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Comprehensive personal RF-EMF exposure map and its potential use in epidemiological studies

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ABSTRACT

In recent years, numerous epidemiological studies, which deal with the potential effects of mobile phone antennas on health, have almost exclusively focused on their distance to mobile phone base stations. Although it is known that this is not the best approach to the problem, this situation occurs due to the numerous difficulties when determining the personal exposure to the radiofrequency electromagnetic fields (RF-EMF).

However, due to the rise of personal exposimeters, the evolution of spatial statistics, the development of geographical information systems and the use of powerful software, new alternatives are available to deal with these epidemiological studies and thus overcome the aforementioned difficulties. Using these tools, this paper presents a lattice map of personal RF-EMF exposure from exterior mobile phone base stations, covering the entire 110 administrative regions in the city of Albacete (Spain). For this purpose, we used a personal exposimeter, Satimo EME Spy 140 model, performing measurements every 4 seconds. The exposimeter was located inside the plastic basket of a bicycle, whose versatility permitted the access to all the zones of the city.

Once the exposure map was prepared, its relation with the known antenna locations was studied. The 64 mobile telephone antennas of the city were also georeferenced; the randomness of both variables (exposure and antennas) were studied by means of the Moran's I test. Results showed that the distribution of the antennas follows a grouped pattern ($p<0.001$), while the distribution of the average exposure values have a random distribution ($p= 0.618$). In addition, we showed two Spearman correlation studies: the first between the average exposure values and the number of mobile telephone antennas per administrative region, and the second, also considering the antennas of the neighbouring regions. No substantial correlation was detected in either of the two cases.

This study also reveals the weaknesses of the epidemiological studies, which only take into account the distance to the antennas, which would provide a new approach to the problem. By precisely knowing the resident population of each administrative region of the city, this proves to be highly useful to rely on a prepared aggregate data map based on the mean exposure values to RF-EMF in these sections. The displayed map would permit the execution of more accurate epidemiological studies, since it would be possible to compare the exposure measurements with the incidence data of a disease.

KEYWORDS

Personal exposimeter (PEM); Radiofrequency electromagnetic fields (RF-EMF); Mobile phone base station; Nondetecs; Spatial data analysis; Radiation map.

1.- INTRODUCTION

During recent decades, the emission of waves produced by radiofrequency electromagnetic fields (RF-EMF) has undergone a major increase (Calvente et al., 2010; Joseph et al., 2008). Recently, the development of personal exposimeters (PEM) has permitted a detailed description of the electromagnetic radiation spectrum to which the population has been subjected and the contribution of each frequency band: radio, television, mobile phone antennas, wireless telephony or Wifi networks in diverse European cities (Bolte et al., 2011; Bolte and Eikelboom, 2012; Frei et al., 2009b; Joseph et al., 2010a; Juhasz et al., 2011; Markakis and Samaras, 2013; Thomas et al., 2008; Thuroczy et al., 2008; J.-F. Viel et al., 2009; J. F. Viel et al., 2009).

Simultaneously with the increased exposure to RF-EMF, the population's concerns have grown with regards to the potential effects on health (Röösli et al., 2010). Among the emission sources, we highlight the mobile phone antennas due to their high number, which have been the object of numerous studies (Röösli et al., 2010). However, almost the majority of these studies, which have dealt with the potential effects of the emitted radiation on health, have focused on the location of the antennas and exclusively in the proximity of the cases of disease (Atzmon et al., 2012; Dode et al., 2011; Elliott et al., 2011, 2010; Shahbazi-Gahrouei et al., 2014; Stewart et al., 2012). Although the use of the distance to the antenna as an exposure indicator has been questioned in several work papers (Foster and Trottier, 2013), few alternatives have been presented for the execution of epidemiological studies on the potential effects of the RF-EMF generated by the telephone antennas.

Fortunately, the use of personal exposimeters, the development of spatial data analysis, modern geographic information systems (GIS) and the software such as R (Bivand et al., 2013), could provide solutions in future investigations.

Studies with PEM mainly have the following aims: first, to characterize the personal exposure of population and secondly, to measure typical exposure levels in different micro-environments, such as public transportation, outdoor urban areas, other zones inside houses, etc. (Frei et al., 2009b). These two objectives must be clearly differentiated because they have major implications on the methodology of the study (Joseph et al., 2008). In addition, several of the problems to be taken into account in these types of studies by means of PEM, include: the anisotropy (Knafl et al., 2008) , the effect of the body (Joseph et al., 2010b; Nájera López et al., 2015; Panagopoulos et al., 2013), the sensitivity of the device (Röösli et al., 2008), measurement errors (Bolte et al., 2011; Knafl et al., 2008; Neubauer et al., 2007) and the fading (temporary reduction of the wave intensity), an essential feature of the RF-EMF which undergo reflections in the buildings and in other structures (Larcheveque et al., 2005). On the other hand, the mobile monitoring of mobile phone base station radiation using PEM is useful because of the high repeatability of exposure levels (Urbinello et al., 2014a). Finally, several studies suggest alternatives to assess the exposure in different micro-environments, through the use of different models prepared based on specific measurements (Aerts et al., 2013a; Beekhuizen et al., 2013; Frei et al., 2009a).

The main objective of this paper was to prepare a lattice map, of the exposure to RF-EMF emitted by mobile phone base stations, through the use of PEM, in the city of Albacete (Spain) as the basis for the execution of future epidemiological studies.

Likewise, the relation was analysed between the exposure and the antenna locations in the entire city. It was determined if the zones with more antennas; inside the city correspond to the zones with the highest intensities and vice versa. For this purpose, we have studied the spatial randomness of the antennas and the measured intensities, as well as the correlation between both variables.

2.- MATERIAL and METHODS

2.1.- Exposimeter

To determine personal exposition, we used an exposimeter EME Spy 140 (Satimo) which records 14 frequency bands (from 88 MHz to 5 GHz) with a maximum sensitivity of 0.005 V/m.

To carry out outdoor measurements, the exposimeter was installed on a bicycle, that permitted the acquisition of a total of 12,019 log entries in the 110 administrative regions of the city.

A plastic basket with the exposimeter was installed in the front section of the bicycle to minimize the potential shielding effect of the body and the bicycle itself.

2.2.- Software

For the log records analysis, in addition to the specific software of the exposimeter EME Spy 140, we used ArcGis 10.2.2 (Environmental Systems Research Institute, ESRI) and R Software 3.2.1. ArcGis is used to prepare and modify shapefile (shp) format maps. The R software is essentially used to carry out the statistical calculations (data normality study, randomness study and correlation analysis) and to work with the shp format maps created with ArcGis. The main R packets used in this project were: spatstat, sp, splancs, maptools, rgdal, RColorBrewer, lattice, nortest, Rcmdr and spdep. The level of significance in the statistical tests used was $p<0.05$.

2.3.- Measurements and data processing

The micro-environments selected in this study were the 110 administrative regions of the city of Albacete. The administrative regions (censal sections) are polygon areas with defined boundaries, with a statistical nature used in the election processes, which prove to be very efficient for different investigations since the resident population in each of them is accurately known. Due to electoral reasons, it is recommended that the size of an administrative region in Spain should not be above 2,500 inhabitants and each inhabitant can only belong to one of them.

The measurements were performed between 30th of January and 29th of April 2015. The timetable to make the measurements was between 20:30 and 23:30 at night, avoiding Fridays and Saturdays, since due to the experience in other cities (Bolte and Eikelboom, 2012) , it is known that the exposure during the afternoon-evening is almost twice as high as the exposure during the day. Inside each section, we travelled almost all the streets, carrying out a measurement every 4 seconds. This interval, which is the exposimeter's minimum reading, makes it possible to make a large number of measurements in a short time period.

A total of 12,019 measurements per frequency were taken, which amounted to a total of 168,266 data, where the figure of 1,540 was the average number of measurement records per administrative region. From these 1,540 log entries, the GSM, DCS and UMTS bands were selected, as well as the DECT wireless telephony, as a control variable. The selection criteria of the mobile telephone antennas (GSM, DCS and UMTS downlink) was because these frequency bands represent approximately 70% of the total outdoor exposure. DECT was selected as a control because the importance of this frequency band is known in the experiment time periods (Bolte and Eikelboom, 2012) and because it appears to be a good control since it also involves wireless telephony with no relation to mobile base stations.

A major aspect to be considered is the analysis and processing of the nondetect values or the values under the device's threshold. When their number is high, they are a challenge for the data analysis in the measurements. Many authors choose to carry out the robust regression on order statistics (ROS) (Bolte and Eikelboom, 2012; Frei et al., 2009b; Juhasz et al., 2011; Markakis & Samaras, 2013; J.-F. Viel et al. 2009). However, Hessel (2005) who describes different solutions when working with nondetects, only recommends the use of the ROS method if the percentage of nondetects is between 50% and 80%. Thus, we decided not to consider them, due to the low percentage which they supposed in the analysed bands (Table 1) thanks to the high sensibility of the exposimeter used (Röösli, 2015).

	DCS	GSM	UMTS	DECT
nondetects	1.20%	0.30%	0.90%	4.10%

Table 1: Nondetects percentage per frequency band.

Once nondetects data was discarded, the average values were calculated and the remaining analysis was executed with R software.

2.4.- Map preparation

In order to prepare the administrative regions map in the shp format, we used data provided by Spain's National Statistics Institute (INE). For this task, the ArcGIS software was used to modify the shp map provided by INE (http://www.ine.es/censos2011_datos/cen11_datos_resultados_seccen.htm) adapting it to the urban centre of the city of Albacete. For this purpose, the "mass" layer (http://www.catastro.minhap.gob.es/ayuda/lang/castellano/ayuda_descarga_shape.htm) provided by the cadastral register (task office) which makes reference to the blocks of the urban centre of the city of Albacete (Figure 1).

Figure 1: Left, administrative regions on the cadastral "mass" layer of the city of Albacete. Right, administrative regions layer once defined.

Once the administrative regions map was prepared for the urban centre of the city of Albacete, the average data of the measurements was entered in the attached database of the shp map. Finally, we georeferenced the 64 antennas registered by the Spanish Ministry of Industry (https://geoportal.minetur.gob.es/VCTEL/vcne.do).

2.5.- Randomness in the distribution of the antennas and the measurements

The Moran's I test measures the spatial autocorrelation based on the locations (Figure 2) and the values of the polygonal entities simultaneously (Burt et al., 2009). Given the set of entities and an associated attribute, we checked if the expressed pattern is grouped, disperse or random (Bivand et al., 2013).

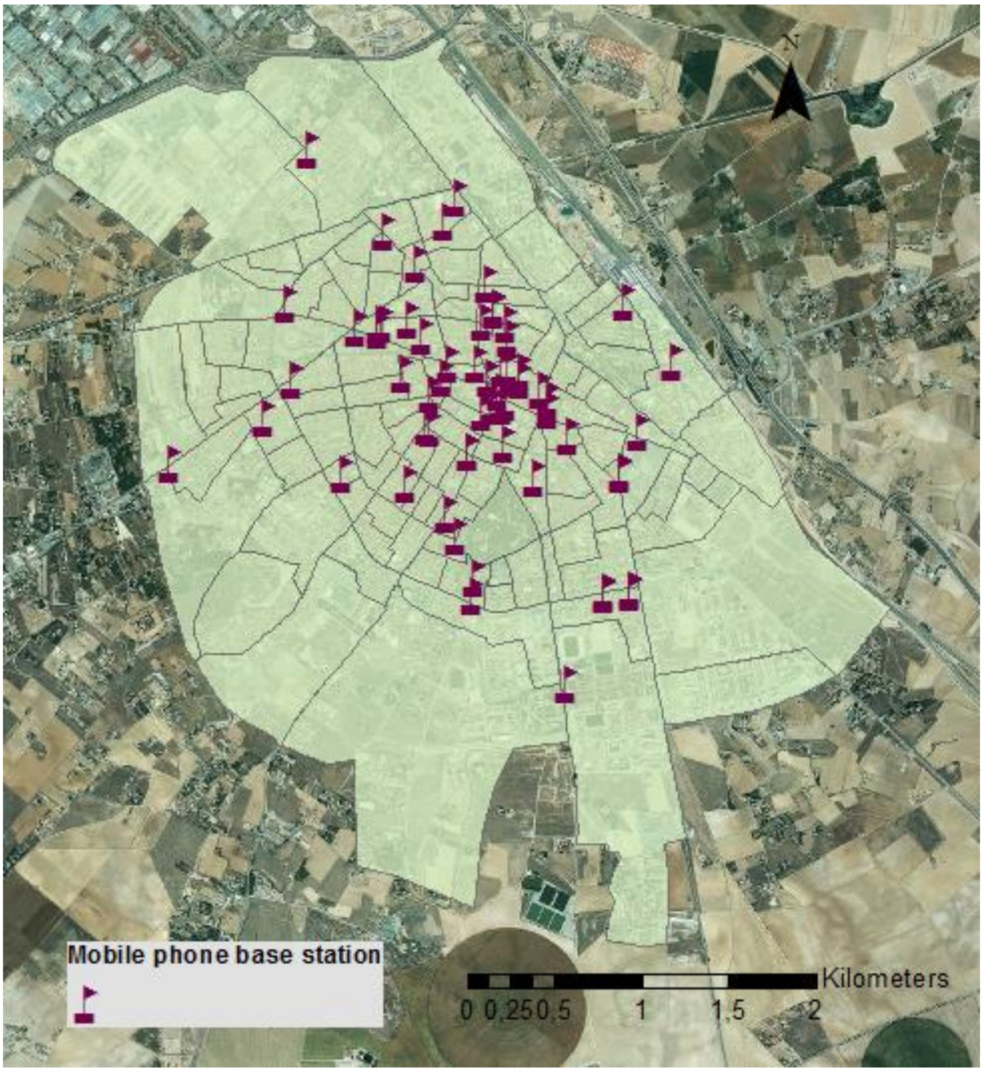

Figure 2: Location of the 64 mobile phone base stations of the city of Albacete (Spain)

2.6.- Correlation study

The correlation was studied between the number of antennas per administrative region and the average value of the measured exposure in each of them. Two studies were carried out: first, the correlation was studied with the specific antennas of each administrative region, and second, the antennas of the neighbouring regions were also taken into account.

The normality of the data was previously studied by the Kolmogorov-Smirnov test (Sheskin, 2003), applying the significance correction proposed by Lilliefor (R software; nortest package). In addition to verifying the consistency of the measured data, the existing correlation was studied between the exposure values of the different bands considered (DCS, GSM and UMTS).

3.- RESULTS AND DISCUSSION

3.1.- Average values by administrative regions

Average personal exposition values for the total city amounted to 0.22 V/m, 0.14 V/m, 0.13 V/m and 0.12 V/m for GSM, DCS, UMTS and DECT respectively. The average value of the contribution of the 3 mobile phone frequency bands amounted to 0.29 V/m.

The maximum average values per administrative region were 0.83 V/m, 0.45 V/m, 0.39 V/m and 0.42 V/m for GSM, DCS, UMTS and DECT respectively. In relation to the maximum average value of the contribution of the 3 bands of mobile telephone, this was 0.89 V/m.

The minimum average values were 0.02 V/m, 0.01 V/m, 0.02 V/m and 0.02 V/m for GSM, DCS, UMTS and DECT respectively. In relation to the minimum value of the contribution of the 3 bands of the base stations, it was 0.04 V/m.

The average exposure values are difficult to compare with other studies conducted in Europe, since they were obtained with different protocols and experimental designs (Gajšek et al., 2015). Likes other studies carried out in Europe (Urbinello et al., 2014b), the obtained exposure levels were well below the international benchmark levels proposed by the ICNIRP (International Commission on Non-Ionizing Radiation Protection). In our case, the obtained values were well below 6.14 V/m, which is the maximum legal level established by the Regional Government (Castilla-La Mancha), where the city of Albacete (Spain) is located.

3.2.- Georeferencing of the mobile phone base stations

As indicated above, the city has a total of 64 mobile telephone base stations (Figure 2). The region with the most stations has a total of 6 antennas; the average number of antennas per administrative region is 0.57 and there are a total of 73 sections (from the total of 110) without an antenna in their interior, however they received radiation from the antennas of the neighbouring regions. For this reason, we also took into account the antennas from the nearby regions in the correlation search. The nearest region has 22 antennas taking into account its own units (3) and those from the neighbouring regions (19). Figure 3 shows a Kernel density map which was prepared based on the georeferencing of the base stations. This map is able to clearly show that the maximum density of antennas is concentrated in the city centre.

Number of network providers operating the antennas depends on each base station. Only 5 of the base stations in Albacete are operated by more than one provider. This fact has not been analysed in detail and could be used in future work. A weakness of the study could be the fact that the size of base stations was not taken into account. There are many different sizes of mobile phone base stations (macrocells, microcells, picocells), and the larger ones emit at much higher power than the small ones (and consequently serve a larger area).

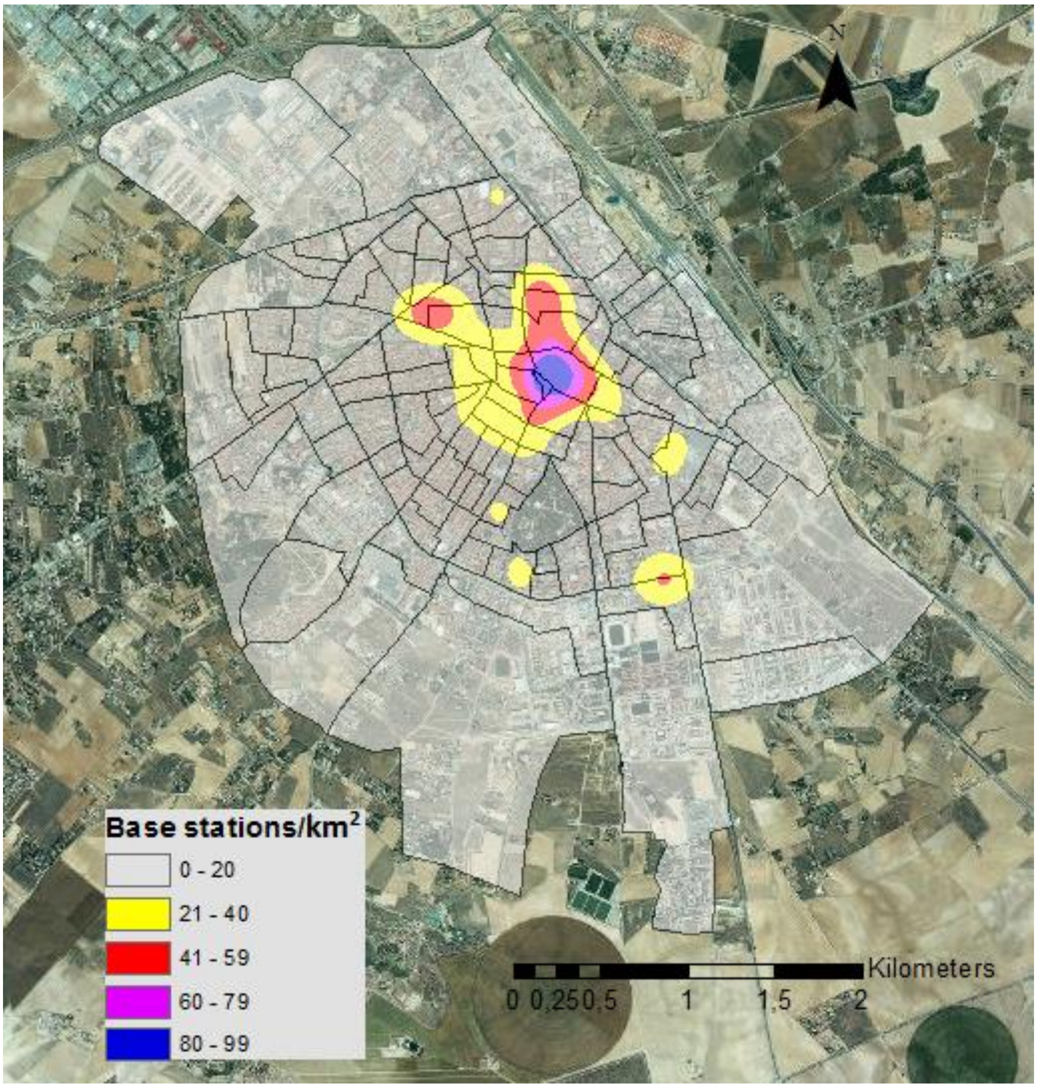

Figure 3: Kernel density map prepared with the location of 64 mobile phone base stations of the city of Albacete (Spain).

3.3.- Radiation Map

Figure 4 shows the RF-EMF exposure map (mean values) emitted by the mobile telephone antennas (GSM+DCS+UMTS), per administrative regions in the city of Albacete. The provided map covers the entire city and not a limited number of zones (Aerts et al., 2013b).

The design of the presented map in future epidemiological studies would permit the comparison of the exposure measurements with the incidence data of any disease. Likewise, thanks to the map features, it would be possible to collect new covariables by means of sampling, since the resident population is exactly known.

Studies have been successfully performed with exposimeters using diverse means of transportation such as car or bicycle to take measurements in large areas (Bolte et al., 2016; Estenberg and Augustsson, 2014). We understand that the bicycle provides the opportunity to reach zones of the city inaccessible by car and to take measurements at a constant speed, and also minimize possible impacts on measurement of its metallic parts. Likewise, our work has attempted to minimize the body shielding effect by placing the exposimeter in a plastic basket in the front section of a bicycle and not attached to the body by means of a backpack.

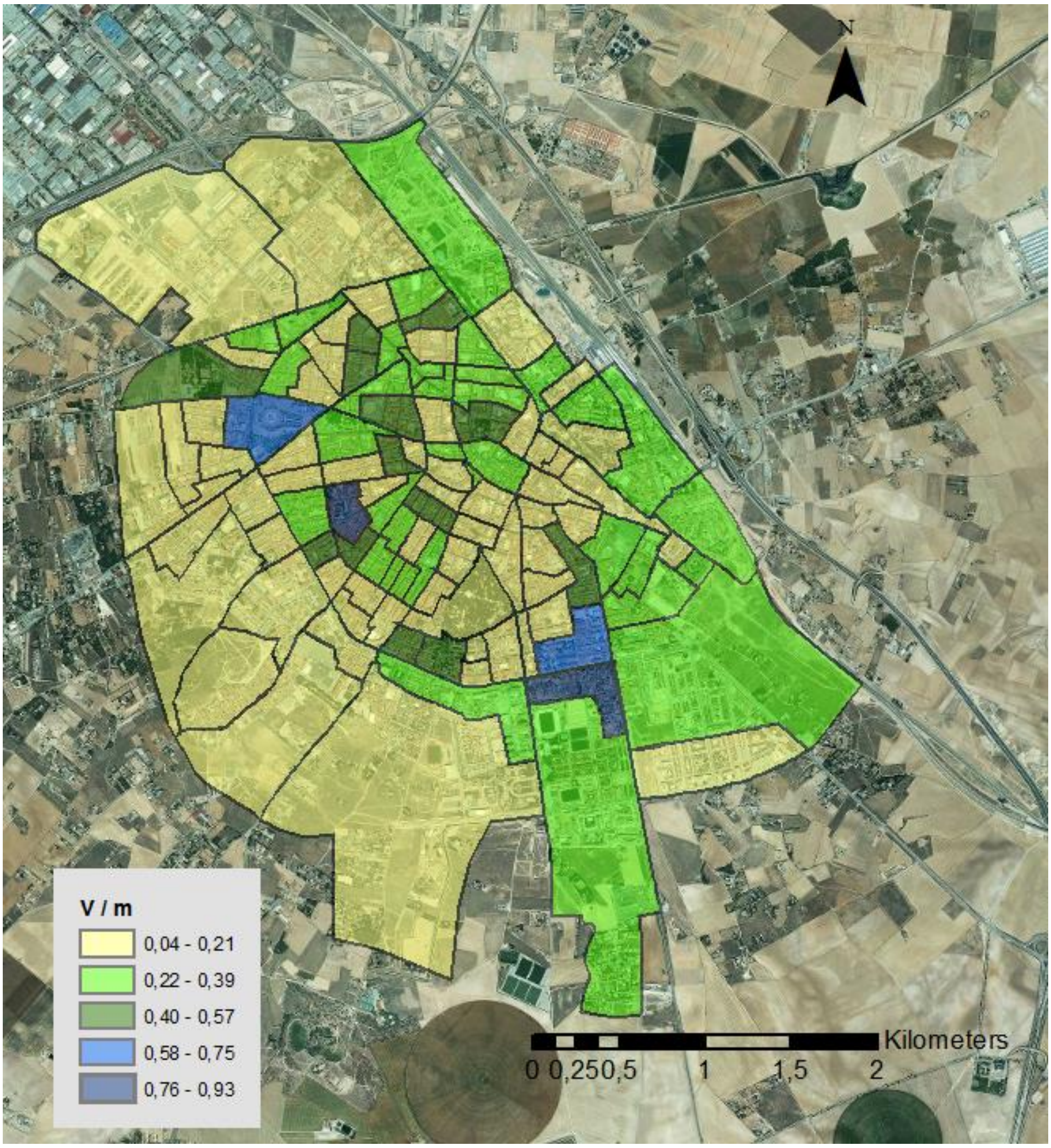

Figure 4: Average exposure values to RF-EMF per administrative region in Albacete (contribution of all the mobile telephone bands: DCS+GSM+UMTS)

Map showed in Figure 4 illustrates that the chosen approach introduces artificial exposure differences between near-by locations: in many cases, one administrative region is assigned a high exposure level, while the neighbouring region has received a very low exposure classification. In reality, persons living in two such regions but near the boundary between them do not have any substantial differences in their exposures. The RF exposure levels do not obey administrative borders between city regions, but this approach was chosen to compare exposure and incidence, whose data were obtained by administrative region.

Although it would be possible to make more accurate exposure maps by means of geostatistics (Bivand et al., 2013), than the aggregate data maps; they would not be as useful in the execution of the epidemiological studies.

3.4.- Randomness in the distribution of the antennas and the measurements

Moran´s I result of 0.113 ($p<0.01$) indicates that the distribution pattern of the mobile base station is grouped and consequently, it is not random. The Moran's I test applied to the average intensities, provides a Moran´s I result of 0.002 ($p=0.62$), indicating that their spatial distribution is random. Consequently, the location of the antennas and the exposure recorded in the different zones of the city do not follow the same pattern.

This analysis confirms the poor metric standard of the distance to the antennas as an exposure indicator in a city. The antennas form aggregates as this analysis shows and this can be seen in figure 3, however, the exposure follows a random pattern inside the city.

The fact that the spatial distribution of the RF-EMF aggregate data is random does not mean that there are no zones inside the city with higher exposure: train stations, bus stops, pubs and business zones (Bolte and Eikelboom, 2012). However these zones do not seem to form aggregates while the antennas do form them.

3.5.- Correlation

Records made in the 110 sections do not follow a normal distribution (Kolmogorov-Smirnov, $p<0.05$) for any of the analysed bands. For this reason, the Spearman correlation test was carried out in the different executed analyses.

First, we studied the correlation between the different frequency bands to view the solidity of the performed measurements. A correlation was obtained between 0.807 and 0.876 for the mobile phone bands studied two by two (Table 2) since the mobile phone base stations usually emit in these three bands in a joint way.

	GSM	**DCS**	**UMTS**
GSM	1.000		
DCS	0.807	1.000	
UMTS	0.876	0.845	1.000

Table 2: Correlation study between the telephone antenna bands (GSM, DCS and UMTS) ($p<0.05$).

The correlation between the average values of RF-EMF exposure in each administrative section and the location of the antennas are small for all the frequency bands, and as expected also for the DECT (Table 3). This type of studies with lattice maps raises a problem with the border regions, hence the correlation test is presented also considering the antennas of the neighbouring regions. A low correlation was also obtained although it was somewhat higher than in the previous case.

	ANTENNAS		ANTENNAS + NEIGHBOURING ANTENNAS	
AVERAGE INTENSITY	ρ Spearman	p-value	ρ Spearman	p-value
GSM	0.138	0.113	0.207	0.030
DCS	0.202	0.083	0.226	0.017
UMTS	0.099	0.023	0.192	0.044
TOTAL	0.181	0.045	0.220	0.020
DECT	0.263	0.003	0.151	0.114

Table 3: Spearman correlation test between the number of antennas per administrative region (of each region and also considering the nearby antennas from the bordering regions) and the average intensity recorded in each region.

To this low correlation between the number of antennas of one region (and the number of neighbouring antennas) with the recorded exposure level, we add the result obtained by means of the Moran's I test, which indicated different distributions for the antennas and average intensity values. Consequently, results seem to indicate that the exposure recorded in the different administrative regions and the location of the antennas are not always related.

Main reasons for the absence of this correlation could involve the orientation of the antennas, the construction features of the buildings, the land's orography, several physical phenomenon such as the reflection of the antennas on the buildings and possibly, the fading. Hence possessing the real exposure of each of the administrative sections, we can make a more accurate description of the exposure to RF-EMF of the city of Albacete and solve the problem of the studies performed with a limited number of data collection (Cucurachi et al., 2013). Consequently, it is suggested that when searching for the effects of radiation on health, it is necessary to consider not only the location of the antennas, but also the exposure of the population, which in all cases, would be the causative agent of the disease.

4.- CONCLUSION

The exposure values recorded in the city of Albacete never surpassed the international benchmark levels proposed by the ICNIRP.

Distribution of the antennas form a grouped pattern and distribution of measurements is random, hence, in the city of Albacete, the zones with the most antennas and their outskirts do not always coincide with the zones with the highest average intensity. Likewise, the Spearman test showed a weak correlation between the location of the antennas and the exposure levels to RF-EMF in the city of Albacete, regardless whether the specific antennas of the administrative region are considered or if the antennas of the bordering regions are also considered. These results reveal the need to study, in addition to the location of the antennas or their distance, other factors such as the exposure or its estimate by means of different models which consider the orography as well as the features and distribution of the buildings in a city.

For future epidemiological studies, it is suggested to possess aggregate data maps such as the one shown. By exactly knowing the resident population of each administrative region of the city, this would be highly useful to prepare a map based on the mean exposure values to RF-EMF in these sections. The described map would permit the execution of more accurate epidemiological studies, since it is possible to compare the exposure measurements with the incidence data of a disease, thus offering a new approach to the problem.

5. ACKNOWLEDGMENTS

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