799.

26 Gunnarsson LG, Lindberg G, Soderfeldt B, Axelson O. *Amyotrophic lateral sclerosis in Sweden in relation to occupation*. Acta Neurol Scand 1991; 83(6): 394-398.

27 Gunnarsson LG, Bodin L, Soderfeldt B, Axelson O. *A case-control study of motor neurone disease: its relation to heritability, and occupational exposures, particularly to solvents*. Br J Ind Med 1992; 49(11): 791-798.

28 Davanipour Z, Sobel E, Bowman JD, Qian Z, Will AD. *Amyotrophic-lateral-sclerosis and occupational exposure to electromagnetic-fields*. Bioelectromagnetics 1997; 18(1): 28-35.

29 Savitz DA, Checkoway H, Loomis DP. *Magnetic field exposure and neurodegenerative disease mortality among electric utility workers*. Epidemiology 1998; 9(4): 398-404.

30 Håkansson N, Gustavsson P, Johansen C, Floderus B. *Neurodegenerative diseases in welders and other workers exposed to high levels of magnetic fields*. Epidemiology 2003; 14(4): 420-426; discussion 427-428.

31 Röösli M, Lortscher M, Egger M, Pfluger D, Schreier N, Lortscher E, et al. *Mortality from neurodegenerative disease and exposure to extremely low-frequency magnetic fields: 31 years of observations on Swiss railway employees*. Neuroepidemiology 2007; 28(4): 197-206.

32 Parlett LE, Bowman JD, van Wijngaarden E. *Evaluation of occupational exposure to magnetic fields and motor neuron disease mortality in a population-based cohort*. J Occup Environ Med 2011; 53(12): 1447-1451.

33 Sorahan T, Mohammed N. *Neurodegenerative disease and magnetic field exposure in UK electricity supply workers*. Occup Med (Lond) 2014; 64(6): 454-460.

34 Fischer H, Kheifets L, Huss A, Peters TL, Vermeulen R, Ye W, et al. *Occupational exposure to electric shocks and magnetic fields and amyotrophic lateral sclerosis in Sweden*. Epidemiology 2015; 26(6): 824-830.

35 Huss A, Spoerri A, Egger M, Kromhout H, Vermeulen R, Swiss National C. *Occupational exposure to magnetic fields and electric shocks and risk of ALS: the Swiss National Cohort*. Amyotroph Lateral Scler Frontotemporal Degener 2015; 16(1-2): 80-85.

36 Koeman T, Slottje P, Schouten LJ, Peters S, Huss A, Veldink JH, et al. *Occupational exposure and amyotrophic lateral sclerosis in a prospective cohort*. Occup Environ Med 2017; 74(8): 578-585.

37 Pedersen C, Poulsen AH, Rod NH, Frei P, Hansen J, Grell K, et al. *Occupational exposure to extremely low-frequency magnetic fields and risk for central nervous system disease: an update of a Danish cohort study among utility workers*. Int Arch Occup Environ Health 2017; 90(7): 619-628.

38 Peters S, Visser AE, D'Ovidio F, Beghi E, Chio A, Logroscino G, et al. *Associations of electric shock and extremely low-frequency magnetic field exposure with the risk of Amyotrophic lateral sclerosis*. Am J Epidemiol 2019; 188(4): 796-805.

39 Chen GX, Mannetje A, Douwes J, van den Berg LH, Pearce N, Kromhout H, et al. *Associations of occupational exposures to electric shocks and extremely low-frequency magnetic fields with motor neurone disease*. Am J Epidemiol 2021; 190(3): 393-402.

40 Savitz DA, Loomis DP, Tse CK. *Electrical occupations and neurodegenerative disease: analysis of U.S. mortality data*. Arch Environ Health 1998; 53(1): 71-74.

41 Noonan CW, Reif JS, Yost M, Touchstone J. *Occupational exposure to magnetic fields in case-referent studies of neurodegenerative diseases*. Scand J Work Environ Health 2002; 28(1): 42-48.

42 Feychting M, Jonsson F, Pedersen NL, Ahlbom A. *Occupational magnetic field exposure and neurodegenerative disease*. Epidemiology 2003; 14(4): 413-419; discussion 427-418.

43 Park RM, Schulte PA, Bowman JD, Walker JT, Bondy SC, Yost MG, et al. *Potential occupational risks for neurodegenerative diseases*. Am J Ind Med 2005; 48(1): 63-77.

44 Vergara X, Mezei G, Kheifets L. *Case-control study of occupational exposure to electric shocks and magnetic fields and mortality from amyotrophic lateral sclerosis in the US, 1991-1999*. J Expo Sci Environ Epidemiol 2015; 25(1): 65-71.

45 Liebl MP, Windschmitt J, Besemer AS, Schafer AK, Reber H, Behl C, et al. *Low-frequency magnetic fields do not aggravate disease in mouse models of Alzheimer's disease and amyotrophic lateral sclerosis*. Sci Rep 2015; 5: 8585.

46 Poulletier de Gannes F, Ruffie G, Taxile M, Ladeveze E, Hurtier A, Haro E, et al. *Amyotrophic lateral sclerosis (ALS) and extremely-low frequency (ELF) magnetic fields: a study in the SOD-1 transgenic mouse model*. Amyotroph Lateral Scler 2009; 10(5-6): 370-373.

47 Consales C, Panatta M, Butera A, Filomeni G, Merla C, Carri MT, et al. *50-Hz magnetic field impairs the expression of iron-related genes in the in vitro SOD1(G93A) model of amyotrophic lateral sclerosis*. Int J Radiat Biol 2019; 95(3): 368-377.

48 Alzheimer Nederland. *Oorzaken Alzheimer*. https://www.alzheimer-nederland.nl/dementie/oorzaken-preventie/oorzaken. Accessed: 09-03-2022.

49 VZinfo. *Dementie.* https://www.volksgezondheidenzorg.info/onderwerp/dementie/cijfers-context/huidige-situatie#node-aantal-mensen-met-dementie. Accessed: 09-03-2022.

50 VZinfo. *Dementie | Leeftijd en geslacht*. https://www.vzinfo.nl/dementie/leeftijd-en-geslacht. Accessed: 09-03-2022.

51 Huss A, Spoerri A, Egger M, Röösli M. *Residence near power lines and mortality from neurodegenerative diseases: longitudinal study of the Swiss population*. Am J Epidemiol 2009; 169(2): 167-175.

52 Gervasi F, Murtas R, Decarli A, Russo AG. *Residential distance from high-voltage overhead power lines and risk of Alzheimer's dementia and Parkinson's disease: a population-based case-control study in a metropolitan area of Northern Italy*. Int J Epidemiol 2019; 48(6): 1949-1957.

53 Sobel E, Davanipour Z, Sulkava R, Erkinjuntti T, Wikstrom J, Henderson VW, et al. *Occupations with exposure to electromagnetic fields: A possible risk factor for Alzheimers disease*. Am J Epidemiol 1995; 142(5): 515-524.

54 Feychting M, Pedersen NL, Svedberg P, Floderus B, Gatz M. *Dementia and occupational exposure to magnetic fields*. Scand J Work Environ Health 1998; 24(1): 46-53.

55 Graves AB, Rosner D, Echeverria D, Yost M, Larson EB. *Occupational exposure to electromagnetic fields and Alzheimer disease*. Alzheimer Dis Assoc Disord 1999; 13(3): 165-170.

56 Harmanci H, Emre M, Gurvit H, Bilgic B, Hanagasi H, Gurol E, et al. *Risk factors for Alzheimer disease: a population-based case-control study in Istanbul, Turkey*. Alzheimer Dis Assoc Disord 2003; 17(3): 139-145.

57 Qiu C, Fratiglioni L, Karp A, Winblad B, Bellander T. *Occupational exposure to electromagnetic fields and risk of Alzheimer's disease*. Epidemiology 2004; 15(6): 687-694.

58 Davanipour Z, Tseng CC, Lee PJ, Sobel E. *A case-control study of occupational magnetic field exposure and Alzheimer's disease: results from the California Alzheimer's Disease Diagnosis and Treatment Centers*. BMC Neurol 2007; 7: 13.

59 Seidler A, Geller P, Nienhaus A, Bernhardt T, Ruppe I, Eggert S, et al. *Occupational exposure to low frequency magnetic fields and dementia: a case-control study*. Occup Environ Med 2007; 64(2): 108-114.

60 Andel R, Crowe M, Feychting M, Pedersen NL, Fratiglioni L, Johansson B, et al. *Work-related exposure to extremely low-frequency magnetic fields and dementia: results from the population-based study of dementia in Swedish twins*. J Gerontol A Biol Sci Med Sci 2010; 65(11): 1220-1227.

61 Koeman T, Schouten LJ, van den Brandt PA, Slottje P, Huss A, Peters S, et al. *Occupational exposures and risk of dementia-related mortality in the prospective Netherlands Cohort Study*. Am J Ind Med 2015; 58(6): 625-635.

62 Akbarnejad Z, Esmaeilpour K, Shabani M, Asadi-Shekaari M, Saeedi Goraghani M, Ahmadi-Zeidabadi M. *Spatial memory recovery in Alzheimer's rat model by electromagnetic field exposure*. Int J Neurosci 2018; 128(8): 691-696.

63 Zuo H, Liu X, Wang D, Li Y, Xu X, Peng R, et al. *RKIP-mediated NF-κB signaling is involved in ELF-MF-mediated improvement in AD rat*. Int J Med Sci 2018; 15(14): 1658-1666.

64 Liu X, Zuo H, Wang D, Peng R, Song T, Wang S, et al. *Improvement of spatial memory disorder and hippocampal damage by exposure to electromagnetic fields in an Alzheimer's disease rat model*. PLoS One 2015; 10(5): e0126963.

65 Hu Y, Lai J, Wan B, Liu X, Zhang Y, Zhang J, et al. *Long-term exposure to ELF-MF ameliorates cognitive deficits and attenuates tau hyperphosphorylation in 3xTg AD mice*. Neurotoxicology 2016; 53: 290-300.

66 Zhang Y, Liu X, Zhang J, Li N. *Short-term effects of extremely low frequency electromagnetic fields exposure on Alzheimer's disease in rats*. Int J Radiat Biol 2015; 91(1): 28-34.

67 Zhang C, Li Y, Wang C, Lv R, Song T. *Extremely low-frequency magnetic exposure appears to have no effect on pathogenesis of Alzheimer's disease in aluminum-overloaded rat*. PLoS One 2013; 8(8): e71087.

[68] Antonini RA, Benfante R, Gotti C, Moretti M, Kuster N, Schuderer J, et al. *Extremely low-frequency electromagnetic field (ELF-EMF) does not affect the expression of alpha3, alpha5 and alpha7 nicotinic receptor subunit genes in SH-SY5Y neuroblastoma cell line*. Toxicol Lett 2006; 164(3): 268-277.

[69] Rao RR, Halper J, Kisaalita WS. *Effects of 60 Hz electromagnetic field exposure on APP695 transcription levels in differentiating human neuroblastoma cells*. Bioelectrochemistry 2002; 57(1): 9-15.

[70] Reale M, Kamal MA, Patruno A, Costantini E, D'Angelo C, Pesce M, et al. *Neuronal cellular responses to extremely low frequency electromagnetic field exposure: implications regarding oxidative stress and neurodegeneration*. PLoS One 2014; 9(8): e104973.

[71] Patruno A, Tabrez S, Amerio P, Pesce M, Vianale G, Franceschelli S, et al. *Kinetic study on the effects of extremely low frequency electromagnetic field on catalase, cytochrome P450 and inducible nitric oxide synthase in human HaCaT and THP-1 cell lines*. CNS Neurol Disord Drug Targets 2011; 10(8): 936-944.

[72] Del Giudice E, Facchinetti F, Nofrate V, Boccaccio P, Minelli T, Dam M, et al. *Fifty Hertz electromagnetic field exposure stimulates secretion of beta-amyloid peptide in cultured human neuroglioma*. Neurosci Lett 2007; 418(1): 9-12.

[73] Zuo H, Liu X, Li Y, Wang D, Hao Y, Yu C, et al. *The mitochondria/caspase-dependent apoptotic pathway plays a role in the positive effects of a power frequency electromagnetic field on Alzheimer's disease neuronal model*. J Chem Neuroanat 2020; 109: 101857.

[74] VZinfo. *Ziekte van Parkinson*. https://www.vzinfo.nl/ziekte-van-parkinson#node-aantal-nieuwe-gevallen-ziekte-van-parkinson-huisartsenpraktijk. Accessed: 09-03-2022.

[75] van der Mark M, Vermeulen R, Nijssen PC, Mulleners WM, Sas AM, van Laar T, et al. *Extremely low-frequency magnetic field exposure, electrical shocks and risk of Parkinson's disease*. Int Arch Occup Environ Health 2015; 88(2): 227-234.

[76] Brouwer M, Koeman T, van den Brandt PA, Kromhout H, Schouten LJ, Peters S, et al. *Occupational exposures and Parkinson's disease mortality in a prospective Dutch cohort*. Occup Environ Med 2015; 72(6): 448-455.

[77] Checkoway H, Ilango S, Li W, Ray RM, Tanner CM, Hu SC, et al. *Occupational exposures and parkinsonism among Shanghai women textile workers*. Am J Ind Med 2018; 61(11): 886-892.

[78] Jadidi M, Biat SM, Sameni HR, Safari M, Vafaei AA, Ghahari L. *Mesenchymal stem cells that located in the electromagnetic fields improves rat model of Parkinson's disease*. Iran J Basic Med Sci 2016; 19(7): 741-748.

[79] Seong Y, Moon J, Kim J. *Egr1 mediated the neuronal differentiation induced by extremely low-frequency electromagnetic fields*. Life Sci 2014; 102(1): 16-27.

[80] Benassi B, Santangeli S, Merla C, Tarantini L, Bollati V, Butera A, et al. *50-Hz MF does not affect global DNA methylation of SH-SY5Y cells treated with the neurotoxin MPP*$^{+}$. Bioelectromagnetics 2019; 40(1): 33-41.

[81] Benassi B, Filomeni G, Montagna C, Merla C, Lopresto V, Pinto R, et al. *Extremely low frequency magnetic field (ELF-MF) exposure sensitizes SH-SY5Y cells to the pro-Parkinson's disease toxin MPP*$^{+}$. Mol Neurobiol 2016; 53(6): 4247-4260.

[82] Consales C, Cirotti C, Filomeni G, Panatta M, Butera A, Merla C, et al. *Fifty-hertz magnetic field affects the epigenetic modulation of the miR-34b/c in neuronal cells*. Mol Neurobiol 2018; 55(7): 5698-5714.

[83] VZinfo. *Ranglijsten | Welke aandoeningen komen het meeste voor?* https://www.volksgezondheidenzorg.info/ranglijst/ranglijst-aandoeningen-op-basis-van-vóórkomen. Accessed: 09-03-2022.

[84] Stecr. *Multiple sclerose*. https://www.stecr.nl/default.asp?page_id=236&name=Multiple_sclerose. Accessed: 09-03-2022.

[85] CBS. *Personen naar bij de huisarts bekende diagnose; leeftijd, geslacht: multiple sclerose*. https://www.cbs.nl/nl-nl/cijfers/detail/83110NED?q=multiple%20sclerose. Accessed: 09-03-2022.

Committee and consulted expert[a]

Members of the Committee on Electromagnetic Fields for the advisory report

Power lines and health: neurodegenerative diseases

- Prof. H. Kromhout, Professor of Epidemiology of Health Effects from Exposure to Electromagnetic Fields, Institute for Risk Assessment Sciences, University of Utrecht, *chairperson*
- Prof. A. Aleman, Professor of Cognitive Neuropsychiatry, University of Groningen
- Dr. A. Huss, Institute for Risk Assessment Sciences, University of Utrecht
- Prof. Dr. S. Le Cessie, Statistician, Department of Clinical Epidemiology and Department of Medical Statistics, Leiden University Medical Centre
- Dr. R.M.C. Mestrom, assistant profesoor, Eindhoven University of Technology
- Prof. Dr. ir. M.M. Paulides, Professor and Chair of the Care & Cure research lab of the Electromagnetics group, Eindhoven University of Technology
- Prof. H.F.J. Savelkoul, Professor of Cell Biology and Immunology, Wageningen University
- Dr. R. van Strien, Epidemiologist, Municipal Health Services, Amsterdam
- Prof. Dr. F. de Vocht, Professor of Epidemiology and Public Health, Population Health Sciences, University of Bristol, United Kingdom
- Dr. G. Kelfkens, Physicist, National Institute for Public Health and the Environment, Bilthoven, *structurally consulted expert*

Incidentally consulted expert[a]:

- Prof. Dr. W.A. van Gool, Professor of Neurology, Amsterdam UMC

Observers[a]

- ir. J.P.M. van Assche, Radiocommunciatons Agency Netherlands, Groningen
- Dr. M.J.M. Pruppers, Physicist, Knowledge Platform Electromagnetic Fields, Bilthoven
- Drs. Ing. T.A.H. van Roermund, Ministry of Economic Affairs and Climate Policy, The Hague
- D. Valk, Ministry of Social Affairs and Employment, The Hague

Scientific Secretaries

- dr. E. van Rongen, Health Council, The Hague
- dr. H.F.G. van Dijk, Health Council, The Hague

[a] Consulted experts are consulted by the committee because of their expertise. Consulted experts and observers are entitled to speak during the meeting. They do not have any voting rights and do not bear any responsibility for the content of the committee's advisory report.

The Health Council of the Netherlands, established in 1902, is an independent scientific advisory body. Its remit is “to advise the government and Parliament on the current level of knowledge with respect to public health issues and health (services) research...” (Section 22, Health Act).
The Health Council receives most requests for advice from the Ministers of Health, Welfare and Sport, Infrastructure and Water Management, Social Affairs and Employment, and Agriculture, Nature and Food Quality. The Council can publish advisory reports on its own initiative. It usually does this in order to ask attention for developments or trends that are thought to be relevant to government policy.
Most Health Council reports are prepared by multidisciplinary committees of Dutch or, sometimes, foreign experts, appointed in a personal capacity.
The reports are available to the public.

This publication can be downloaded from www.healthcouncil.nl.

Preferred citation:
Health Council of the Netherlands. Power lines and health: neurodegenerative diseases.
The Hague: Health Council of the Netherlands, 2022; publication no. 2022/13e.