Effects of cell phone radio-frequency radiation on the sleep outcomes: A systematic review and Meta-Analysis of randomized controlled trials

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Abstract: Sleep disorders have become an important public health issue affecting people's physical health. In recent years, the impact of mobile phone radio-frequency (RF) radiation on the outcome of sleep caused the attention of scholars. We systematically searched EMBASE, Web of Science, Cochrane Library and PubMed until November 2018. All articles on the relationship between radiofrequency radiation and sleep results from polysomnography were included. These articles were randomized controlled trials (RCT) in English only. The aim was to investigate the effects of radio frequency (RF) radiation from mobile phones on sleep outcomes. 17 RCTs, including 398 participants, met the criteria for a meta-analysis. The results showed that exposure to mobile phone radio frequency radiation had no effect on sleep staging indicators and sleep quality indicators. However, results of subgroup analysis according to the exposure frequency, publication years, and exposure time demonstrated that exposure to non-217Hz RF radiation could increase arousal-index per hour (standardized mean difference = 1.22, 95% confidence interval [0.68, 1.76]; p < 0.001). The articles published before 2000 showed that total sleep time (mean difference = 4.80, 95% confidence interval=[3.70, 5.90]; p < 0.001) had increased, whereas articles published after 2001 showed that total sleep time (mean difference = -2.56, 95% confidence interval= [-4.25, -0.87]; p = 0.003) had decreased. RF exposure before sleep could increase the time of stage 1 (mean difference = 0.91, 95% confidence interval=[0.32, 1.50]; p = 0.003). Therefore, short-term exposure to cell phone RF radiation had no impacts on people's overall sleep outcomes.

Keywords: Cell phone; RF radiation; Sleep; Meta-analysis

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1. Introduction

According to the World Health Organization (WHO), 27% of people worldwide has sleep disorders, which has become a major public health problem in the world. Many people suffered from sleep disorders such as insufficient sleep and daytime sleepiness, etc. [1, 2] Fernando AT et al. found that 37.2% subjects were suffering from sleep-phase disorders in New Zealand[3]. Falavigna A et al. found that 60 percent of people were reported sleeping problems in Southern Brazil[4]. Decreased sleep quality in adults could lead to short- and long-term detrimental health outcomes, including an increase in daily stress, impaired memory, emotional abnormalities, reduced athletic ability, reduced immunity, stunted growth, accelerated aging, and substance abuse, etc.[5-10] Therefore, good sleep quality be beneficial to prevent a range of disorders and keep health.

Sleep problems can be caused by several factors including disease status, dietary factors, mental health, and lifestyle. The number of people using mobile phones is growing year by year [11]. More and more scholars believed that radio-frequency (RF) radiation from cell phones can be an important factor affecting the quality of sleep. The potential health effects of mobile phone (MP) electromagnetic field (EMF) exposure has been identified by WHO as a high priority research area, and the health effects of prolonged exposure to RF radiation needed to be studied further[12]. Whether the use of cell phones could result in prolonged sleep latency and subsequent side effects remains unclear[13]. Several studies has found that RF radiation of a cell phone can cause sleep disorders by changing rapid-eye movement (REM) sleep[14, 15]. Some believed that exposure to RF radiation in cell phones could shorten slow wave sleep (SWS) time[16, 17] or extend the REM sleep latency[18], while others argued that RF radiation has no effects on sleep outcomes[19-23].

To sum up, the effects of cell phone RF radiation on sleep outcomes remains controversial and there be no evidence of the overall effects' evaluation. Therefore, we performed meta-analysis and systematic review to explore the impacts of mobile phone RF radiation on sleep outcomes.

2. Method

2.1. Types of participants

All subjects were non-smokers and reported to be healthy and had no sleep problems. Elimination of personal or family psychopathology, chronic illness, sleep disorders, and current history of the use of psychotropic or other medications. During the study
Chronic Diseases Prevention Review

2.2. Types of studies and interventions
Randomized controlled double-blind crossover design experiment. The control group was sham group, and the experimental group was radio frequency radiation (cell phone or analog cell phone signal) exposure group.

2.3. Search strategy
This search strategy was developed in order to identify studies which explored the association between exposure to cell phone RF and sleep outcomes. This review was conducted using PRISMA-P guidelines[24]. We conducted MeSH and keywords search using terms such as RF, sleep, and cell phone, etc. Search queries were performed on the electronic databases PubMed, EMBASE, Web of Science and the Cochrane Library. The entire search process was completed on November 17th, 2018. PubMed was searched using the following terminology: (‘cell phone’ OR ‘mobile phone’ OR ‘cellular phone’ OR ‘smart phone’ OR ‘electronic media’ OR ‘cell phone’ [MeSH Terms] OR ‘mobile equipment’ OR ‘mobile communication’ OR ‘handset’ OR ‘mobile telephone’) AND (‘RF’ OR ‘radio frequency’ OR ‘radiation’ OR ‘RF energy’) AND (‘sleep’ OR ‘sleep’ [MeSH Terms]) AND (‘randomized controlled trial’ [Publication Type] OR ‘random’ OR ‘controlled’ OR ‘trial’). The other databases were searched using similar terminologies. Specific search strategies were detailed in supplement Figure 1.

Figure 1. PRISMA Flowchart of the Searched, Identified, and Included Studies.

2.4. Inclusion and exclusion criteria
Included studies met the following criteria: (a) original double-blinded randomized controlled trials;
Chronic Diseases Prevention Review

(b) RF radiation signals generated strictly from cell phones; (c) outcomes including sleep staging and sleep quality experimented by polysomnography analyzer; (d) complete data records and (e) the study was published in English as a full-text article in journal. Excluded studies if (a) Animal experiments, (b) Non-English papers, (c) Reviews, letters or comments and (d) Incomplete data. The development of the standard was independently evaluated by two researchers (Han Zhou and Feng Zhong).

2.5. Data extraction and management

The full texts of all relevant articles were retrieved and assessed for eligibility. Two reviewers independently extracted the data, and a third reviewer was responsible for resolving the differences. Relevant data included first author's surname, year of publication, participant's country of origin, age, gender, the sample size of control and experimental groups, sleep outcomes, signal type and experimental stage. We conducted quality assessments and publication bias evaluations for all of the articles included[25]. For details, see Figure 1 and Figure 2.

2.6. Definition of indexes

Our data were all continuous variables based on the polysomnography analyzer. Polysomnography recorded electroencephalogram (EEG), electrocardiogram, electromyography, and electrooculogram to determine sleep status and sleep parameters. Exposure to RF radiation prior to nighttime sleep was classified as "RF exposure before sleep". No intermittent exposures throughout the night and discontinuous RF sequence exposure were classified as "RF exposure all night." The number of awakenings or awakening time during sleep was defined as "waking in the sleep". Short-term exposure to mobile phone RF radiation was defined as a contact time of 10 days (determined based on the experimental time included in the literature). Sleep outcomes consisted of sleep staging indexes and sleep quality indexes. The sleep staging indexes included REM sleep, SWS, stage 1, stage 2, total sleep time (TST), sleep period time (SPT). The sleep quality indexes included sleep latency, REM sleep latency, waking during sleep, movement time, arousal index (per hour).

2.7. Assessment of risk of bias

Review Manager 5.3 was used to assess the risk in our study. Authors Han Zhou, Feng Zhong, Rui Xu and Kunxiang Ding independently assessed the risk in all domains including random number generation, allocation concealment, blinding of intervention and outcome assessors, completeness of follow-up, selectivity of reporting and other potential sources of bias. The risk was assessed as low, high or unclear risk based on the Cochrane Collaboration guidelines.

2.8. Statistical analysis

We used Review Manager 5.3 for the following statistical analysis. The quality assessment tool contained seven questions about the quality assessment of the paper. Two independent reviewers assessed risk of bias using the Cochrane Collaboration's Risk of Bias Tool for RCT. The following individual domains were assessed by two investigators as either low, unclear, or high risk of bias. The research data contained continuous variables in the form of Mean ± SD. We used standardized mean difference (SMD) for the calculation when the measurement units were inconsistent and Weighted Mean Difference (WMD) if the units of measure were consistent. The Cochran Q test and I² values were used to determine the heterogeneity of the study. The model was based on

Figure 2. Risk of bias graph.
the size of $I^2$. Considering the existence of heterogeneity, when $I^2 > 50\%$, a random effects model was used, and a fixed effects model was used when $I^2 \leq 50\%$. We performed a subgroup analysis of the study of $I^2 > 25\%$[26]. After comparisons with significant heterogeneity, we made a sensitivity analysis in which one study was removed to identify the possible source of heterogeneity; the study that resulted in the greatest decrease in heterogeneity was excluded. Subgroup analyses were also performed to check for possible sources of heterogeneity attributable to the study characteristics. Review manager 5.3 was used for sensitivity, heterogeneity analyses, quality assessment and publication bias.

3. Results

3.1. Characteristics of Studies

A PRISMA flow diagram of the search results was seen in Figure 1. 17 experiments were included in this meta-analysis. Overall, studies in the meta-analysis included Germans (n = 6); Swiss (n = 7); Swedes (n = 1); Japanese (n = 1); and Australians (n = 2). The subjects in nine trials were exposed to RF radiation before going to sleep, and the others were exposed all night. A comparison of the included study characteristics was detailed in Table 1. All records of sleep outcomes were based on polysomnography.

3.2. Risk of bias in included studies

The small sample size (< 20 people) was classified as high risk[17]. Both blinding of outcome assessment not mentioned and the subjects only including males were considered to unclear risk. The risk of bias assessment for each included study was shown in Figure 2 and Figure 3. All RCTs had a low risk of bias for random sequence generation, allocation concealment, incomplete data reporting and blinding of participants and personnel. Blinding of outcomes assessment among all the articles were unclear risk because they were not mentioned in the articles. Seven studies (7 [41.2%]) had a high risk of bias for selective reporting. The other bias was unclear risk (12 [71.0%]) in 12 studies in which the subjects were only males.

3.3. Effects of RF radiation from cell phones on sleep staging indexes

Exposure to RF radiation shortened the SPT (MD, -2.28 [-3.29, -1.26]; $P < 0.001$). But, the results of the sensitivity analysis showed that the change of SPT was completely caused by one of the articles, this positive result was excluded. So, compared with the control groups, there was no statistical significance on the influences of cell phone RF radiation on sleep staging indexes (REM sleep, SWS, stage 1, stage 2, TST, SPT) in the RF radiation group, which was shown in the Figure 5.
Figure 4. Sleep quality indexes with RF radiation. Effect of cell phone RF (radio-frequency) radiation on people sleep quality indexes [Sleep latency; REM (rapid-eye-movement) sleep latency; Waking in the sleep; Movement time; Arousal index (per hour); Sleep efficiency].

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Figure 5. Sleep staging indexes with RF radiation. Effect of cell phone RF (radio-frequency) radiation on people Sleep staging indexes [REM (rapid-eye-movement) sleep; SWS (slow wave sleep); Stage 1; Stage 2; TST (total sleep time); SPT (sleep period time)].
Table 1. Characteristics of included studies

<table>
<thead>
<tr>
<th>First author and year</th>
<th>Type of study</th>
<th>Blind</th>
<th>Country</th>
<th>Age range</th>
<th>N</th>
<th>n/Gender</th>
<th>Exposure time</th>
<th>sleeping time</th>
<th>Signal type</th>
<th>Sleep Outcomes</th>
<th>Experimental stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borbély, AA. 1999 27</td>
<td>RCT</td>
<td>Double blind</td>
<td>Switzerland</td>
<td>27.3±4.2</td>
<td>24 (24-24)</td>
<td>24 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 900 MHz 1736Hz (2, 8, 217, 1736 Hz) base station-like signal</td>
<td>(1)(2)(4)(5)(8)(9)</td>
<td>4d* Two stages Interval 1 week</td>
</tr>
<tr>
<td>Danker-Hopfe, H. 2011</td>
<td>RCT</td>
<td>Double blind</td>
<td>Germany</td>
<td>25.3 ± 2.6</td>
<td>30 (30-30)</td>
<td>30 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 900 217Hz (217 Hz), Hand-set like signal WCDMA/UMTS (1966 MHz)</td>
<td>(1)(2)(3)(4)(5)(7)(8)(9)(10)(11)</td>
<td>10d* Interval 1 week</td>
</tr>
<tr>
<td>Fritzler, G. 2007</td>
<td>RCT</td>
<td>Double blind</td>
<td>Germany</td>
<td>28.3±4.1</td>
<td>20 (10-10)</td>
<td>20 males</td>
<td>All night</td>
<td>10:00/12:00-6:45</td>
<td>GSM 900 (2, 8, 217 Hz and 1736 Hz) handset-like signal</td>
<td>(1)(2)(3)(4)(5)(6)(7)(8)(9)(10)(12)</td>
<td>8d* One stages</td>
</tr>
<tr>
<td>Hinrichs, H. 2005</td>
<td>RCT</td>
<td>Double blind</td>
<td>Germany</td>
<td>20-28</td>
<td>13 (13-13)</td>
<td>12 females 1 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 1800 (Far-field characteristic, 1736 Hz pulse frequency) Base station like signal</td>
<td>(1)(2)(3)(4)(6)(7)(8)(9)(10)(11)</td>
<td>5d* One stages</td>
</tr>
<tr>
<td>Huber, R. 2000</td>
<td>RCT</td>
<td>Double blind</td>
<td>Switzerland</td>
<td>20-25</td>
<td>16 (16-16)</td>
<td>16 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 900 1736Hz (2, 8, 217, 1736 Hz) base station-like signal GSM900 2,8,217,1736 Hz (Non-modulated continuous wave and pulse-modulated signal) handset-like signal</td>
<td>(1)(2)(3)(4)(5)(6)(8)(9)(10)</td>
<td>6d* Three stages Interval 1 week</td>
</tr>
<tr>
<td>Huber, R. 2002</td>
<td>RCT</td>
<td>Double blind</td>
<td>Switzerland</td>
<td>20-25</td>
<td>16 (16-16)</td>
<td>16 males</td>
<td>Before sleep</td>
<td>23:00-7:00</td>
<td>GSM900 2,884 MHz/1736Hz (2,8,217 Hz and 1736 Hz) handset-like signal</td>
<td>(1)(2)(3)(4)(5)(6)(9)(10)</td>
<td>4d* Two stages Interval 1 week</td>
</tr>
<tr>
<td>Loughran, SP. 2005</td>
<td>RCT</td>
<td>Double blind</td>
<td>Australia</td>
<td>27.9 ± 7.9</td>
<td>50 (50-50)</td>
<td>23 females 27 males</td>
<td>Before sleep</td>
<td>22:30-6:00</td>
<td>GSM900 217 Hz Handset-like signal</td>
<td>(1)(2)(3)(5)(7)(8)(9)(10)(11)</td>
<td>4d* Two stages Interval 1 week</td>
</tr>
<tr>
<td>Loughran, SP. 2012</td>
<td>RCT</td>
<td>Double blind</td>
<td>Australia</td>
<td>27.9 ± 6.5</td>
<td>20 (20-20)</td>
<td>13 females 7 males</td>
<td>Before sleep</td>
<td>22:00-6:00</td>
<td>GSM 894.6 217 Hz Handset-like signal</td>
<td>(1)(3)(7)(10)(12)</td>
<td>3d* One stages</td>
</tr>
<tr>
<td>Lowden, A. 2011</td>
<td>RCT</td>
<td>Double blind</td>
<td>Sweden</td>
<td>18-44</td>
<td>48 (48-48)</td>
<td>27 females 21 males</td>
<td>Before sleep</td>
<td>23:30-6:30</td>
<td>GSM 884 MHz/1736Hz (2,8,217 Hz and 1736 Hz) handset-like signal</td>
<td>(2)(4)(7)(8)(9)(10)(11)(12)</td>
<td>2d* Two stages Interval 1 week</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Study Authors</th>
<th>Design</th>
<th>Country</th>
<th>Mean ± SD</th>
<th>Gender</th>
<th>Time Period</th>
<th>RF Frequency</th>
<th>Modulation</th>
<th>Duration</th>
<th>Stages</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lustenberger, C.</td>
<td>RCT</td>
<td>Switzerland</td>
<td>23.3 ± 0.5</td>
<td>19 males</td>
<td>Before sleep</td>
<td>10:50-6:50/11:40-7:40</td>
<td>GSM 900 Hz (Modulation 2 Hz, 8 Hz and harmonics o20 Hz)</td>
<td>4d*</td>
<td>Two stages Interval 1 week</td>
<td></td>
</tr>
<tr>
<td>Mann, K.</td>
<td>RCT</td>
<td>Germany</td>
<td>27.3 ± 4.2</td>
<td>12 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 900 Hz 217 Hz Handset-like signal</td>
<td>3d*</td>
<td>One stages</td>
<td></td>
</tr>
<tr>
<td>Nakatani, S.</td>
<td>RCT</td>
<td>Japan</td>
<td>30.6 ± 6.1</td>
<td>19 females</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>WCDMA 1950 MHz</td>
<td>3d*</td>
<td>One stages</td>
<td></td>
</tr>
<tr>
<td>Regel, SJ.</td>
<td>RCT</td>
<td>Switzerland</td>
<td>22.4 ± 0.4</td>
<td>15 males</td>
<td>Before sleep</td>
<td>23:00-7:00</td>
<td>GSM 900 MHz 1736 Hz (2, 217, 1736 Hz) base station-like signal</td>
<td>6d*</td>
<td>Three stages Interval 1 week</td>
<td></td>
</tr>
<tr>
<td>Schmid, MR.</td>
<td>RCT</td>
<td>Switzerland</td>
<td>23.2 ± 0.4</td>
<td>25 males</td>
<td>Before sleep</td>
<td>22:40-6:40/23:20-7:20</td>
<td>GSM 900 MHz 2, 8, 14 or 217 Hz</td>
<td>6d*</td>
<td>Two stages Interval 1 week</td>
<td></td>
</tr>
<tr>
<td>Schmid, MR.</td>
<td>RCT</td>
<td>Switzerland</td>
<td>23.0 ± 3.0</td>
<td>29 males</td>
<td>Before sleep</td>
<td>22:40-6:40/23:20-7:20</td>
<td>1) Magnetic field (2Hz pulsed) 2) RF 900 MHz (Modulation 2 Hz, 8 Hz and harmonics o20 Hz)</td>
<td>6d*</td>
<td>Two stages Interval 1 week</td>
<td></td>
</tr>
<tr>
<td>Wagner, P.</td>
<td>RCT</td>
<td>Germany</td>
<td>18-37</td>
<td>22 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 900 Hz 217 Hz Handset-like signal</td>
<td>3d*</td>
<td>One stages</td>
<td></td>
</tr>
<tr>
<td>Wagner, P.</td>
<td>RCT</td>
<td>Germany</td>
<td>20.0 ± 4.0</td>
<td>20 males</td>
<td>All night</td>
<td>23:00-7:00</td>
<td>GSM 900 Hz 217 Hz Handset-like signal</td>
<td>3d*</td>
<td>Three stages Interval 1 week</td>
<td></td>
</tr>
</tbody>
</table>

Data presented as mean ± standard deviation. RCT, Randomized Controlled Trial; N, sample size; GSM, Global System for Mobile communication.
Note: (1) sleep latency (2) REM sleep (3) REM sleep latency (4) waking in the sleep (5) slow-wave sleep (6) movement time (7) sleep efficiency (8) stage 1 (9) stage 2 (10) TST (11) SPT (12) Arousal index (per hour)
*The actual time of the experiment

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### Table 2. Effects by subgroup analysis

<table>
<thead>
<tr>
<th>Project</th>
<th>Indexes</th>
<th>Subgroups</th>
<th>No. of studies/Sample</th>
<th>SMD or MD (95% CI)</th>
<th>I² (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep quality indexes</td>
<td>Sleep latency</td>
<td>The sample content ≥25 persons</td>
<td>4/134</td>
<td>0.20 (-0.04, 0.44)</td>
<td>0</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The sample content &lt;25 persons</td>
<td>12/206</td>
<td>0.18 (-0.24, 0.60)</td>
<td>77</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>REM sleep latency</td>
<td>The Germany people</td>
<td>6/107</td>
<td>3.02 (-1.62, 7.67)</td>
<td>0</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not the Germany people</td>
<td>11/279</td>
<td>1.02 (-1.77, 3.82)</td>
<td>89</td>
<td>0.47</td>
</tr>
<tr>
<td>Waking in the sleep</td>
<td>With subjects over 35 years of age</td>
<td></td>
<td>3/90</td>
<td>-0.06 (-0.36, 0.23)</td>
<td>0</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Without subjects over 35 years of age</td>
<td></td>
<td>10/209</td>
<td>0.03 (-0.72, 0.78)</td>
<td>92</td>
<td>0.94</td>
</tr>
<tr>
<td>Movement time</td>
<td>Pulse-modulated</td>
<td></td>
<td>2/29</td>
<td>-0.19 (-0.71, 0.33)</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Non-pulse-modulated</td>
<td></td>
<td>5/107</td>
<td>-0.35 (-1.03, 0.33)</td>
<td>83</td>
<td>0.32</td>
</tr>
<tr>
<td>Arousal index (per hour)</td>
<td>217 Hz</td>
<td></td>
<td>4/128</td>
<td>0.16 (-0.30, 0.63)</td>
<td>67</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Non-217 Hz</td>
<td></td>
<td>2/32</td>
<td>1.22 (0.68, 1.76)</td>
<td>0</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sleep efficiency</td>
<td>GSM 900</td>
<td></td>
<td>8/196</td>
<td>-0.12 (-0.28, 0.04)</td>
<td>0</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>No GSM 900</td>
<td></td>
<td>4/100</td>
<td>-0.31 (-1.19, 0.57)</td>
<td>88</td>
<td>0.49</td>
</tr>
<tr>
<td>Sleep staging indexes</td>
<td>REM sleep</td>
<td>With subjects over 35 years of age</td>
<td>5/150</td>
<td>-0.17 (-0.40, 0.06)</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Without subjects over 35 years of age</td>
<td></td>
<td>10/197</td>
<td>-0.39 (-1.11, 0.33)</td>
<td>91</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>SWS</td>
<td>Not had subgroup analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1</td>
<td>RF exposure before sleep</td>
<td></td>
<td>3/114</td>
<td>0.32 (0.05, 0.60)</td>
<td>7</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>RF exposure all night</td>
<td></td>
<td>7/131</td>
<td>-0.01 (-0.41, 0.38)</td>
<td>59</td>
<td>0.94</td>
</tr>
<tr>
<td>Stage 2</td>
<td>The Germany people</td>
<td></td>
<td>6/107</td>
<td>0.06 (-0.21, 0.33)</td>
<td>0</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Not the Germany people</td>
<td></td>
<td>8/221</td>
<td>0.48 (-0.16, 1.13)</td>
<td>90</td>
<td>0.14</td>
</tr>
<tr>
<td>TST</td>
<td>Article before 2000</td>
<td></td>
<td>5/94</td>
<td>4.80 (3.70, 5.90)</td>
<td>0</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Article after 2001</td>
<td></td>
<td>9/244</td>
<td>-2.56 (-4.25, -0.87)</td>
<td>76</td>
<td>0.003</td>
</tr>
<tr>
<td>SPT</td>
<td></td>
<td>Not had subgroup analysis</td>
<td></td>
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Subgroup analysis results showed that the effectiveness of exposure RF radiation for sleep outcomes was significant for both the articles published before 2000 and the articles published after 2001. Stage 1 time (RF radiation before sleep) was extended in the RF radiation group (MD, 0.91 [0.32, 1.50]; P = 0.003). No statistically significant differences were found in RF radiation in all night subgroups. Additionally, no statistically significant differences in REM sleep (with subjects over 35 years of age or without subjects over 35 years of age) and stage 2 (RF radiation exposure is before sleep or all night) were found. Details are shown in Table 2.

3.4. Effects of RF radiation on sleep quality indexes

The exposure to the cell phone RF radiation revealed no significant effects on sleep quality indexes including sleep latency, REM sleep latency, waking during sleep, movement time, arousal index (per hour), and sleep efficiency. The details could be seen in Figure 4. Subgroup analysis indicated that the non-217Hz RF could increase arousal index (per hour) (SMD, 1.22 [0.68, 1.76]; P < 0.001). The 217Hz RF had no significant impact on arousal index (per hour). In the other subgroups, no significant difference was found between experiments groups and control groups.

4. Discussion

Our research provided evidence that short-term exposure to cell phone RF radiation had no impacts on people's sleep outcomes (including sleep staging indexes and sleep quality indexes). In previous studies, many results had shown that cell phone RF exposure had effects on sleep outcomes, but whether the effects were harmful to the body remained unclear. For example, some researchers had found that prolonged RF radiation could change SWS time and stage 2[16, 17], or minimized frequency of waking during sleep[27]. In addition, exposure to RF radiation could reduce the REM sleep latency[28, 29]. Others believed that exposure to RF radiation could prolong REM sleep latency[18]. However, there were also many other studies which showed that RF radiation had no effects on sleep outcomes[19-23]. An one-year cohort study by Evelyn Mohler showed that RF-EMF exposure in the environment (including cell phones) had no effects on sleep quality[30]. Therefore, it was important to analyze these studies, and our findings provide a comprehensive analysis of the results of all RCT trials.

In general, global system for mobile communications (GSM) cell phone generates 217Hz electromagnetic field. In other cases, GSM cell phone also generates magnetic field of other frequencies such as low-frequency radios or high-frequency radios. Pall's research showed that low frequency RF could cause a wide range of changes in the nervous system, resulting in a variety of mental symptoms or nerve dysfunction including sleep disorders[31, 32]. Our analysis had shown that the non-217Hz RF could increase the arousal index (per hour). Pall's research was supported by the non-217Hz subgroup containing low-frequency radios such as 2, 4, and 8Hz in our results. In addition, Huber[33, 34] found that pulsed RF EMF could alter the awake and sleep state of EEG. As mentioned above, the equipments and frequencies used in different experiments were different. The operating frequencies of cell phones such as 217Hz RF radiation could affect the level of electromagnetic absorption of the human brain[35]. However, the overall results mask this effect because of all radiation at frequencies incorporated in our study. Therefore, we believe that non-217Hz frequency radio frequencies may reduce sleep quality.

Our data suggest that the cell phone RF radiation could increase TST in the articles published before 2000 (MD: 4.80). And cell phone RF radiation could decrease TST in the articles published after 2001 (MD: -2.56). The reason may be the difference in results caused by changes in mobile communication networks. Around 2000, cell phone communication had changed from a 2G network to a 3G network, and its frequency and mode of occurrence had also changed. Today, 4G and 5G networks were gradually evolving, however relevant research data was lack. Moreover, it was a common phenomenon for people to use cell phones before going to bed, which will inevitably lose sleep time[36]. Therefore, we could only think that this result may be related to the change of mobile communication technology and cell phone user's habit. Some research had shown that insufficient sleep was associated with decreased alertness and impairment of cognitive ability[37]. In addition, sufficient sleep could improve sustained attention and reduce sleep pressure. So, the shortening of the TST time caused by the RF radiation from cell phones should also attract people's attention.

Finally, stage 1 represents the stage before the sleep begins, which means that using the phone before going to bed could cause a delay in sleep. We believed that RF radiation may affect stage1 by stimulating the brain nervous system. Indeed, in the current study, the exposure time and the process of "exposure to cell phone RF radiation" in different experiments were quite different. One possible explanation was that the effects was not constant and ever changing throughout the night, so the level of significance may not always be reached, especially considering individual differences in response. So, the result of "RF exposure all night" was not
The effects of radiofrequency radiation from cell phones on sleep outcomes were influenced by many other factors. For example, we suspect that the prolonged use of a cell phone may lead to changes in sleep habits. During a short period of time, subjects may not be able to effectively adjust their sleep habits when exposed to cellular RF radiation, which resulted in differences in outcomes. However, there was currently no relevant placebo-controlled study, so further research was needed. Equipment and RF frequencies used in the experiment were not exactly the same. Some researchers used GSM 900 or GSM 1800, some used 217Hz RF or not. Some studies used pulse-modulated RF, others used hand base signals. Research showed that when the distance between the brain and the RF radiation point was 40cm[17], the REM sleep was extended, and when the distance was 3 meters[22], the influence disappears. In the studies that we included, the distance between the radiation points and the brain was not identical. So, this distance may also be a potential factor affecting sleep outcomes.

The results of this study were meaningful. Above all, all experiments included were double-blind, randomized controlled studies. Although meta-analysis found significant heterogeneity between studies, further sensitivity analyses and publication bias tests favored the coherence effects among different populations. Next, the experiments conducted in different countries and regions followed the same design method. Thirdly, polyvsonography analyzer was used to objectively record sleep outcome indicators. Therefore, we had reason to believe that at least the overall role of the radio band (short-time) included in this study does not had much impacts on human sleep. These results were important in guiding the current assessment of evidences and the formulation of public health strategies.

We analyzed the overall results of previous studies through systematic quality assessments for the first time and concluded from the subgroup that different RF exposure times and frequencies may had impacts on total sleep time, number of awakenings during sleep, and time to fall asleep. However, our analysis still had some limitations. First, the results of the data assessment were a synthesis of the results contained only in our study. Second, the research project did not involve the use of the screen blue light of cell phones on the quality of sleep, because they were not within the evaluation range. Third, although our studies were all RCT studies, the confusion and bias could not be completely avoided. Finally, all studies were from developed countries, we do not know the specific situations in developing countries. Even so, the study could serve as a guide for the use of cell phones to encourage young people to appropriately reduce the use of cell phones, and ensure adequate sleep. At present, experimental data on the effects of long-term radiofrequency radiation on sleep are lacking. No one has done research on the susceptibility of sleep disturbance caused by RF radiation, which may be the future research directions.

5. Conclusions
In this meta-analysis, there was no statistically significant association between RF exposure and sleep outcomes. Therefore, at least in our study, we believe that short-term exposure to mobile phone RF radiation had no effects on sleep outcomes. However, considering the impact of mobile phone usage time and non-RF radiation factors on sleep, we recommend to rationalize the use of mobile phones and develop good sleep hygiene habits.

Author Contributions
The abstracts of citations obtained from the primary broad search were read independently by reviewers Han Zhou, Feng Zhong, Rui Xu, Cuiping Liu and Kunxiang Ding to identify potentially eligible studies. Full-text articles of these studies were obtained and assessed for eligibility by reviewers Han Zhou, Feng Zhong, and Rui Xu independently, using the predefined eligibility criteria. Differences in opinion were resolved by panel discussion to reach a consistent result. To avoid duplication of data, care was taken to ensure that multiple publications of the same study were excluded.

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References


