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Effects of mobile phone usage on sperm quality – No time-dependent relationship on usage: A systematic review and updated meta-analysis

Sungjoon Kim [a,1], Donghyun Han [a,1], Jiwoo Ryu [a,1], Kihun Kim [b,2,**], Yun Hak Kim [c,d,e,2,*]

[a] Department of Medicine, School of Medicine, Pusan National University, 50612, Yangsan, Republic of Korea
[b] Department of Occupational and Environmental Medicine, Kosin University Gospel Hospital, 49267, Busan, Republic of Korea
[c] Department of Anatomy, School of Medicine, Pusan National University, 50612, Yangsan, Republic of Korea
[d] Department of Biomedical Informatics, School of Medicine, Pusan National University, 50612, Yangsan, Republic of Korea
[e] Biomedical Research Institute, Pusan National University Hospital, Republic of Korea

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ABSTRACT

Background: Mobile phones emit radiofrequency (RF) electromagnetic waves (EMWs), a low-level RF that can be absorbed by the human body and exert potential adverse effects on the brain, heart, endocrine system, and reproductive function. Owing to the novel findings of numerous studies published since 2012 regarding the effect of mobile phone use on sperm quality, we conducted a systematic review and updated meta-analysis to determine whether the exposure to RF-EMWs affects human sperm quality.

Methods: This study was conducted in accordance with the PRISMA guidelines. The outcome measures depicting sperm quality were motility, viability, and concentration, which are the most frequently used parameters in clinical settings to assess fertility.

Results: We evaluated 18 studies that included 4280 samples. Exposure to mobile phones is associated with reduced sperm motility, viability, and concentration. The decrease in sperm quality after RF-EMW exposure was not significant, even when the mobile phone usage increased. This finding was consistent across experimental *in vitro* and observational *in vivo* studies.

Discussion: Accumulated data from *in vivo* studies show that mobile phone usage is harmful to sperm quality. Additional studies are needed to determine the effect of the exposure to EMWs from new mobile phone models used in the present digital environment.

1. Introduction

Globalization and modernization have made humankind excessively dependent on electronic gadgets on a day-to-day basis (Malini, 2017a). Cell phones are widely used among all age groups, and people spend long hours on their cell phones for different purposes (Al-Bayyari, 2017a; Ding et al., 2018b). The smartphone penetration rate in most developed countries has exceeded 80%; in Korea, this rate reached approximately 95% in 2019 (Statista, 2021, Feb 11; Statista, 2021, Mar 5). Phones emit radiofrequency-electromagnetic waves (RF-EMWs), a low-level RF between 800 and 2200 MHz that can be absorbed by the human body and have potential adverse effects on the brain, heart, endocrine system, and reproductive function (Al-Bayyari, 2017a). Currently, the association between mobile phone use and the risk of development of several cancers, including childhood cancer, has not been clearly established (Benson et al., 2013; Cardis et al., 2007, 2011; Frei et al., 2011; Grell et al., 2016; Group, 2010; Johansen et al., 2001; Larjavaara et al., 2011; Schoemaker et al., 2005; Schüz et al., 2006). A recent systemic review reported that long-term cell phone use for more than 10 years might increase the risk of brain tumor (Prasad et al., 2017).

Some reports have shown that the count, vitality, and motility of sperm decreases significantly upon exposure to RF-EMWs emitted by cell phones (Agarwal et al., 2008, 2009; Ding et al., 2018b). RF-EMWs

* Corresponding author. Department of Anatomy and Department of Biomedical Informatics, School of Medicine, Pusan National University, Yangsan, 50612, Republic of Korea.
** Corresponding author.
E-mail addresses: kihun7603@naver.com (K. Kim), yunhak10510@pusan.ac.kr (Y.H. Kim).
[1] Sungjoon Kim, Donghyun Han, and Jiwoo Ryu equally contributed to this study.
[2] KK and YHK equally contributed to this study.

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Table 1
Study characteristics for the meta-analysis of mobile phone exposure and sperm quality (- denotes information not provided).

Sperm parameters										
References	Sample size	Study design	Participant group	[a]M	[b]V	[c]C	Radiofrequency (MHz)	SAR (W/kg)	Exposure time	Comments
Agarwal et al. (2008)	361	*In vivo*	Fertility clinic	✓	✓	✓	–	–	2 h, 4 h	Exposed to commercially available mobile phones
Agarwal et al. (2009)	64	*In vitro*	Fertility clinic	✓	✓	✓	850	1.46	60 min	Exposed to Sony Ericsson w300i
Ahmed and Baig (2011)	44	*In vitro*	Population	✓			900	1.3	60 min	Exposed to Nokia 112 in talk mode
Al-Bayyari N. (2017)	159	*In vivo*	Fertility clinic	✓		✓	800–2202	–	1 h	Exposed to commercially available mobile phones/Exclude 3 non-users in Sample counting on "effect of time spent in calling and receiving"
De Iuliis et al. (2009)	8	*In vitro*	Population	✓	✓		1800	1	16 h	Exposed using a waveguide connected to a function generator and RF amplifier
Ding S. -S. et al. (2018)	270	*In vivo*	Fertility clinic	✓	✓	✓	1800	–	30 min, 120 min	Exposed to commercially available mobile phones with 2.45 GHz Wi-Fi
Dkhil et al. (2011)	40	*In vitro*	Population		✓		850	1.46	60 min	Nokia 73 in talk mode
Erogul et al. (2006)	54 (27)	*In vitro*	Population	✓		✓	900	–	25 min	Exposed to commercially available mobile phones
Falzone et al. (2008)	24	*In vitro*	Population	✓			900	2	60 min	RF-EMW chamber
Fejes ef al. (2005)	254	*In vivo*	Fertility clinic	✓		✓	–	–	–	Exposed to commercially available mobile phones
Kaya C. et al. (2020)	1311	*In vivo*	Fertility clinic	✓		✓	–	–	10 year	Exposed to commercially available mobile phones
Malini S.S. (2017)	50	*In vivo*	Population	✓		✓	–	–	1–5 h, 6–10 h	–
Rago R. et al. (2013)	63	*In vivo*	Population	✓		✓	–	–	2 h, 4 h	Exposed to commercially available mobile phones
Sajeda and Al-Watter (2011)	300	*In vivo*	Fertility clinic	✓		✓	–	–	–	Exposed to commercially available mobile phones
Veerachari S.B. et al. (2012)	20	*In vitro*	Population	✓	✓	✓	900	–	1 h	Exposed to commercially available mobile phones
Wdowiak A. et al. (2018)	103	*In vitro*	Population	✓			0.42 (0.417)	–	3 h, 12 h, 24 h	Did not use mobile phone; Used generator/ Viability only checked after 3 h of exposure
Yildirim M.E. et al. (2015)	1031	*In vivo*	Population			✓	850–1800	–	30 min, 2 h	–
Zalata A. et al. (2015)	124	*In vitro*	Fertility clinic	✓			850	1.6	1 h	–

[a] M: Motility.
[b] V: Viability.
[c] C: Concentration.

not only reduce motility and vitality by enhancing reactive oxygen species production in human spermatozoa, but also induce DNA fragmentation through the stimulation of DNA base adduct formation (De Iuliis et al., 2009). DNA fragmentation could lead to adverse effects, such as decreased fertility, increased miscarriage rates, and fetal complications (Aitken et al., 2009; Evenson and Wixon, 2006). In particular, among several cell types, human spermatozoa are more susceptible to oxidative stress, which can be particularly sensitive to the effects of RF-EMRs (De Iuliis et al., 2009). RF-EMRs might also affect the activity of kinases in the sperm cell cycle, leading to mitochondrial apoptosis, as well as chromosomal damage and genomic instability (Kesari and Behari, 2010, 2012; Luzhna et al., 2013). In addition to the adverse effects on human cells, RF-EMRs induce hormonal changes in the testis, reducing the number of spermatogenic cells (Fejes et al., 2005). Although several studies have revealed the negative outcomes of using RF-EMWs, the effects of EMWs on the body remain controversial.

Several studies have assessed the relationship between sperm quality and EMWs (Agarwal et al., 2009; Dkhil et al., 2011; Falzone et al., 2008). A previous meta-analysis from 2011 evaluated the reductions in mobility, viability, and concentration of sperm; however, these effects were analyzed based on the presence or absence of exposure in the included studies (Adams et al., 2014). However, it is assumed that there are few people who do not use mobile phones in developed countries. As the use of mobile phones has become more common, recently published papers have carried out analyses according to mobile phone usage (Kaya et al., 2020; Rago et al., 2013; Zalata et al., 2015). Therefore, it is necessary to evaluate the effect of sperm quality according to the duration of use, rather than mobile phone usage, to reflect the current situation in more detail. As subgroup analysis in previous studies, including both *in vitro* and *in vivo* studies, had high heterogeneity (I^2), a re-analysis is warranted. Therefore, we overcame the limitations of the existing meta-analyses by performing a novel subgroup analysis and including recently published studies to present more refined results.

2. Methods

2.1. Search strategy

We conducted a systematic search using Embase to identify all relevant studies published between 2012 and 2021 (performed on January 28, 2021). The study protocol is registered with PROSPERO (Registration no: CRD 42021241963). We used all combinations of the following keywords: [semen, sperm*, steril*, fertil*, azoospermia, oligospermia] and [cell phone, cellular phone, mobile phone, handphone, hand phone, electromagnetic, frequency]. We limited the search to studies that included human subjects and to those that have been published (not in press). Studies that reported information on basic semen parameters, including motility, viability, and concentration, were

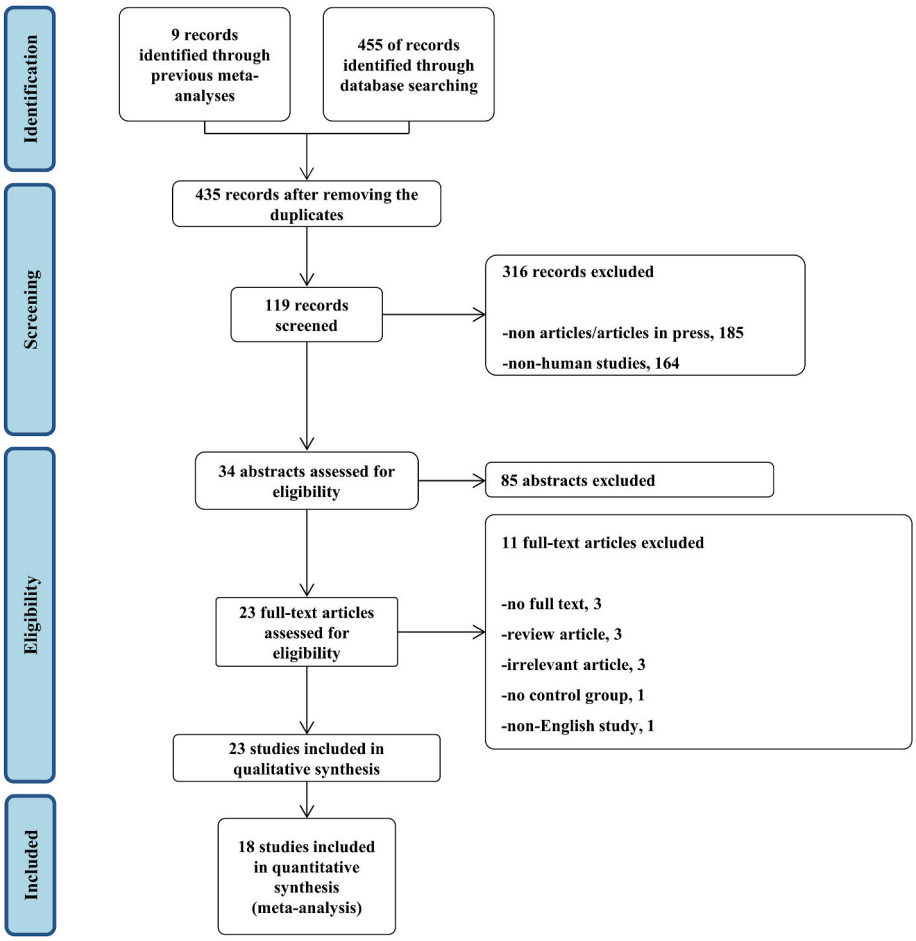


Fig. 1. PRISMA flowchart.

included. The units of measurement used for motility, viability, and concentration were %, %, and 10^6/mL, respectively. Review articles and reference lists were manually searched.

2.2. Eligibility

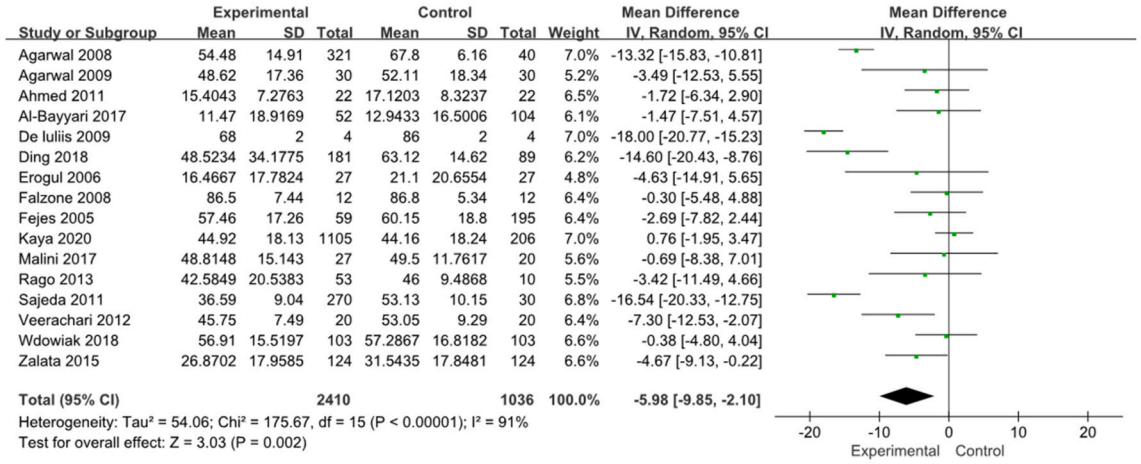
Papers with unpublished or incomplete datasets were excluded. Articles were only included if: they were written in English, reported results regarding human participants, and were not review articles. We incorporated both *in vitro* and *in vivo* studies, provided that they met our inclusion criteria. We adhered to the PRISMA guidelines and provide the PRISMA checklist in the Supporting Information. The literature search was conducted independently by three authors (KS, HD, and RJ) and the title and abstract of each study were checked thoroughly. The full-text articles were reviewed by the same authors to decide on their inclusion. Any disagreements were resolved through discussion.

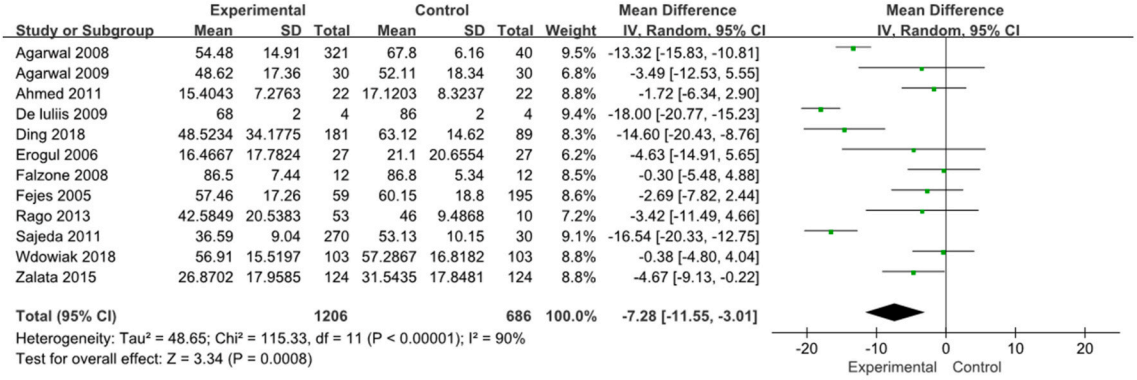
2.3. Analysis

Statistical analysis was performed using Review Manager (RevMan, version 5.4, The Cochrane Collaboration, 2020). Statistical heterogeneity among the studies was examined using I^2 statistics. Random effects model (REM) was selected when the I^2 value was higher than 50%, and the fixed effects model (FEM) was selected when the I^2 value was lower than 50% (Higgins and Thompson, 2002). The mean differences (MD) between the experimental and control groups were calculated to determine the size of the effect. Forest plots were drawn to clearly visualize synthesized risk. We also conducted a subgroup analysis depending on whether the study was conducted *in vivo* or *in vitro*, whether the group of participants was from a fertility clinic or population study, whether the exposure time lasted more than 4 h, and whether the phone storage location was the trousers or not. We also compared and analyzed the MD values for groups in which the control group was non-exposed and less exposed. A funnel plot was used to visually assess the publication bias (Supplementary Fig. 1).

3. Results

A total of 119 articles were identified from the titles using the inclusion criteria. Upon reading the abstract of these papers, this number was reduced to 34 papers. Thereafter, this number was further reduced to 23 potentially suitable articles, following the exclusion of review articles, no full-text, irrelevant articles, no control group, and non-English studies. Finally, 18 studies fulfilled all inclusion criteria and were included in the meta-analysis (Table 1 and Fig. 1) (Agarwal et al., 2008, 2009; Ahmad and Baig, 2011; Al-Bayyari, 2017b; De Iuliis et al., 2009; Ding et al., 2018a; Dkhil et al., 2011; Erogul et al., 2006; Falzone et al., 2008; Fejes et al., 2005; Kaya et al., 2020; Malini, 2017b; Rago et al., 2013; Sajeda and Al-Watter, 2011; Veerachari and Vasan, 2012; Wdowiak et al., 2018; Yildirim et al., 2015; Zalata et al., 2015). Nine studies from a previous meta-analysis and nine new studies that included 4280 samples were used for analysis. One conference paper included in the previous study was excluded. The sperm quality parameters established in each paper varied and were subjected to a meta-analysis; 16 papers provided data on sperm motility, 6 provided data on sperm viability, and 12 provided data on sperm concentration. All *in vitro* studies were experimental, whereas all *in vivo* studies were observational. We identified the MD values of the entire 4280 samples





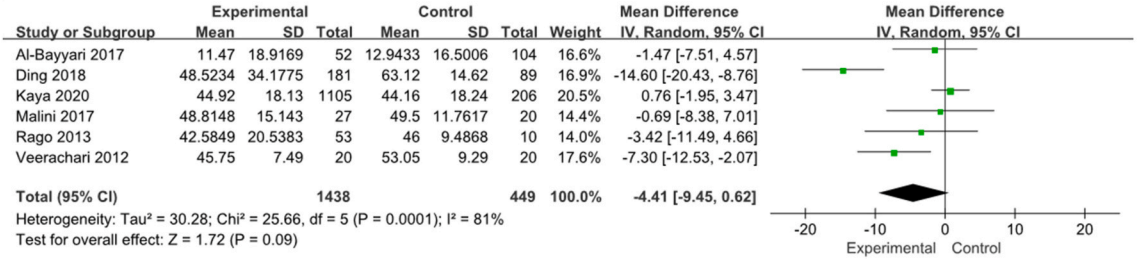


Fig. 2. A. Forest plot depicting the overall effect of the exposure to mobile phones on human sperm. Fig. 2B. Subgroup analysis of the effect of chronic exposure to mobile phones on human sperm (exposure vs. non-exposure). Fig. 2C. Subgroup analysis of the effect of chronic exposure to mobile phones on human sperm (more exposure vs. less exposure).

and analyzed the MD values of each group after classifying them according to four criteria: control group setting (non-exposure vs. less exposure), study design (*in vivo* and *in vitro*), participant group (fertility clinic and population), and storage location (trousers or not).

3.1. Motility

Sixteen studies with 3446 samples were included for the motility analysis (Fig. 2A). The mean total motility (%) ranged from 11.47% to 86.8%. Twelve studies reported that mobile phone exposure had a significant negative effect on human sperm motility (Fig. 2A, $I^2 = 89\%$, MD $= -6.67$, 95% CI: -10.37 to -2.97). In the subgroup analysis classified by the control group setting, 12 studies were included in the non-exposure control group, with a total of 1892 samples (Fig. 2B). The mean total motility (%) ranged from 26.87% to 86.8% in the included studies. For the MD of motility in this subgroup, phone exposure was found to significantly decrease motility (Fig. 2B, $I^2 = 89\%$, MD $= -8.12$, 95% CI: -12.27 to -3.97). However, the MD of motility between the less- and more-exposure groups (1887 samples) was lower than that found in other motility analyses (Fig. 2C, $I^2 = 75\%$, MD $= -4.60$, 95% CI: -9.37 to 0.18). The subgroup analysis results according to the study design, participant group, and storage location are shown in Table 2 and Supplementary Fig. 2.

Table 2
Subgroup analyses of sperm motility, viability, and concentration.

Subgroup analyses	Subgroup	Number of studies (k)	Mean difference, (95% CI)	I^2 (%)	Statistical model
Motility					
Control group setting	Non-exposure	12	−8.12 [-12.27, −3.97]	89	REM
	Less exposure	6	−4.60 [-9.37, 0.18]	75	REM
Study design	*In vivo* groups	8	−6.84 [-12.06, −1.63]	90	REM
	In vitro groups	8	−6.50 [-12.37, −0.63]	91	REM
Participant group	Fertility clinic	8	−7.24 [-12.13, −2.35]	90	REM
	Population	8	−6.06 [-12.40, 0.27]	91	REM
Storage location	Trouser pocket	2	−6.74 [-13.86, 0.37]	0	FEM
Viability					
Control group setting	Non-exposure	4	−12.10 [-22.47, −1.74]	98	REM
	Less exposure	2	−10.19 [-23.18, 2.79]	96	REM
Study design	*In vivo* groups	2	−14.92 [-17.13, −12.71]	29	FEM
	In vitro groups	4	−9.47 [-19.71, 0.77]	98	REM
Participant group	Fertility clinic	3	−13.39 [-17.72, −9.07]	69	REM
	Population	3	−10.33 [-22.66, 1.99]	99	REM
Concentration					
Control group setting	Non-exposure	7	−7.30 [-15.03, 0.43]	94	REM
	Less exposure	4	−3.58 [-11.67, 4.51]	94	REM
Study design	*In vivo* groups	8	−7.07 [-12.00, −2.13]	96	REM
	In vitro groups	3	−0.39 [-8.54, 7.77]	0	FEM
Participant group	Fertility clinic	6	−8.36 [-13.87, −2.85]	94	REM
	Population	5	−1.60 [-3.07, −0.14]	0	FEM
Storage location	Trouser pocket	2	−0.45 [-3.39, 2.49]	0	FEM

3.2. Viability

Six studies with 783 samples were analyzed for viability, and all six papers revealed a negative relationship between the mobile phone use and semen viability. The range of mean viability (%) obtained was 51.3%–89% in all included studies. Further, viability was found to be reduced in all included studies (Fig. 3A, $I^2 = 90\%$, MD = −11.47, 95% Cl: −18.8 to −4.07). Subgroup analyses of viability were conducted in the same manner as those of motility. Four studies were included in the non-exposure control group, with a total of 473 samples. The mean viability (%) ranged from 52.33% to 89%, and the MD decreased significantly in this subgroup (Fig. 3B, $I^2 = 89\%$, MD = −12.10, 95% Cl: −22.47 to −1.74). In the less-exposed control group, two studies were included, with 310 semen samples. The mean viability (%) ranged from 47.7% to 65.37%, and the MD was −10.19 (Fig. 3C, $I^2 = 75\%$, 95% Cl: −23.18 to 2.79). The results of subgroup analysis according to the study design, participant group, and storage location are shown in Table 2 and Supplementary Fig. 3.

3.3. Concentration

Twelve studies including 3796 samples were selected for this analysis. The range of mean sperm concentration (10^6/mL) was 12.84%–85.89%. The overall MD for concentration was −5.94 (Fig. 4A, $I^2 = 94\%$, 95% Cl: −10.41 to −1.48). In the subgroup analysis, seven studies were included in the non-exposure control group, with a total of 2127 samples. The range of mean viability (%) was 12.98%–85.89%, and the MD value was −7.30 (Fig. 4B, $I^2 = 94\%$, 95% Cl: −15.03 to 0.43). In the less-exposed control group, four studies were included with 1668 semen samples. The mean viability (%) ranged from 12.84% to 50.65%, and the MD was likely to decrease (Fig. 4C, $I^2 = 94\%$, MD = −3.58, 95% Cl: −11.67 to 45.1). The results of subgroup analysis according to the study design, participant group, and storage location are shown in Table 2 and Supplementary Fig. 4.

4. Discussion

Recently, an increasing number of people have become cell phone owners. Hence, assessment of the effect of phone use on semen quality has increased. In a meta-analysis conducted in 2011, the overall effect of cell phone use was summarized from 10 articles and approximately 1500 samples (Adams et al., 2014). Many studies have been conducted since this meta-analysis, and some of the results contradict previous results (Adams et al., 2014). In addition, as the penetration rate of smartphones has increased following the advent of newer types of mobile phones, there is the need to summarize the overall effect using recent data. In a previous study, meaningful results were obtained by assessing *in vitro* studies; however, the researchers could not consider the interactions with cells and efficiently reflect the real *in vivo* effect owing to a lack of data. For these reasons, we carried out an updated meta-analysis to assess the effects of mobile phone use on sperm quality, focusing mainly on observational *in vivo* studies.

Consistent with the results of a previous meta-analysis, the overall effect of mobile phone use on sperm quality was found to be harmful (Adams et al., 2014). The mechanisms of the mobile phone effect can be divided into two types. RF-EMWs, which are mainly released by mobile devices, may have both thermal and non-thermal effects. The thermal effect could increase the intensity of heat near the testis and outer gonadal organs, thereby damaging sperm production (Agarwal et al., 2011). The closer the phone is placed to the body, the more heat is generated by the phone; thus, the effect that the phone has on the body may differ by location, such as the trouser pocket or hand bag (Yildirim et al., 2015). Non-thermal radiation is known to cause damage to sperm by producing reactive oxygen species (ROS). ROS attack the nuclear DNA of spermatozoa, causing impaired mitochondrial electron transport chain and isocitrate dehydrogenase activity (Ding et al., 2018b; Hagras et al., 2016). Consequently, sperm quality is decreased, which corresponds with our results; in particular, sperm viability was found to decrease.

To identify the effect of cell phone usage and exposure time on semen quality, we included only *in vivo* studies that assessed the usage patterns (Agarwal et al., 2008; Al-Bayyari, 2017b; Ding et al., 2018a; Fejes et al., 2005; Kaya et al., 2020; Malini, 2017b; Rago et al., 2013; Sajeda and Al-Watter, 2011; Yildirim et al., 2015). First, we divided the studies according to whether the exposure time of the control group was zero. Thereafter, we compared the results between the less- and more-exposed

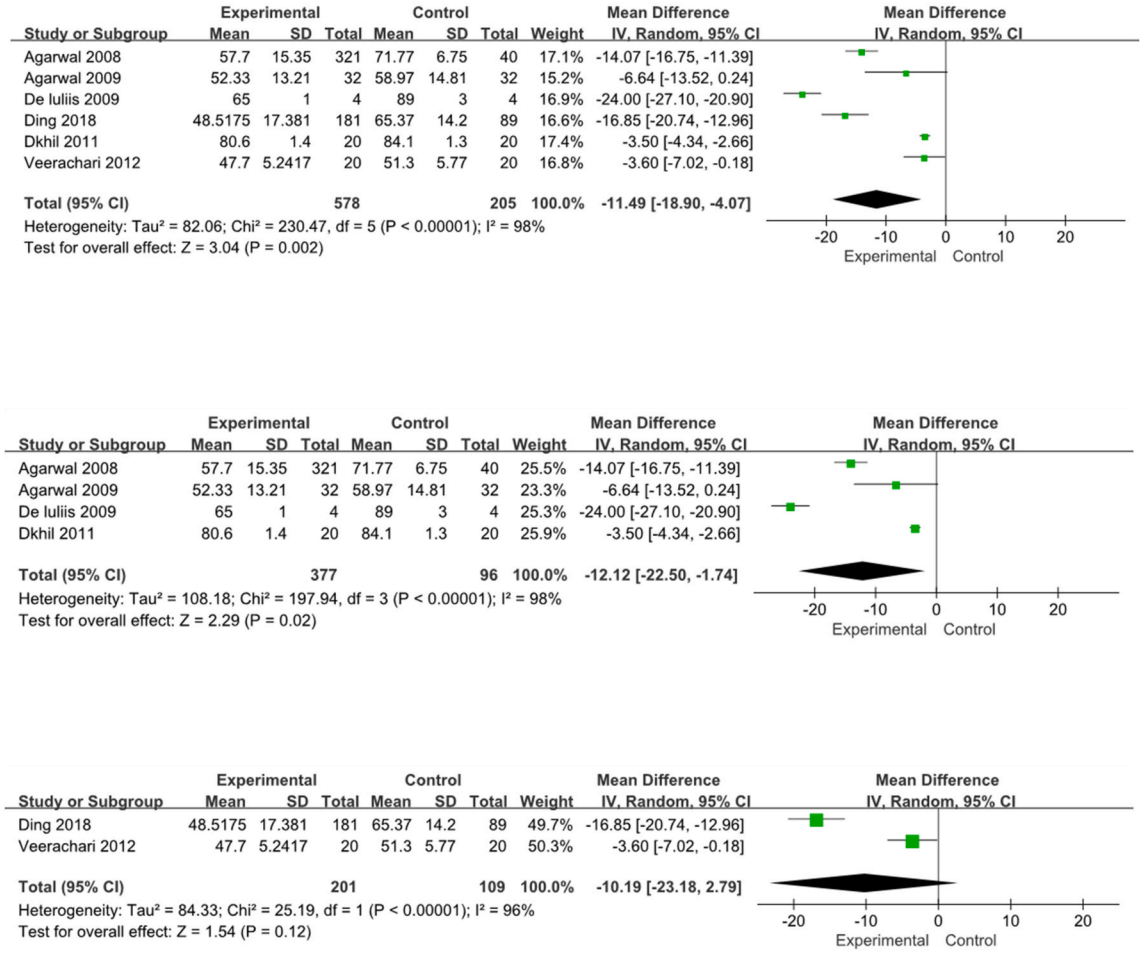


Fig. 3. A. Forest plot depicting the overall effect of the exposure to mobile phones on human sperm. Fig. 3B. Subgroup analysis of the effect of chronic exposure to mobile phones on human sperm (exposure vs. non-exposure). Fig. 3C. Subgroup analysis of the effect of chronic exposure to mobile phones on human sperm (more exposure vs. less exposure).

groups. When comparing the use of mobile phones with the no use, the MD was approximately twice as large as that obtained when comparing the usage times. Such finding indicates that sperm quality declines when people start using a mobile phone, regardless of the usage time. In modern society, mobile phones have been used since childhood, which is a major cause of male infertility.

In the subgroup analysis, unlike in the previous meta-analysis, the MD in the *in vivo* studies was consistently higher than that in the *in vitro* studies (Adams et al., 2014). This is because, compared with the previous meta-analysis, more *in vivo* studies have been included, thereby increasing the level of evidence. There was no significant difference in the subgroup analysis of location (Rago et al., 2013; Yildirim et al., 2015). If the thermal effect was larger than the non-thermal effect, people storing mobile phones in a trouser pocket (experimental group) would display a significant decrease in sperm motility. Although more research is still needed, the association between trouser pocket storage and sperm quality was not found to be significant.

This study has some limitations. Each study had its own some measurement standards (units, mobile phone exposure times, and study design). Thus, there is a possibility of confounding variables. Herein, we included an article that conducted incidental surveys on mobile phones. In such studies, researchers usually focus on lifestyle factors, such as alcohol intake, smoking cigarettes, obesity, and the use of tight underwear (Kaya et al., 2020). Therefore, the results obtained for mobile phones might not solely reflect the reality, since they are affected by other factors. We also used articles that focused on the mobile phone effects combined with other radiation factors, such as wireless internet and Wi-Fi use (Ding et al., 2018b; Yildirim et al., 2015). Hence, it is virtually impossible to completely separate the variables. However, weight assessment showed that there was no significant extreme value; therefore, our conclusions are valid. The results obtained from the fertility clinic may have also been biased and may have distorted the overall results. Further, this information may not be representative of the total human population. In the subgroup analysis, the average semen mean difference was higher than that of the general population (motility, MD = −7.24%, 95% CI: −12.13 to 2.35; concentration, MD = −8.36, 95% CI: −13.87 to −2.85; viability, MD = −13.39%, 95% CI: −17.72 to −9.07). Nonetheless, the difference relative to the population group was not significant (≤2%), except for the concentration, suggesting no marked bias in the participant group. In addition, because the effects of cell phone use including oxidative stress, DNA fragmentation, disturbance of the normal cell cycle, and testis hormonal changes, are diverse on the human body, the individual effects of mobile phone could not be identified (De Iuliis et al., 2009; Fejes et al., 2005; Kesari and Behari, 2010, 2012; Luzhna et al., 2013).

The exposure to RF-EMWs emitted by mobile phones is expected to increase in the future. In addition, more individuals might gradually own cell phones. Therefore, along with a decreased sperm quality, male infertility might increase because of this increased exposure. Hence, RF-EMWs from smartphones may become a bigger problem in the future. In the US, the penetration rate of smartphones has increased rapidly over 10 years; in 2021, nearly 72% of people are expected to be smartphone

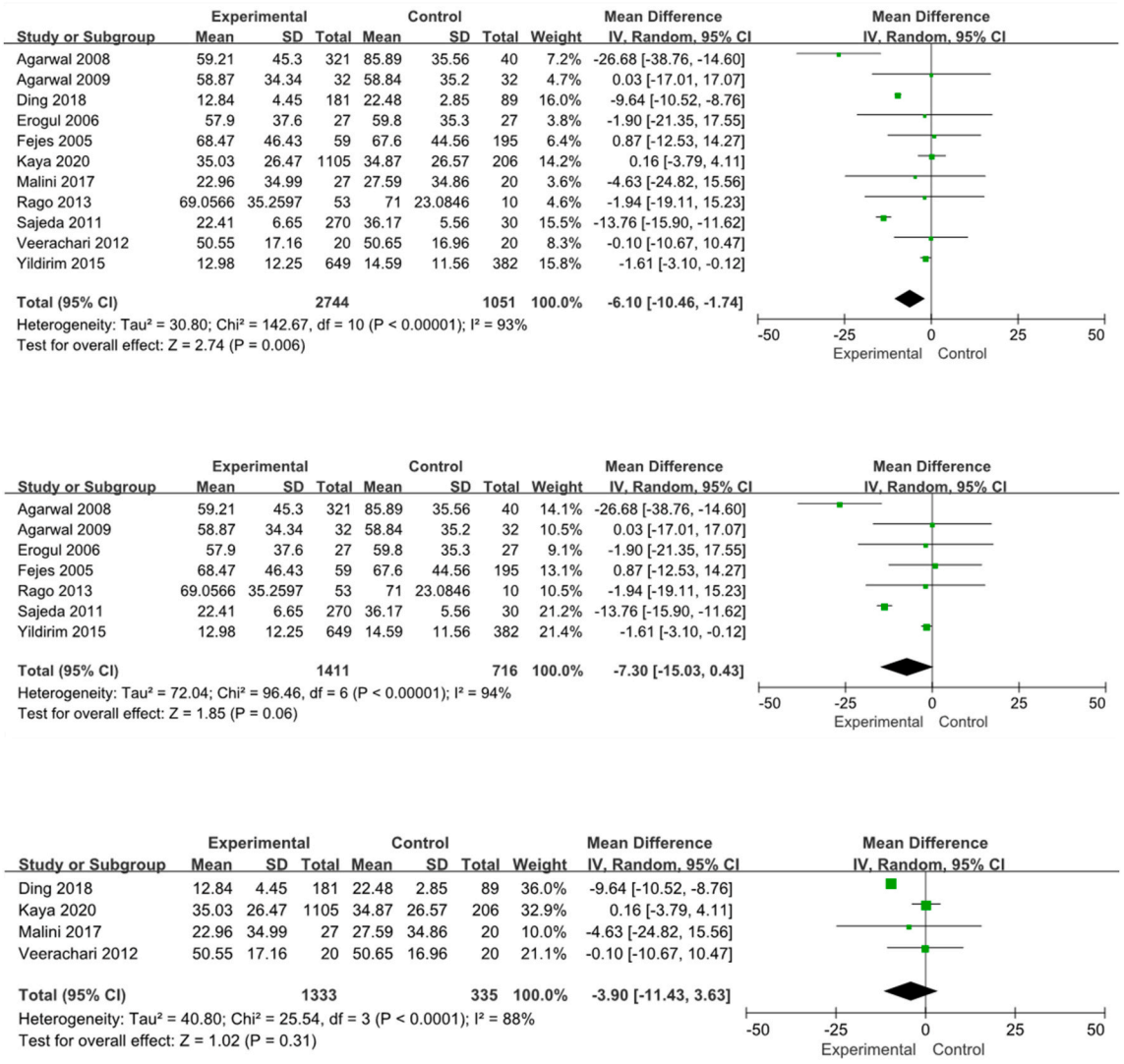


Fig. 4. A. Forest plot depicting the overall effect of the exposure to mobile phones on human sperm. Fig. 4B. Subgroup analysis of the effect of chronic exposure to mobile phones on human sperm (exposure vs. non-exposure). Fig. 4C. Subgroup analysis of the effect of chronic exposure to mobile phones on human sperm (more exposure vs. less exposure).

users (IIA, 2018). However, as EMWs from smartphones differ from those of existing 2G or 3G phones, a new study should be carried out with accumulated data on smartphone exposure. In our study, the phone models differed by time. Some old models, such as Nokia, have not been widely used recently (Dkhil et al., 2011). Future smartphones may use other broadband channels. Therefore, to be applied to clinical care, research on the latest models is needed. In our subgroup analysis, the confidence interval was large owing to an insufficient number of studies. If more research is carried out in the future and more data are accumulated, they will supplement the already existing research. We recommend the use of two new parameters by the successive researchers: morphology and vitality. These parameters were extracted once full-text articles were identified. Many articles have been published on these parameters. The morphology results were similar to the results obtained using our main parameter. Although morphology was not employed in the present study, owing to the use of a previous meta-analysis and since too much information was already being assessed, new parameters would allow more reliable results to be obtained in the future. Furthermore, a longitudinal prospective study is recommended. The studies included herein, especially those carried out nearly a decade ago, were almost retrospective observational studies. However, relying on memory without tracking may lead to inaccurate results. It is also problematic for people to fill out a questionnaire. People cannot memorize everything with a high degree of accuracy, which can distort the results. Our research is clinically meaningful for everyday life events and presents valid results, despite including cell phone use data from earlier years. Subsequent research needs to be performed to more accurately assess the effect of mobile phone RF-EMW exposure. Although this study has some limitations, meaningful results are presented. First, we upgraded the existing meta-analysis by adding new studies and amplifying the number of samples. Second, we selected various new subgroups as much as possible to complement them. Finally, we concluded that the chronic use of mobile phones has a harmful effect on sperm quality. Therefore, male users should strive to reduce the usage of mobile phones to protect sperm quality.

5. Conclusion

Mobile phone use decreased the overall sperm quality by affecting the motility, viability, and concentration. It was further reduced in the group with high mobile phone usage. In particular, the decrease was remarkable in *in vivo* studies with stronger clinical significance in subgroup analysis. Therefore, long-term cell phone use is a factor that must be considered as a cause of sperm quality reduction. Additional studies

are needed to determine the effect of the exposure to EMWs emitted from new mobile phone models in the present digital environment.

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.

Acknowledgments

Not applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111784.

Author contributions

KK and YK designed the study; SK, DH, and JR collected, selected, and analyzed the data; SK, DH, and JR drafted the manuscript; and KK and YK revised the manuscript.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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