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Environmental Research 226 (2023) 115657

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

# The relationship between radiofrequency-electromagnetic radiation from cell phones and brain tumor: The brain tumor incidence trends in South Korea

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ARTICLE INFO

Handling Editor: Jose L Domingo

*Keywords:*
Radiofrequency-electromagnetic radiation
Cell phone
Brain tumor
Subscription rate
Age-standardized incidence rate
Correlation coefficient

ABSTRACT

*Introduction:* The aim of this study is to investigate the relationship between the nationwide cell phone subscription rate and the nationwide incidence of brain tumors in South Korea. The nationwide cell phone subscription rate was used as a proxy for the RF-EMR exposure assessment.
*Methods:* The data for cell phone subscriptions per 100 persons from 1985 to 2019 were found in the Statistics, International Telecom Union (ITU). The brain tumor incidence data from 1999 to 2018 provided by the South Korea Central Cancer Registry operated by the National Cancer Center were used.
*Results:* In South Korea, the subscription rate increased from 0 per 100 persons in 1991 to 57 per 100 persons in 2000. The subscription rate became 97 per 100 persons in 2009 and 135 per 100 persons in 2019. For the correlation coefficient between cell phone subscription rate before 10 years and ASIR per 100,000, a positive correlation coefficient with a statistical significance was reported in 3 benign brain tumors (International Classification of Diseases, ICD-10 code, D32, D33, and D32.0) and in 3 malignant brain tumors (ICD-10 code, C71.0, C71.1, and C71.2). Positive correlation coefficients with a statistical significance in malignant brain tumors ranged from 0.75 (95% CI 0.46–0.90) for C71.0 to 0.85 (95% CI 0.63–0.93) for C71.1.
*Discussion:* In consideration of the fact that the main route for RF-EMR exposure has been through the frontotemporal side of the brain (the location of both ears), the positive correlation coefficient with a statistical significance in the frontal lobe (C71.1) and temporal lobe (C71.2) can be understood. Statistically insignificant results from recent cohort and large population international studies and contrasting results from many previous case-control studies could indicate a difficulty in identifying a factor as a determinant of a disease in ecological study design.

## 1. Introduction

Numerous systematic reviews and meta-analyses on the association between Radiofrequency-Electromagnetic Radiation (RF-EMR) exposure from cell phones and the incidence of brain tumors have been published until the present time (Belpomme et al., 2018; Elwood, 2003; Morgan et al., 2015; Myung et al., 2009; Wang et al., 2018). The conclusion of each study varied depending on the magnitude of exposure, the location of brain tumors, the histologic type of brain tumors, and a number of confounding factors such as research team and funding source (Belpomme et al., 2018; Hardell et al., 2008a; Morgan et al., 2015; Wang et al., 2018).

The epidemiological studies for the health effects of RF-EMR exposure could be complex because precise exposure to RF-EMR from cellular phones is difficult to be assessed. The current survey questions for exposure assessment, such as the years of cellular phone use (≥10 years or <10 years), the cumulative call time, and the number of calls per week, etc., are essentially crude proxies for accurate RF-EMR exposure. The emitted RF-EMR magnitude fluctuates according to a number of external/internal conditions, including cell phone models, used networks, location of uses, and applied network technologies for cellular phones. Furthermore, the recent widespread Bluetooth technology is making the distance between the brain and cellular phones more irregular (sometimes farther than before). In addition, in current society, nearly all people are using their mobile phones not only for calling but also for nearly everything in their daily lives, such as

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https://doi.org/10.1016/j.envres.2023.115657
Received 5 June 2021; Received in revised form 6 March 2023; Accepted 7 March 2023
Available online 10 March 2023
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searching for information (web-surfing), watching videos (YouTube), connecting to social network services (Facebook or Tweeter), recording schedules, etc. What is worse is that they use their mobile phones as a morning alarm device, leaving their mobile phones beside their head all night. The exposed RF-EMR amount during these activities other than calling might be different from the RF-EMR amount during calls. This factor also should be considered when researchers calculate the RF-EMR exposure to a person (Wall et al., 2019). The correct exposure assessment should be based on the site-specific, time-integral of specific absorption rate (SAR) if the changing patterns of mobile phone use and the developing Bluetooth technology are considered (Auvinen et al., 2006).

At this present, in consideration of limited data for accurate RF-EMR exposure assessment, the best strategy to approach this topic is the triangulation of the pieces of information from the different types of epidemiologic studies (de Vocht and Röösli, 2021). As one piece of information from this perspective, we looked over the incidence trend of brain tumors classified by the histological types and the location of brain tumors in South Korea. Even though the nationwide cell phone subscription rate was used as a crude proxy of the assessment for RF-EMR exposure, this proxy could not reflect the accurate RF-EMR exposure patterns in the population. However, because no data for this information is available at the current time, we used the cell phone subscriptions per 100 persons as a surrogate marker of exposure assessment for RF-EMR from cellular phones. South Korea is a country with a fast-growing and extremely high cell phone penetration rate since the introduction of cellular phones. The current discussion about the relationship between RF-EMR exposure from cell phones and brain tumor incidence is incomplete because of the incomplete available data. This paper could be of meaningful help in understanding this topic and in designing future research. Finally, the aim of this study is to investigate the relationship between the nationwide cell phone subscription rate and the nationwide incidence of brain tumors in South Korea.

## 2. Methods

For the cell phone penetration rate in South Korea, Taiwan, the US, Finland, and the UK, the data for cell phone subscriptions per 100 persons from 1985 to 2019 were found from the Statistics, International Telecom Union (ITU) (https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx).

For the brain tumor incidence trend in South Korea, the brain tumor incidence data from 1999 to 2018 provided by the Korea Central Cancer Registry operated by the National Cancer Center were used. If researchers request the data for a type of cancer with specific requirements, the Korean Central Cancer Registry provides the researchers with the requested dataset within a month.

The Age-Standardized Incidence Rate (ASIR) per 100,000 for the International Classification of Diseases-10 (ICD-10) codes for brain tumors were used: D32, D33, and D32.0 for benign brain tumors, and C70, C71, C72, C71.1, and C71.2 for malignant brain tumors. Average Annual Percentage Change (AAPC) was calculated using the package 'segmented' in the R statistical software. The time-series graphs were also plotted.

## 3. Results

In Fig. 1, the time trend of cell phone subscriptions per 100 persons in South Korea, Taiwan, the US, Finland, and the UK is provided. The detailed numbers are in Supplementary material A. In South Korea, the subscription rate was 0 per 100 persons until 1991. However, the subscription rate rose to 57 per 100 persons in 2000. The subscription rate approached nearly 100% (97 per 100 persons) in 2009. In 2019, the subscription rate became 135 per 100 persons.

In Figs. 2–1, 2-2, and 2–3, the plot for the time trend of ASIR per 100,000 for each type of brain tumor is provided. Figs. 2–1 and 2-2 are for malignant brain tumors, and Figs. 2–3 is for benign brain tumors. Figs. 2–1 deals with the plot for C70, C72, C70.0, C70.9, C71.0, and C72.0. Fig. 2– deals with the plot for C71, C71.1, C71.2, and C71.9. Figs. 2–3 deals with the plot for D32, D33, and D32.0. The ASIR per 100,000 for each type of brain tumor in each year is provided in Supplementary material B.

In Table 1, the AAPC (%) with a 95% Confidence Interval (CI) for each type of brain tumor from 1999 to 2018 in South Korea is provided. The AAPC for C72, C71.0, C71.1, C71.2, C72.0, D32, D33, and D32.0 was positive with statistical significance. The AAPC for C71 and C70.9 was statistically insignificant. The AAPC for C70, C70.0, and C71.9 was negative with statistical significance. The statistically significant positive AAPCs range from 0.21 (95% CI 0.03–0.46) % to 1.53 (95% CI

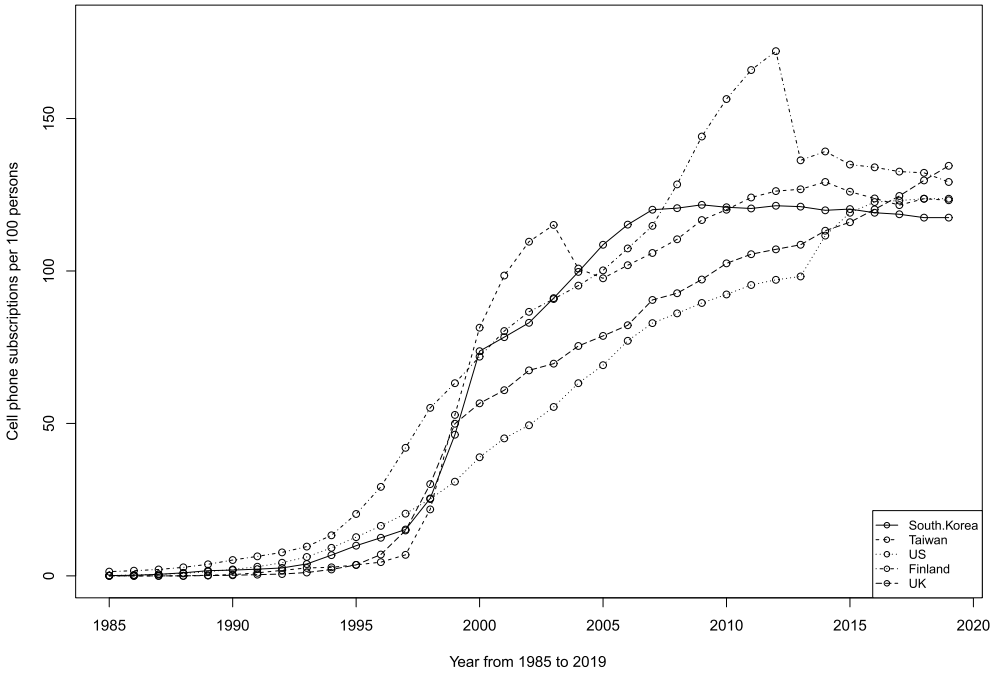
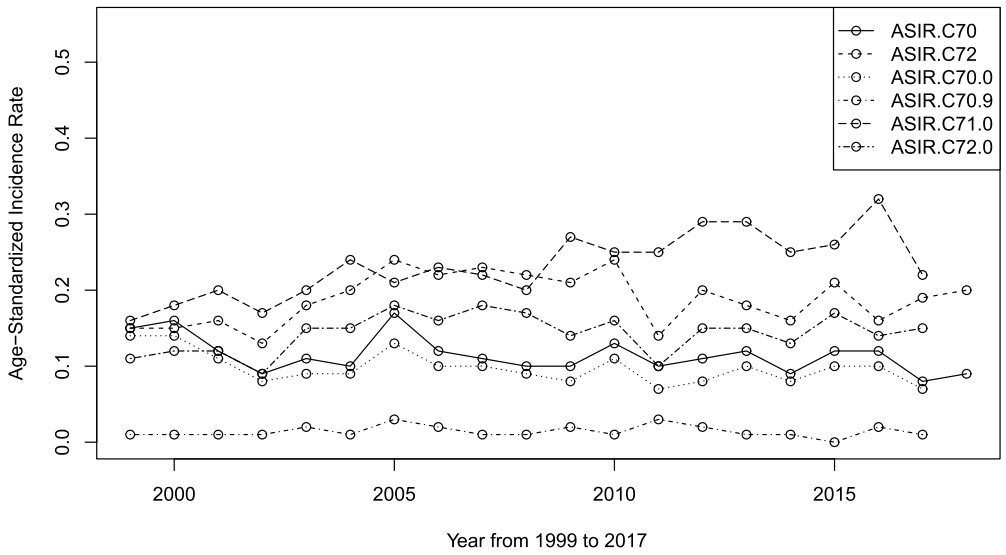
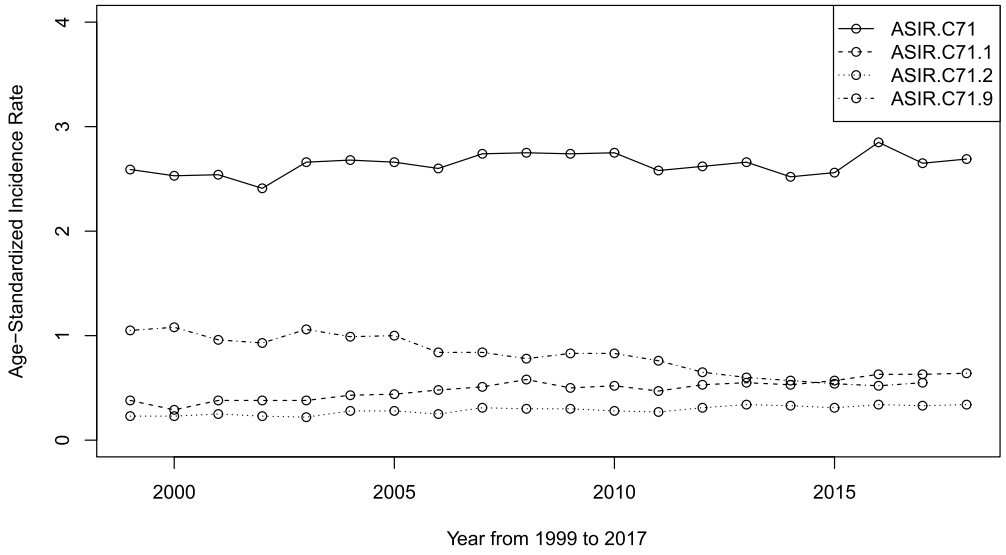



**Fig. 1.** The time trend of mobile-cellular telephone subscriptions in each country.



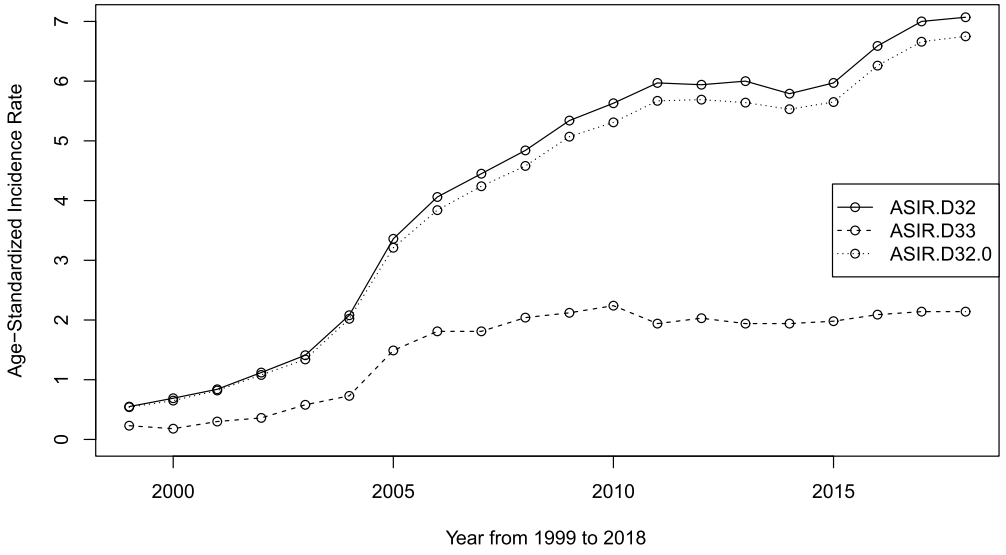




**Fig. 2.** **1**. The time trend of ASIR per 100,000 for C70, C72, C70.0, C70.9, C71.0, and C72.0; **2**. The time trend of ASIR per 100,000 for C71, C71.1, C71.2, and C71.9; **3**. The time trend of ASIR per 100,000 for D32, D33, and D32.0.

**Table 1**
The AAPC for each type of brain tumor in South Korea (1999–2018).

| Classification | ICD-10 code | Tumor type | AAPC (%) (95% CI) |
|---|---|---|---|
| Malignant brain tumor | C70 | Malignant neoplasm of meninges | −0.30 (−0.53–−0.10)* |
| | C71 | Malignant neoplasm of brain | 0.68 (−0.21–1.57) |
| | C72 | Malignant neoplasm of the spinal cord, cranial nerves, and other parts of the central nervous system | 0.21 (0.03–0.46)* |
| | C70.0 | Malignant neoplasm of cerebral meninges | −0.33 (−0.50–−0.16)* |
| | C70.9 | Malignant neoplasm of meninges, unspecified | 0.02 (−0.06-0.09) |
| | C71.0 | Malignant neoplasm of cerebrum, except lobes and ventricles | 0.48 (0.21–0.76)* |
| | C71.1 | Malignant neoplasm of the frontal lobe | 1.53 (1.18–1.89)* |
| | C71.2 | Malignant neoplasm of the temporal lobe | 0.63 (0.44–0.82)* |
| | C71.9 | Malignant neoplasm of brain, unspecified | −3.05 (−3.60–−2.51)* |
| | C72.0 | Malignant neoplasm of spinal cord | 0.22 (0.02–0.43)* |
| Benign brain tumor | D32 | Benign neoplasm of meninges | 36.69 (33.53–39.85)* |
| | D33 | Benign neoplasm of brain and other parts of the central nervous system | 11.39 (9.77–13.00)* |
| | D32.0 | Benign neoplasm of brain, supratentorial | 34.85 (31.87–37.83)* |

The brain tumor incidence data (Cancer Statistics) provided by the Korea Central Cancer Registry, National Cancer Center.
AAPC: Average Annual Percentage Change
*Statistically significant.

1.18–1.89) % for malignant tumors. The statistically significant positive AAPCs range from 11.39 (95% CI 9.77–13.00) % to 36.69 (95% CI 33.53–39.85) % for benign tumors. The statistically significant negative AAPCs range from −3.05 (−3.60–2.51) % to −0.30 (−0.53–0.10) % for malignant tumors.

Table 2 provides the correlation coefficient between cell phone subscription rate before 10 years and ASIR, its confidence interval, and its *p*-value for each type of brain tumor. The interval of 10 years between the cell phone subscription rate and ASIR was applied based on the data provided in Supplementary materials A and B. In Supplementary material A, the cell phone subscription rate increased from 0 in 1991 to 103 in 2010. However, in Supplementary material B, overall ASIRs increased abruptly from 2001 to 2018. Therefore, the author concluded that 10 years of latency time is appropriate based on these data. A positive correlation coefficient with statistical significance was reported in 3 malignant brain tumors: C71.0, C71.1, and C71.2. A positive correlation coefficient with statistical significance was reported in 3 benign brain tumors: D32, D33, and D32.0. A negative correlation coefficient with statistical significance was reported in 3 malignant brain tumors: C70, C70.0, and C71.9. Positive correlation coefficients with a statistical significance in malignant brain tumors range from 0.75 (95% CI 0.46–0.90) to 0.85 (95% CI 0.63–0.93). Positive correlation coefficients with a statistical significance in benign brain tumors range from 0.79 (0.54–0.92) to 0.92 (0.80–0.97). Negative correlation coefficients with a statistical significance range from −0.90 (−0.96–0.75) to −0.45 (−0.74–0.01).

Table 3 provides the correlation coefficient between cell phone subscription rate and ASIR, its confidence interval, and its *p*-value for each type of brain tumor. A positive correlation coefficient with statistical significance was reported in 3 malignant brain tumors: C71.0, C71.1, and C71.2. A positive correlation coefficient with statistical significance was reported in 3 benign brain tumors: D32, D33, and D32.0. A negative correlation coefficient with statistical significance was reported in 3 malignant brain tumors: C70, C70.0, and C71.9. Positive correlation coefficients with a statistical significance in malignant brain tumors range from 0.79 (95% CI 0.52–0.92) to 0.93 (95% CI 0.82–0.97). Positive correlation coefficients with a statistical significance in benign brain tumors range from 0.89 (0.75–0.96) to 0.98 (0.94–0.99). Negative correlation coefficients with a statistical significance range from −0.94 (−0.98–0.84) to −0.51 (−0.78–0.09).

## 4. Discussion

In South Korea, the subscription rate increased from 0 per 100 persons in 1991 to 57 per 100 persons in 2000. The subscription rate became 97 per 100 persons in 2009 and 135 per 100 persons in 2019. For the correlation coefficient between cell phone subscription rate before 10 years and ASIR per 100,000, a positive correlation coefficient with a statistical significance was reported in 3 benign brain tumors (D32, D33, and D32.0) and in 3 malignant brain tumors (C71.0, C71.1, and C71.2).

**Table 2**
The correlation coefficient between cell phone subscription rate before 10 years and age-standardized incidence rate, confidence interval, and *p*-value for each type of brain tumor.

| ICD-10 code for brain tumor | Correlation Coefficient | 95% Confidence Interval | *p*-value |
|---|---|---|---|
| C70 | −0.45 | −0.74–0.01 | 0.05* |
| C71 | 0.29 | −0.17-0.65 | 0.21 |
| C72 | 0.07 | −0.39-0.49 | 0.78 |
| C70.0 | −0.50 | −0.78–0.06 | 0.03* |
| C70.9 | −0.07 | −0.51-0.40 | 0.78 |
| C71.0 | 0.75 | 0.46–0.90 | 0.00* |
| C71.1 | 0.85 | 0.66–0.94 | 0.00* |
| C71.2 | 0.84 | 0.63–0.93 | 0.00* |
| C71.9 | −0.90 | −0.96–0.75 | 0.00* |
| C72.0 | 0.29 | −0.19-0.66 | 0.23 |
| D32 | 0.92 | 0.80–0.97 | 0.00* |
| D33 | 0.79 | 0.54–0.92 | 0.00* |
| D32.0 | 0.92 | 0.80–0.97 | 0.00* |

*Statistically significant.

**Table 3**
The correlation coefficient between cell phone subscription rate and age-standardized incidence rate, confidence interval, and *p*-value for each type of brain tumor.

| ICD-10 code for brain tumor | Correlation Coefficient | 95% Confidence Interval | *p*-value |
|---|---|---|---|
| C70 | −0.51 | −0.78–0.09 | 0.02* |
| C71 | 0.40 | −0.06-0.71 | 0.08 |
| C72 | 0.26 | −0.21-0.63 | 0.28 |
| C70.0 | −0.59 | −0.83–0.19 | 0.01* |
| C70.9 | 0.02 | −0.44-0.47 | 0.95 |
| C71.0 | 0.79 | 0.52–0.92 | 0.00* |
| C71.1 | 0.93 | 0.82–0.97 | 0.00* |
| C71.2 | 0.89 | 0.74–0.96 | 0.00* |
| C71.9 | −0.94 | −0.98–0.84 | 0.00* |
| C72.0 | 0.34 | −0.14-0.69 | 0.16 |
| D32 | 0.98 | 0.94–0.99 | 0.00* |
| D33 | 0.89 | 0.75–0.96 | 0.00* |
| D32.0 | 0.98 | 0.94–0.99 | 0.00* |

*Statistically significant.

### 4.1. Interpretation of results

In consideration of the fact that the main route for RF-EMR exposure has been through the frontotemporal side of the brain (the location of both ears), the positive correlation coefficient with a statistical significance in the frontal lobe (C71.1) and temporal lobe (C71.2) can be understood.

Meanwhile, even if the specific locations of tumors were not specified, in consideration of possible increased RF-EMR exposure due to the increased subscription rate of cell phones, the positive correlation coefficient with a statistical significance for C71.0 (malignant neoplasm of cerebrum, except lobes and ventricles) can be understood.

However, the positive correlation coefficient with a statistical significance for D32 (benign neoplasm of meninges), D33 (benign neoplasm of brain and other parts of the central nervous system), and D32.0 (benign neoplasm of brain, supratentorial) should be understood cautiously. In contrast to malignant brain tumors, some benign brain tumors are not fatal and might not be discovered for a long time without imaging diagnostic tools such as Computerized Tomography (CT) or Magnetic Resonance Imaging (MRI). Therefore, the development of modern medical imaging tools such as CT and MRI could be a source of increased detection and positive correlation coefficients with statistical significance.

### 4.2. Other possible hypotheses for the increasing incidence of brain tumors

Possible hypotheses other than the increased RF-EMR exposure from cell phones should be considered. The first possible scenario is the increased detection of hidden brain tumors because of the increased use of imaging studies such as CT and MRI. In the US, the incidence rate of childhood brain tumors has increased since the mid-1980s and stabilized over the past two decades. Many studies analyzed that this trend is due to the improvement of diagnostic techniques, including imaging modalities such as CT and MRI (Hardell and Carlberg, 2015; McKean-Cowdin et al., 2013; Modan et al., 1992). Studies with similar conclusions were published in several countries (Caldarella et al., 2011; Dho et al., 2017). For benign brain tumors, this hypothesis could be plausible because benign brain tumors could be undiagnosed for many years. However, for malignant brain tumors, this hypothesis does not apply. Even though undiagnosed at initial times, malignant brain tumors would cause a fatal result in a few years.

The second possibility is the increased dose of exposed radiation from the use of these imaging diagnostic modalities. A recent study in the Netherlands reported that CT-related radiation exposure increased the risk of brain tumors with a statistical significance (Excess Relative Risk/100 mGy = 0.86 (95% CI 0.2–2.22)) (Meulepas et al., 2019). According to a meta-analysis paper published in 2018, brain tumor incidence increased with the increased use of pediatric head CT scans in a dose-response manner (Sheppard et al., 2018). The increased radiation dose to the brain from the increased use of radiation-emitting imaging modalities such as CT scan or Positron Emission Tomography (PET)/CT scan has been reported and discussed in many previous studies (Brenner and Hall, 2007; Huang et al., 2009; Lee et al., 2004; Mattsson and Söderberg, 2011; Smith-Bindman, 2010). However, this hypothesis also cannot explain why malignant brain tumors in the frontal and temporal lobes selectively show a statistically significant correlation coefficient. Considering the spatial relationship between RF-EMR emitted from cell phones and the affected brain parts, an association with RF-EMR from cellular phones is more plausible.

The third possibility is the influence of continuously aggravating air pollution. Many recent studies supported the hypothesis that long-term exposure to ambient air pollutants could cause malignant brain tumors (Andersen et al., 2018; Harbo Poulsen et al., 2020; Jørgensen et al., 2016; Poulsen et al., 2020; Weichenthal et al., 2020; Wu et al., 2020). However, a clear causal association was not observed in benign tumors (Andersen et al., 2018). In addition, the causal association with malignant brain tumors was relatively weak (Harbo Poulsen et al., 2020; Poulsen et al., 2020) and was selective for some subjects with special traits (Jørgensen et al., 2016; Wu et al., 2020). For this causal relationship to be established firmly, more conclusive studies on a large scale are needed.

The fourth possibility is the influence of the increased use of chemicals. N-nitroso compounds and pesticides have been reported as environmental risk factors for brain tumors (Preston-Martin et al., 1982; Vienne-Jumeau et al., 2019). Vinyl chloride also has been reported as a possible agent in some exposed workers in occupational settings (Austin and Schnatter, 1983; Moss, 1985). For this causal relationship to be established firmly as the cause of the continuously increasing incidence of brain tumors, further informative studies are needed.

### 4.3. Previous literature on the association between RF-EMR from cellular phones and brain tumor

The impact of RF-EMR released from mobile electronic devices on human health has been discussed by numerous studies since the invention of the codeless phone through the development of cellular phones to the present day. Numerous researchers hypothesized a causal link between RF-EMR exposure and the frequency of brain tumors as one of the probable negative health effects. However, no firm inference has been made on this potential causative relationship as of yet. According to the International Agency for Research on Cancer (IARC), there is only weak evidence that RF-EMR exposure causes cancer in people, while there are positive connections between RF-EMR exposure from cellular phones and gliomas and auditory neuromas (IARC_Working_Group, 2013).

As most principal investigators worldwide understand, the Hardell group reported strong positive causal associations between RF-EMR exposure from wireless phones and glioma and acoustic neuroma incidence. On the contrary, the Interphone group reported that they could not observe a statistically significant positive causal association between RF-EMR exposure from wireless phones and brain tumor incidence. Hardell group and the advocates of this group pointed out several epidemiological weaknesses in the Interphone studies. In contrast, the Interphone study group and the advocates of this group defended their position, referring to logical epidemiological reasons for the reliability of their results. (Hardell et al., 2008b; Momoli et al., 2017). Despite these fierce debates between the two groups, a definitive conclusion has not been made.

As for national brain cancer incidence trends, the Interphone group and their advocates refer to the stable trend of brain tumor incidence even though the penetration rate of cellular phones is increasing (Benson et al., 2013; Frei et al., 2011). In contrast, the Hardell group and their advocates refer to the increasing incidence of brain tumors using national cancer registry data (Hardell and Carlberg, 2017). Considering that these national trend studies for brain tumor incidence provide valuable epidemiologic information for the triangulation of existing evidence, we should carefully follow these incidence trends in various countries.

### 4.4. Accurate exposure assessment for individual RF-EMR exposure from cellular phones: the key to summarizing current complex phenomena into a single plausible theory

In 2006, Auvinen et al. published a paper on the accuracy of exposure assessment for RF-EMR from cellular phones (Auvinen et al., 2006). They discussed the inaccuracy of RF-EMR exposure assessment in real-world settings deeply. If an improvement in this exposure assessment for RF-EMR from cellular phones is achieved, statistically more significant relationships can be observed for the association between RF-EMR exposure and the incidence of brain tumors in future studies. Theoretically, the accurate assessment of RF-EMR exposure should be based on (i) site-specific, (ii) time-integral of (iii) specific absorption rate

(SAR).

As for the third 'SAR' component, SAR consists of 2 sub-components, 'cellular phone use time' and 'power'. The usual exposure assessment measures for cellular phone use time, such as the years of cellular phone use, the cumulative duration of calls, and the number of calls per week, are all proxy indicators for mobile phone use. The output power varies considerably across phone models, the used network, the location of use, and the applied technologies in the mobile phone. For example, if discontinuous transmission (DTX) technology was applied to a mobile phone, the power during a complete silent period would be reduced to about 10% of the emitted power in which the DTX technology was not applied (Wiart et al., 2000). The calculation of power should consider these complex characteristics of cellular phone use.

As for the first 'site-specific' component, the distance between the cellular phone and each part of the brain should be carefully considered. However, with advancing Bluetooth technology, the distance between the phone and the brain is becoming distant these days. Recently more people are using a wireless Bluetooth headset or an earphone not only when they call people but also when they listen to music or watch a video through YouTube. This important factor should be considered in future studies.

As for the second 'time-integral' component, the appropriate exposure assessment measure would be a weighted average of the cumulative time of cellular phone use weighted by power, stratified by the side of the head, in consideration of the use of Bluetooth hands-free devices. These days, many people are using mobile phones for other activities than calling: web surfing, watching movies and videos through YouTube or other applications, connecting to social network services like Facebook or Twitter, text messaging, morning alarm, recording schedules, catching a taxi, and even meditation purposes. In the current society, all essential services, such as Uber, booking a restaurant, checking out today's weather, etc., are available through applications on cellular phones (mobile phones). Therefore, the time of cellular phone use is becoming continuous and irregular, regardless of pure calling time. Even Bluetooth technology supports these irregular and continuous cellular phone uses. Therefore, the accurate exposure assessment for RF-EMR from cellular phones would become more difficult in future studies. The exposure to RF-EMR from cellular phones should be carefully assessed by adequate experts. The strict rigor for exposure assessment of RF-EMR from cellular phones should be complied with for all study types, including cohort studies.

### 4.5. Statistically insignificant results of recent main studies: other alternative explanations

Until now, 2 cohort studies are available on this topic (Benson et al., 2013; Frei et al., 2011). Benson et al. classified the exposure into ever/never use, < daily/daily use, and <5/5–9/10+ years of use. Only the acoustic neuroma with 5–9 (1.80 (95% CI 1.08–3.03)) and ≥10 years of use (2.46 (95% CI 1.07–5.64)) and pituitary tumor with <5 years of use (2.31 (95% CI 1.31–4.06)) showed a statistically significantly increased relative risk (Benson et al., 2013). All other tumor types showed no statistically significant result. Frei et al. classified the exposure into non-subscribers/subscribers and years of subscription (1–4/5-9/≥10). In this study, all results were statistically insignificant (Frei et al., 2011).

Another recently published case-control study is the international MOBI-Kids study (Castaño-Vinyals et al., 2022). This study only targeted patients diagnosed with a benign or malignant brain tumor at 10–24 years of age. This study classified the exposure into regular/non-regular users, years of use <1/1–4/5-9/10+ years of use, and the cumulative number of calls, stratified by the location of brain tumors (temporal/frontal or parietal/cerebellum/others) and the histologic type of brain tumors (neuro-epithelial/non-neuro-epithelial). All results were statistically insignificant in this study.

However, the exposure assessment proxies for RF-EMR from cellular phones applied in this study are not accurate, strictly speaking. Theoretically, (i) site-specific, (ii) time-integral of (iii) SAR for an individual is the most accurate exposure assessment method for RF-EMR from cellular phones. In another co-submitted manuscript of the author to *Environmental Research* (ER-21-3692R1), the author applied a more accurate exposure assessment proxy (the cumulative hours of use), and the calculated results changed from statistically insignificant ones to statistically significant ones. The same phenomenon could be observed in these recent studies with statistically insignificant results.

Another explanation is that ASIRs per 100,000 for brain tumors are extremely low that conventional case-control and cohort studies with a population size under 10,000 cannot capture the increased risk of brain tumors due to RF-EMR exposure from cellular phones with a statistical significance. As provided in Supplementary material B, the ASIRs per 100,000 for benign tumors range from 0.18 to 7.07. The ASIRs per 100,000 for malignant brain tumors range from 0.08 to 2.75. Under this extremely low ASIR per 100,000, capturing increased odds ratios or risk ratios with statistical significance could be difficult in case-control and cohort studies with a population size under 10,000.

Another alternative explanation is that the increased risk of brain tumors due to exposure to RF-EMR from cellular phones is so slight (but statistically significant) that only studies with massive populations can capture the causal relationship with statistical significance.

In consideration of these statistically insignificant results from recent cohort or large population international studies, contrasting results from many previous case-control studies, and the results of this correlation study, the author concludes that a statistically significant increased risk can be found if (i) a more accurate exposure assessment such as site-specific, time-integral of SAR for each individual is applied or (ii) massive populations over 100,000 are studied.

### 4.6. Limitations of this study

First, because of the relatively short observation period of 20 years (from 1999 to 2018), brain tumor risks due to RF-EMR exposure from cell phones could be underestimated. Most of the tumors caused by any carcinogen occur decades after exposure, and most of the burden of cancer cases is observed in individuals over 60 years of age. For this reason, 20 years observation period could be relatively short when compared to typical epidemiologic features of brain tumors (Bondy et al., 2008).

Second, this study does not consider the age of subjects as a confounding factor. However, both the age of RF-EMR exposure and the age of brain tumor diagnosis is essential when analyzing the possible tumorigenic effect of RF-EMR exposure from cell phones. These types of information were not provided by the Korea Central Cancer Registry. In later years, if these types of information become available, other essential findings can be found in analyses.

Third, this study is basically an ecological study with a population cellular phone penetration rate as the exposure of interest and the ASIR per 100,000 brain tumors as the outcome of interest. Ecological studies are prone to ecological fallacy (Piantadosi et al., 1988). Considering this limitation, four alternative hypotheses are provided in subsection 4.2. However, these hypotheses cannot explain the statistically significant correlation coefficient for malignant brain tumors (hypothesis 1) and the selective association in frontal and temporal lobes (hypothesis 2). Hypothesis 3 and 4 need more studies to be established as reliable causes.

## 5. Conclusion

In South Korea, for the correlation coefficient between cell phone subscription rate before 10 years and ASIR per 100,000, a positive correlation coefficient with a statistical significance was reported in 3 malignant brain tumors (C71.0, C71.1, and C71.2) and 3 benign brain tumors (D32, D33, and D32.0). Among these results, that for malignant brain tumors in the frontal lobe (C71.1) and in the temporal lobe (C71.2)

is suspicious of the association with RF-EMR emitted from cellular phones. The other 4 possible hypotheses do not fit well with the observed phenomena.

Statistically insignificant results from recent cohort or large population international studies and contrasting results from many previous case-control studies might come from several issues. A statistically significant increased risk can be found if (i) a more accurate exposure assessment such as site-specific, time-integral of SAR for each individual is applied or (ii) massive populations over 100,000 are studied.

## Author contribution

Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing –Review & Editing, Visualization, Supervision, Project administration: Jinyoung Moon.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

## Acknowledgements

None.

## Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.envres.2023.115657.

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Environmental Research

Volume 228, Issue , 1 July 2023, Page

DOI: https://doi.org/10.1016/j.envres.2023.115890

Environmental Research 228 (2023) 115890



Contents lists available at ScienceDirect

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# Corrigendum to "The relationship between radiofrequency-electromagnetic radiation from cell phones and brain tumor: The brain tumor incidence trends in South Korea" [Environ. Res. 226 (2023) 115657]

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The authors regret the final sentence of the abstract, "Statistically insignificant results from recent cohort and large population international studies and contrasting results from many previous case-control studies could indicate a difficulty in identifying a factor as a determinant of a disease in ecological study design.", is a wrong sentence. This sentence should be changed into the following sentence: "However, this study is an ecological study, and identifying a factor as a determinant of a disease in ecological study design could be difficult."

The authors would like to apologize for any inconvenience caused.

DOI of original article: https://doi.org/10.1016/j.envres.2023.115657.
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https://doi.org/10.1016/j.envres.2023.115890

Available online 13 April 2023
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## Update 2 of 2


## Environmental Research

**Volume 231, Issue P1, 15 August 2023, Page**

**DOI: https://doi.org/10.1016/j.envres.2023.116166**

Environmental Research 231 (2023) 116166



Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres





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The author regrets that several minus signs after an en dash were replaced with a single en dash in the published article.

(1) On page 4, the 4th line, "… -3.05 (−3.60–2.51) % to −0.30 (−0.53–0.10) % …" must be changed to "… -3.05 (−3.60 to −2.51) % to −0.30 (−0.53 to −0.10) % …".
(2) On page 4, from the 25th to 26th line, "… -0.90 (−0.96–0.75) to −0.45 (−0.74–0.01) …" must be changed to "… -0.90 (−0.96 to −0.75) to −0.45 (−0.74 to −0.01) …".
(3) On page 4, the 40th line, "… -0.94 (−0.98–0.84) to −0.51 (−0.78–0.09) …" must be changed to "… -0.94 (−0.98 to −0.84) to −0.51 (−0.78 to −0.09) …".
(4) In Table 2, the 3rd column of the 3rd row, "-0.74–0.01", must be changed to "-0.74 to −0.01".
(5) In Table 2, the 3rd column of the 6th row, "-0.78–0.06", must be changed to "-0.78 to −0.06".
(6) In Table 2, the 3rd column of the 11th row, "-0.96–0.75", must be changed to "-0.96 to −0.75".
(7) In Table 3, the 3rd column of the 3rd row, "-0.78–0.09", must be changed to "-0.78 to −0.09".
(8) In Table 3, the 3rd column of the 6th row, "-0.83–0.19", must be changed to "-0.78 to −0.19".
(9) In Table 3, the 3rd column of the 11th row, "-0.98–0.84", must be changed to "-0.98 to −0.84".

Additionally, the author regrets that "Fig. 2–" on the 12th line of the result section must be changed to "Fig. 2–2".

The author would like to apologize for any inconvenience caused.

DOI of original article: https://doi.org/10.1016/j.envres.2023.115657.
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https://doi.org/10.1016/j.envres.2023.116166

Available online 16 May 2023
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