

RESEARCH ARTICLE

Exposure Variability Between 1- or 6-Minute and 30-Minute Averaging Time Lengths in Radiofrequency-Electromagnetic Field Exposure Monitoring

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ABSTRACT

Different averaging time lengths (ATLs) are widely used in radiofrequency-electromagnetic field (RF-EMF) exposure monitoring. This study evaluated variability in RF-EMF exposure associated with the ATLs of 1- and 6-min normalised to 30-min data. For 15 frequency bands of interest, RF-EMF exposures were collected in contiguous 1-min blocks over 30 min at four sites (two outdoor and two indoor). Frequency-band and site-specific variability in exposure between the three ATLs was assessed. First, the variability in terms of relative deviation (in dB) between 1- or 6-min and 30-min were estimated. Second, the overall exposure variability (in $\mu\text{W}/\text{m}^2$) were compared between 1- or 6-min and 30-min blocks statistically using the quantile regression method. The overall exposure variability on ATL of 1-min or 6-min was considered different to 30-min if a majority of respective sub-pair comparisons across different percentiles (P_5 , P_{25} , P_{50} , P_{75} , P_{95}) were significantly different. The study largely showed that the exposure variability (i.e., relative deviation) of different ATLs was within ± 3 dB. Further, the overall exposure variability between 1- or 6-min and 30-min ATLs showed inconsistent outcomes. Frequency bands of broadcast and most of the mobile services < 2 GHz demonstrated overall similar exposure variability for 1-min and 6-min ATLs.

1 | Introduction

Measurements to evaluate radiofrequency-electromagnetic field (RF-EMF) in human environments can generally only be acquired over a limited time period. RF-EMF exposure limits given by the national and international standards or guidelines are specified in terms of average exposures over any continuous 30-min or 6-min time period for the whole body and localised exposures, respectively (International Commission on Nonionizing Radiation Protection ICNIRP 2020; ARPANSA standard 2021; IEEE Standards 2019). These “averaging times” relate to the elevation of tissue temperature as a result of RF-EMF exposure, and hence it may not necessarily be the same as the “measurement duration” required to characterise RF-EMF sources. However,

averaging time lengths (ATLs) have been sometimes translated into “measurement duration” while conducting ambient or personal RF-EMF exposure assessments (Asadi et al. 2023, 2020; Ramirez-Vazquez et al. 2023a; Sagar et al. 2018; Jalilian et al. 2019; Ramirez-Vazquez et al. 2023b; Bhatt et al. 2017; Onishi et al. 2021; Henderson et al. 2023; Sagar et al. 2016; Huss et al. 2021; Urbinello et al. 2014; Bhatt et al. 2024). According to the International Telecommunication Union defines “averaging time” as “the appropriate time period over which exposure is averaged for purposes of determining compliance with the limits” (The International Telecommunication Union 2020). This raises a question whether it is necessary to use an equivalent measurement duration to determine the exposure in view of comparing it with the time-averaged limit.

Summary

- Comparison of RF-EMF exposure variability between ATLs of 1- or 6- and 30-min was undertaken.
- Exposure variability (i.e., descriptive or relative variability) largely remained within ± 3 dB.
- Exposure variability (i.e., “statistical” or overall outcome) results were inconsistent.

Exposure data collected through measurements using different “measurement durations” have been used for characterising sources and levels of RF-EMF exposures (e.g., mean or median) in human environments (Ramirez-Vazquez et al. 2023a; Sagar et al. 2018; Jalilian et al. 2019; Ramirez-Vazquez et al. 2023b; Bhatt et al. 2017; Onishi et al. 2021; Henderson et al. 2023; Sagar et al. 2016; Huss et al. 2021; Urbinello et al. 2014; Bhatt et al. 2024; The International Telecommunication Union 2020; Joseph et al. 2012). For example, spot measurements have generally used 6-min measurement duration (Ramirez-Vazquez et al. 2023b; Bhatt et al. 2017) while other studies have even shorter duration such as 1-min (Henderson et al. 2023; Onishi et al. 2021) to characterise sources and levels of RF-EMF exposure in human environments. Further, measurement time duration up to 30 min have been used in evaluating personal (micro-environmental) or environmental RF-EMF exposures (Sagar et al. 2016; Huss et al. 2021; Urbinello et al. 2014; Bhatt et al. 2024; International Telecommunication Union 2020; Joseph et al. 2012). ATL refers to the measurement duration, which is distinct from the exposure period associated with the evaluation of safety limits.

RF-EMF exposure data collected over different measurement durations (e.g., 1-min or 6-min) may exhibit exposure variability (The United States Environmental Protection Agency 2024). A longer measurement time tends to better capture measurement variability while estimating ambient or personal instantaneous exposure levels (Aerts et al. 2018; Joseph and Verloock 2010; Iakovidis et al. 2025). It is important to strive to reduce variability in any exposure assessment to better characterise the exposure and provide consistent results. This delivers more confidence in both the exposure assessment and subsequent estimation of health risk associated with human RF-EMF exposure. However, achieving longer measurement times, which potentially better capture the temporal variability of RF-EMF exposure, is not always feasible practically. Therefore, RF-EMF exposure assessors require practically achievable measurement times, such as shorter ATLs of measurements, such as 1-min or 6-min.

Only a limited number of studies have compared different averaging time lengths (Asadi et al. 2023, 2020; Šuka et al. 2019). Asadi et al. (2023, 2020) assessed the effect of different averaging time lengths (30 s, 1 min, and 6 min) on average exposure levels of measured data for the frequency range of 3 MHz–18 GHz. Šuka et al. (2019) undertook spot RF-EMF exposure measurements to assess measurement uncertainties associated with different measurement durations such as 30 s up to 24 h (Asadi et al. 2020). These studies have provided indications that shorter ATL can provide reliable RF-EMF exposure data and hence could be used in environmental

RF-EMF monitoring practice (Asadi et al. 2020; Ramirez-Vazquez et al. 2023a). However, these studies lacked examination of exposure variability across the data distribution for a range of measurable frequency bands.

This study aimed to assess RF-EMF exposure variability associated with ATLs of 1- and 6-min compared to 30-min.

2 | Methods

2.1 | Measurements

The measurements involved the collection of ambient power density values (in W/m^2) for 15 frequency bands using a Narda SRM-3006 spectrum analyser (SRM-3006, Narda GmbH, Germany) and one of three different 3-axis probes connected via a 1.5 m RF cable. The measurement protocol included a range of frequency bands (100 kHz to 6 GHz) representing several radio-telecommunication technologies, such as broadcast services (AM, FM, and digital radio as well as digital TV), industrial scientific and medical (ISM) bands of AMI smart meters and mobile phone base station downlink bands. The three probe types and their frequency ranges were: H-field 9 kHz—250 MHz (Narda 3581/02), E-field 75 MHz—3 GHz (Narda 3501/01), and E-field 420 MHz–6 GHz (Narda 3502/01). Instrument settings and expanded uncertainties in relation to the measurements are listed in Table 1.

The two outdoor and two indoor measurement sites in Melbourne (Australia) were chosen for the study. The outdoor measurements were collected at Yallambie (backyard of the ARPANSA office) and Springvale (Norman Luth Reserve). The measurement site at Yallambie had three mobile phone base stations within a 1-km radius, while at Springvale, there was only one. In addition, the closest radio broadcast transmitters located near Yallambie (AM radio) and Springvale (FM radio) sites were located about 1.5 km and 9.5 km away, respectively. These two outdoor sites were also the sites for an environmental RF-EMF exposure assessment in Melbourne (Henderson et al. 2023). Two indoor locations, the ARPANSA office (Yallambie) and one researcher's residential property (Noble Park), were chosen based on convenience for Wi-Fi measurements (non-line of sight, 10 m away from the Wi-Fi sources). These measurement sites represented residential and office environments in suburban areas of Melbourne, Victoria (Australia). Similar measurement sites have been selected by other researchers to assess the temporal variability of RF-EMF exposure (Joseph and Verloock 2010). All measurements for the current study were conducted in April–May 2021.

Assessment of RF-EMF exposures at all locations used the same measurement device and operator. The outdoor sites were chosen for collecting exposure data from broadcast and radios, TV, and mobile telecommunication services, whereas the indoor sites were for collecting Wi-Fi exposure data. One of three probes, depending on the frequency of the target service, were mounted on a wooden tripod at 1.5 m above ground level and connected to the spectrum analyser with a 1.5 m long RF cable to collect the exposure data. Researchers turned off their mobile phones during the measurements allowing frequency-selective measurements under passive conditions. All mobile

TABLE 1 | Settings used on Narda SRM-3006 spectrum analyser for different frequency bands. Note that the sweep time parameter is not user selectable, it is the result of the choice of frequency range, resolution bandwidth (RBW), and measurement range (MR) settings. Expanded measurement uncertainty provided by the manufacturer for each probe in conjunction with the SRM basic unit and 1.5 m cable.

Frequency band	F _{min} [MHz]	F _{max} [MHz]	RBW [kHz]	MR [W/m ²]	Sweep time [ms]	Probe	Expanded uncertainty
AM radio	0.5265	1.6065	1	0.008	103	H-field	± 2.5 dB
FM radio	87.5	108	20	0.01	112	E-field 3 GHz	+ 2.5/- 3.6 dB
VHF band III	174	230	50	0.008	96	H-field	± 3.3 dB
Mobile 700 MHz	758	803	20	0.01	150	E-field 6 GHz	+ 2.0/- 2.6 dB
Mobile 800 MHz	870	890	20	0.01	112	E-field 6 GHz	+ 2.0/- 2.6 dB
Mobile 900 MHz	935	960	20	0.01	114	E-field 6 GHz	+ 2.0/- 2.6 dB
ISM band	915	928	10	0.032	95	E-field 6 GHz	+ 2.0/- 2.6 dB
Mobile 1800 MHz	1805	1880	50	0.01	111	E-field 6 GHz	+ 2.1/- 2.9 dB
DECT (cordless phone)	1880	1900	20	0.01	112	E-field 6 GHz	+ 1.9/- 2.5 dB
Mobile 2100 MHz	2110	2170	30	0.01	135	E-field 6 GHz	+ 2.0/- 2.6 dB
Mobile 2300 MHz	2302	2400	100	0.032	96	E-field 6 GHz	+ 2.0/- 2.6 dB
Wi-Fi 2.4 GHz	2400	2500	100	0.01	97	E-field 6 GHz	+ 2.0/- 2.6 dB
Mobile 2600 MHz	2620	2690	50	0.01	110	E-field 6 GHz	+ 2.0/- 2.6 dB
Mobile 3.4 GHz (5G-NR)	3425	3700	200	0.01	138	E-field 6 GHz	+ 2.1/- 2.9 dB
Wi-Fi 5 GHz	5150	5850	1000	0.01	197	E-field 6 GHz	+ 3.2/- 5.1 dB

telecommunication frequencies in Australia operated in frequency division duplex (FDD) mode, except mobile 2300 MHz and 3.5 GHz (5G-NR), which operated in time division duplexing (TDD) mode. The average spectral traces of the detected E- or H-field levels, expressed as power density values (herein also referred to simply as a “RF-EMF exposure”), were collected in consecutive 1-min blocks over 30-min. The measurements were conducted in accordance with AS/NZS 2772.2:2016 standard (AS/NZS 2772.2:2016 Amd1 2018).

2.2 | Data Analysis

The comparison of RF-EMF exposure variability between ATLs of 1- or 6-min and 30-min was undertaken using two approaches. First, the variability in exposure, in terms of relative deviation (in dB), between 1- or 6-min and 30-min were estimated using a descriptive approach. Second, the variability (in $\mu\text{W}/\text{m}^2$) were compared between 1- or 6-min and 30-min blocks statistically using quantile regression (QR) (i.e., “statistical” method). These approaches are discussed below. Measured spectra were integrated across the frequency band of interest to determine the power in band for each of the ATL. Figure 1 shows an example (e.g., mobile 1800 MHz band) of 1-, 6-, and 30-min average spectra measured at the Yallambie site. For each instrument configuration, the background noise was measured by setting up the equipment in a shielded room (anechoic chamber) with no RF sources present. Background noise power density in each frequency band was then subtracted from the measured values to give a net power density in the band. It was this net power density in the band that was used for the analysis.

2.2.1 | Evaluation of Relative Exposure Variability (Descriptive Approach)

The 30 min of average exposure data were analysed in three ways: as a single block, as five consecutive 6-min blocks, and as 30 consecutive 1-min blocks. Mean power density ($\mu\text{W}/\text{m}^2$) was determined for each block of data. Then, the maximum and minimum values of the mean power density within blocks were calculated. For example, for the 1-min block, the highest and lowest of the 30 mean power density levels were reported as the maximum (MAX1), and minimum (MIN1), and for the 6-min block, the highest and lowest of the five mean power densities were reported as the maximum (MAX6), and minimum

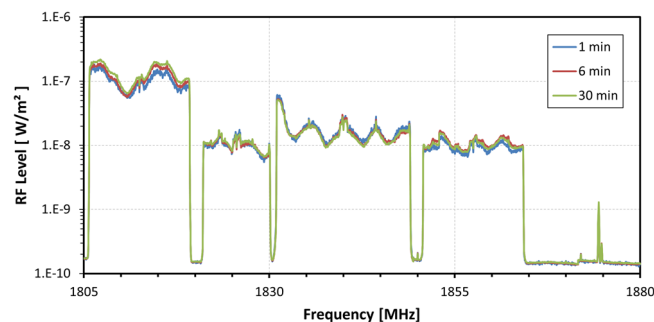


FIGURE 1 | An example of the mobile 1800 MHz band showing 1-, 6-, and 30-min average spectra measured (in W/m^2) at Yallambie.

(MIN6). The exposure variability (dB) was estimated and compared for two pairs of measurement blocks, Pair 1 (1-min vs 30-min) and Pair 2 (6-min vs 30-min), at minimum and maximum values. The variability was calculated for individual frequency bands for each measurement site.

In Table 2, the highest and lowest of the 30 total power density levels for the 1-min ATL data are reported as MAX1 and MIN1 for each frequency band. For the 6-min ATL data, the highest and lowest of the five total power densities were reported as MAX6 and MIN6. Also shown is the reference total power density value derived from the 30-min (reference ATL) mean spectrum, REF30. Exposure variability was calculated as $10 \times \log_{10} [(X/\text{REF30})]$ where X is MAX1, MIN1, MAX6 or MIN6. Similar formulae have been used previously to assess temporal variability in RF-EMF exposure (Aerts et al. 2018; Joseph and Verloock 2010; Iakovidis et al. 2025).

2.2.2 | Evaluation of Exposure Variability by Statistical Approach

In each frequency band, percentile levels up to P_{99} were calculated, and the whole data distribution was compared separately; the 30-min block to those of 1-min or 6-min. This comparison resulted in graphs (Figures 2 and 3) that facilitated comparison. Only five percentile levels, 5th (P_5), 25th (P_{25}), 50th (P_{50}), 75th (P_{75}) and 95th (P_{95}), of the two measurement block pairs (Pairs 1 and 2) were compared to facilitate the interpretation of exposure variability quantitatively (e.g., see Tables 4 and 5 showing comparison for mobile 1800 MHz band) (Fang et al. 2007). Pair 1 comprised of RF-EMF exposure data distribution of each 1-min block ($n = 30$) and a single 30-min block. Similarly, Pair 2 comprised of RF-EMF exposure data distribution of each 6-min block ($n = 5$) and a single 30-min block.

Each of the 30 individual 1-min blocks were compared with the remaining 29-min of the entire 30-min block. In each step of the comparison, a particular 1-min block to be compared was excluded from the 30-min block, resulting in the actual comparison of the 1-min block with the rest of the 29 (30 minus 1) min block, and so on. Similarly, each particular 6-min block (i.e., $n = 5$ blocks) was compared with the remaining 24-min of the entire 30-min block. In each comparison step, a particular 6-min block from the 30-min block was excluded to enable statistical comparison between that particular 6-min block and the rest of the 24-min block. Therefore, 29-min blocks (30 minus 1) and 24-min blocks (30 minus 6) were used as the proxy ATL for 30-min block for comparing it with 1-min and 6-min blocks, respectively, to enable the statistical comparison. These proxy measures of 30-min ATLs were hereafter referred to as “30-min” ATL.

Simultaneous QR analyses were conducted for statistical comparison of these blocks. The QR model is suitable for evaluating the comparison of skewed data with outliers (Chen and Westgate 2020; Bhatia et al. 2019); therefore, it has been applied in comparing multiple percentiles of RF-EMF exposure (Bhatt et al. 2024). The distribution of RF-EMF exposure values was then statistically compared in the following blocks: (i) the 30-min block and 30 different 1-min block data (30 subpair

TABLE 2 | Relative exposure variability (dB) of mean RF-EMF exposure levels relative to the 30-min reference value for the two averaging time lengths in different frequency bands at the measurement sites.

Frequency bands	1-min vs 30-min (pair type 1)		6-min vs 30-min (pair type 2)		REF (The International Telecommunication Union 2024b)
	Min	Max	Min	Max	
AM radio					
Yallambie	−0.09 dB	0.08 dB	−0.03 dB	0.03 dB	1970 $\mu\text{W}/\text{m}^2$
Springvale	−0.08 dB	0.08 dB	−0.03 dB	0.02 dB	35.88 $\mu\text{W}/\text{m}^2$
FM radio					
Yallambie	−0.25 dB	0.26 dB	−0.03 dB	0.04 dB	1.27 $\mu\text{W}/\text{m}^2$
Springvale	−0.24 dB	0.62 dB	−0.14 dB	0.30 dB	1.86 $\mu\text{W}/\text{m}^2$
VHF (very high frequency) band III					
Yallambie	−0.03 dB	0.03 dB	−0.01 dB	−0.01 dB	5.02 $\mu\text{W}/\text{m}^2$
Springvale	−0.01 dB	0.02 dB	−0.01 dB	0.01 dB	6.20 $\mu\text{W}/\text{m}^2$
Mobile 700 MHz					
Yallambie	−0.87 dB	0.86 dB	−0.27 dB	0.32 dB	284.95 $\mu\text{W}/\text{m}^2$
Springvale	−2.01 dB	2.11 dB	−0.91 dB	0.71 dB	5.43 $\mu\text{W}/\text{m}^2$
Mobile 800 MHz					
Yallambie	−0.81 dB	0.96 dB	−0.24 dB	0.35 dB	97.53 $\mu\text{W}/\text{m}^2$
Springvale	−0.68 dB	0.94 dB	−0.16 dB	0.26 dB	5.37 $\mu\text{W}/\text{m}^2$
Mobile 900 MHz					
Yallambie	−1.10 dB	2.97 dB	−0.71 dB	1.35 dB	18.66 $\mu\text{W}/\text{m}^2$
Springvale	−0.31 dB	0.68 dB	−0.14 dB	0.21 dB	13.69 $\mu\text{W}/\text{m}^2$
ISM band					
Yallambie ^a	−1.67 dB	1.64 dB	−1.05 dB	0.82 dB	0.08 $\mu\text{W}/\text{m}^2$
Springvale	−0.12 dB	0.14 dB	−0.06 dB	0.05 dB	0.26 $\mu\text{W}/\text{m}^2$
Mobile 1800 MHz					
Yallambie	−1.26 dB	0.87 dB	−0.34 dB	0.39 dB	45.76 $\mu\text{W}/\text{m}^2$
Springvale	−1.71 dB	2.39 dB	−0.43 dB	1.00 dB	18.98 $\mu\text{W}/\text{m}^2$
DECT (cordless phone)					
Yallambie ^a	−0.05 dB	0.07 dB	−0.05 dB	0.04 dB	0.04 $\mu\text{W}/\text{m}^2$
Springvale ^a	−0.28 dB	0.24 dB	−0.17 dB	0.19 dB	0.04 $\mu\text{W}/\text{m}^2$
Mobile 2100 MHz					
Yallambie	−2.22 dB	1.61 dB	−0.80 dB	0.65 dB	21.52 $\mu\text{W}/\text{m}^2$
Springvale	−1.05 dB	1.83 dB	−0.55 dB	0.45 dB	15.54 $\mu\text{W}/\text{m}^2$
Mobile 2300 MHz					
Yallambie	−2.98 dB	1.78 dB	−0.96 dB	1.31 dB	4.84 $\mu\text{W}/\text{m}^2$
Springvale	−0.38 dB	0.56 dB	−0.26 dB	0.10 dB	19.64 $\mu\text{W}/\text{m}^2$
Wi-Fi 2.4 GHz					
Yallambie	−5.13 dB	3.66 dB	−1.24 dB	1.54 dB	52.42 $\mu\text{W}/\text{m}^2$
Noble Park	−1.05 dB	1.07 dB	−0.33 dB	0.20 dB	1.18 $\mu\text{W}/\text{m}^2$
Mobile 2600 MHz					
Yallambie	−0.30 dB	0.49 dB	−0.13 dB	0.18 dB	1.01 $\mu\text{W}/\text{m}^2$
Springvale	−1.39 dB	1.17 dB	−0.69 dB	0.32 dB	0.73 $\mu\text{W}/\text{m}^2$

(Continues)

TABLE 2 | (Continued)

	1-min vs 30-min (pair type 1)		6-min vs 30-min (pair type 2)		REF (The International Telecommunication Union 2024b)
Frequency bands	Min	Max	Min	Max	
Mobile 3.4 GHz (5G-NR)					
Yallambie ^a	−0.27 dB	0.43 dB	−0.15 dB	0.25 dB	2.53 μW/m ²
Springvale	−0.32 dB	0.25 dB	−0.26 dB	0.19 dB	2.65 μW/m ²
Wi-Fi 5 GHz					
Yallambie	−0.25 dB	0.26 dB	−0.16 dB	0.20 dB	43.59 μW/m ²
Noble Park ^a	−0.31 dB	0.29 dB	−0.15 dB	0.15 dB	36.13 μW/m ²

^aVery low level of exposure close to or within the noise level.

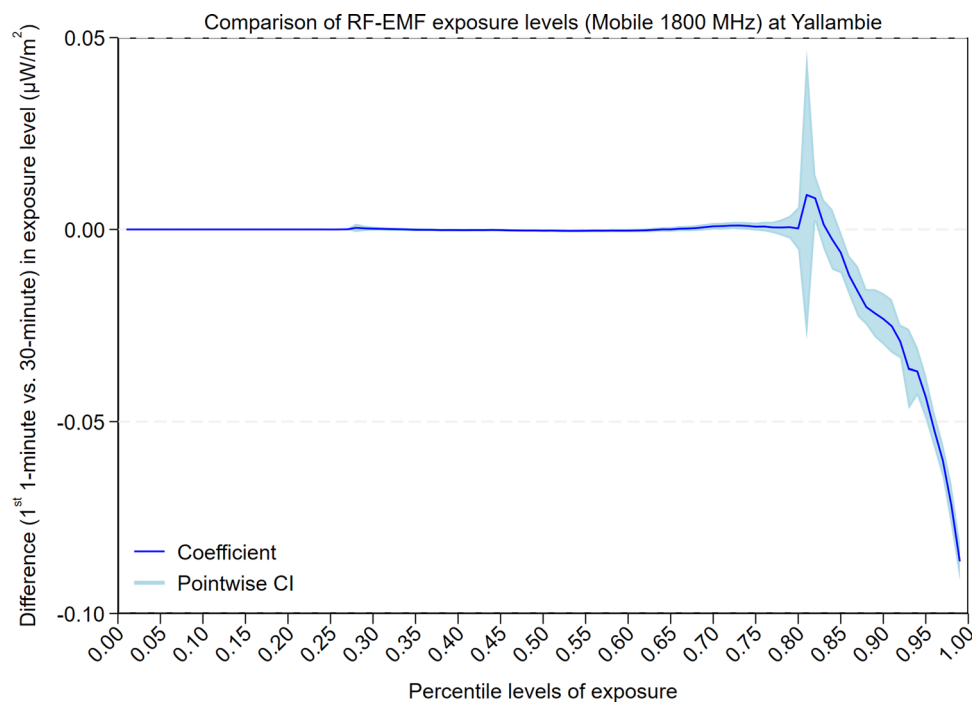


FIGURE 2 | Simultaneous quantile regression-based exposure trend showing estimated coefficients (in $\mu\text{W}/\text{m}^2$) by percentile levels (from 0.01 to 0.99 by 0.01; with 95% confidence interval) for Mobile 1800 MHz (Yallambie) frequency band. It illustrates the exposure difference between 1st 1-min and 30-min ATL blocks.

comparisons), and (ii) the 30-min block with five different 6-min block data (5 subpair comparisons). The Bonferroni correction was applied to the p -values associated with each individual test to maintain the α level over all tests at 0.05 (Sedgwick 2012). All statistical data analyses were carried out using StataSE 19 (StataCorp, College Station, TX, USA).

2.3 | Interpretation of Exposure Variability Analysis

The simultaneous QR model results provided a statistical comparison between 6- and 30-min or 1- and 30-min exposure distributions. For the interpretation of the results of these comparisons, we provide here a detailed comparison of these distributions for one of the key radio frequency bands

(mobile 1800 MHz) (Urbiniello et al. 2014). The comparison between 1st 6-min and 30-min blocks, and 1st 1-min and 30-min blocks (mobile 1800 MHz band) are included in Section 3 (Tables 4 and 5, respectively). The tables provide calculated differences in mean power density levels across five compared percentile levels for the distribution of data collected over different ATLs. For example, 1st row in Table 4, at Yallambie site, the calculated exposure difference (in $\mu\text{W}/\text{m}^2$) between ATLs of first 6- and 30-min blocks at the 5th percentile level was in the order of 10^{-06} , which was not significantly different (p -value = 0.88). On the other hand, for the same measurement site, the calculated difference (in $\mu\text{W}/\text{m}^2$) of the same block pairs at the 75th and 95th percentiles were in the order of 10^{-03} and 10^{-02} (significantly different, p -values < 0.0001), respectively. Detailed results for the other frequency bands (as shown in Tables 4 and 5) are not presented here. The difference in

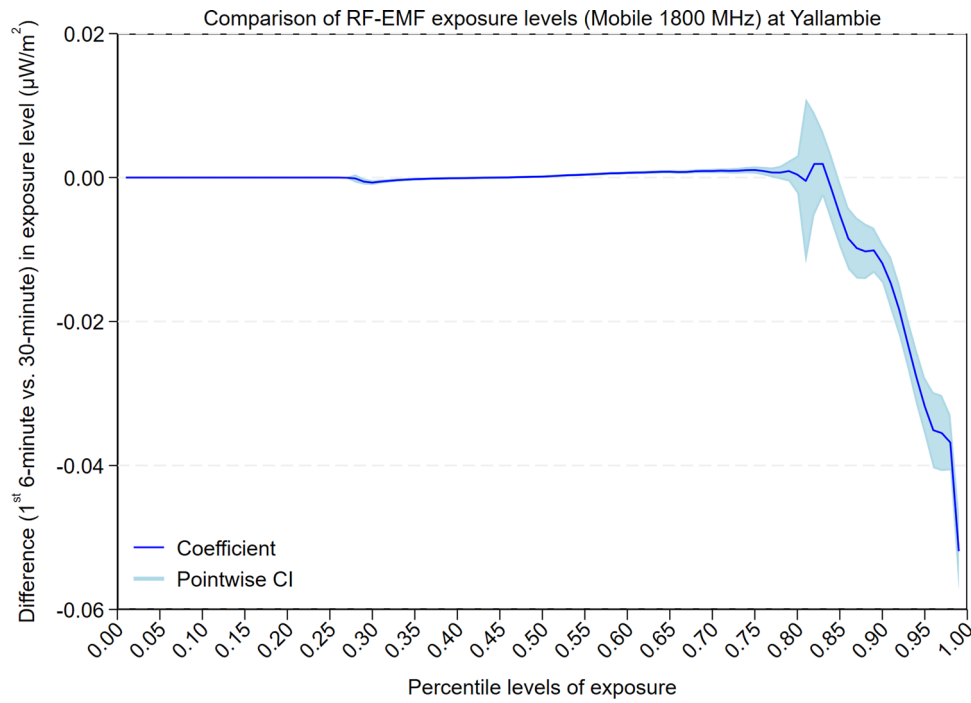


FIGURE 3 | Simultaneous quantile regression-based exposure trend showing estimated coefficients (in $\mu\text{W}/\text{m}^2$) by percentile levels (from 0.01 to 0.99 by 0.01; with 95% confidence interval) for Mobile 1800 MHz (Yallambie) frequency band. It illustrates the exposure difference between 1st 6-min and 30-min ATL blocks.

measured exposure ($\mu\text{W}/\text{m}^2$) across the five percentiles P_i with $i \in \{5, 25, 50, 75, 95\}$ were given for the two measurement sites (Yallambie and Springvale) separately. At the Yallambie site, the 1st 6-min block (compared with 30-min block) showed significantly lower exposure levels at a majority of percentiles (i.e., P_{25} , P_{50} , and P_{95}). At the Springvale site, the difference in exposure was significant across all the reported five percentiles. A graphical representation of the simultaneous QR model across all compared percentile levels was also shown for a mobile frequency of 1800 MHz (Figures 2 and 3).

Of the five reported exposure percentile levels in each frequency band, each pair of comparison (1-min vs. 30-min or 6-min vs. 30-min) was considered significantly different if a majority (at least, 3 of 5) of the reported percentiles had statistically different exposure levels. In other words, two ATLs would yield similar exposure distribution if the above condition was not fulfilled. The results of these comparisons (referred to as “overall outcome”) are summarised in Table 3 for each measurement site and frequency band. For example, none of the reported percentile comparisons were different for AM radio, which indicates that there is no difference between the ATLs for this frequency band.

3 | Results

The findings are presented in two separate subsections. First, the results of the nonstatistical evaluation, relative variability (in dB), of measurements associated with 1- and 6-min ATL, compared with 30-min ATL, are presented. Second, the results of the statistical comparison of RF-EMF exposure distribution of 1- or 6-min ATL to 30-min ATL using QR are presented. Very low level of mean REF30 values (in Table 2) measured for

DECT at both sites, ISM and Mobile 3.4 GHz bands at Yallambie, and Wi-Fi 5 GHz at Noble Park were within or close to the noise levels. Therefore, since the signals in these bands could not be reliably distinguished from background noise, we excluded them from the statistical comparison of exposure variability (in Table 3, marked as not applicable (“NA”).

3.1 | Evaluation of Relative Measurement Variabilities (1- vs. 30-min; 6- vs. 30-min)

Table 2 shows the relative variability in measurements for highest and lowest mean values for 1-min versus 30-min and 6-min versus 30-min ATLs. In general, the measurement variabilities were slightly higher for 1-min versus 30-min ATL compared with 6-min versus 30-min ATL. Almost all the variability values were within ± 3 dB for both ATLs. The only exception was for the non-line-of-sight 2.4 GHz Wi-Fi 1-min versus 30-min comparison in Yallambie. In this case, there were large variations in the measured spectrum over the 30 min, resulting in differences ranging from -5.1 dB to $+3.7$ dB.

3.2 | Evaluation of Overall Exposure Variability (1- vs. 30-min and 6- vs. 30-min)

This analysis provides the assessment of overall outcome of exposure variability (across data distribution) of two ATL pairs; Pair 1 (1- vs. 30-min) and Pair 2 (6- vs. 30-min) measured at two locations. Overall exposure variability of the given ATLs pair comparisons is summarised in Table 3. The full results of the comparison of measured exposure values (P_5 , P_{25} , P_{50} , P_{75} , and P_{95}) at two sites for each ATL pair of each frequency band are

TABLE 3 | Summary of overall exposure variability in RF-EMF exposure distribution for two averaging time length pairs (1-min vs 30-min; and 6-min vs 30-min).

Frequency bands	1-min ^b vs 30-min ^c (× pair type 1; total no. of pairs = 30)		6-min ^d vs 30-min ^c (×× pair type 2; total no. of pairs = 5)	
	Significantly different data distribution sub-pairs, % (n) ^a	Overall exposure variability [Different if % is > 50] ^e	Significantly different data distribution sub-pairs, % (n) ^a	Overall exposure variability [Different if % is > 50] ^e
AM Radio				
Yallambie	0% (0)	Not different	0 (0%)	Not different
Springvale	0% (0)	Not different	0 (0%)	Not different
FM Radio				
Yallambie	100% (30)	Different	100% (5)	Different
Springvale	36.7% (11)	Not different	80% (4)	Different
VHF (very high frequency) band III				
Yallambie	83.3% (25)	Different	0% (0)	Not different
Springvale	3.3% (1)	Not different	20% (1)	Not different
Mobile 700 MHz				
Yallambie	33.3% (10)	Not different	60% (3)	Different
Springvale	56.7.3% (17)	Different	100% (5)	Different
Mobile 800 MHz				
Yallambie	10% (3)	Not different	0% (0)	Not different
Springvale	16.7% (5)	Not different	40% (2)	Not different
Mobile 900 MHz				
Yallambie	0% (0)	Not different	0% (0)	Not different
Springvale	0% (0)	Not different	0% (0)	Not different
ISM Band				
Yallambie	NA	NA	NA	NA
Springvale	80% (24)	Different	100% (5)	Different
Mobile 1800 MHz				
Yallambie	33.3% (10)	Not different	40% (2)	Not different
Springvale	3.3% (1)	Not different	20% (1)	Not different
DECT (cordless phone)				
Yallambie	NA	NA	NA	NA
Springvale	NA	NA	NA	NA
Mobile 2100 MHz				
Yallambie	33.3% (10)	Not different	80% (4)	Different
Springvale	33.3% (10)	Not different	60% (3)	Different
Mobile 2300 MHz				
Yallambie	43.3% (13)	Not different	80% (4)	Different
Springvale	0% (0)	Not different	0% (0)	Not different
Wi-Fi 2.4 GHz				
Yallambie	3.3% (1)	Not different	40% (2)	Not different
Noble Park	80% (24)	Different	100% (5)	Different
Mobile 2600 MHz				

(Continues)

TABLE 3 | (Continued)

Frequency bands	1-min ^b vs 30-min ^c ([×] pair type 1; total no. of pairs = 30)		6-min ^d vs 30-min ^c ([×] pair type 2; total no. of pairs = 5)	
	Significantly different data distribution sub-pairs, % (n) ^a	Overall exposure variability [Different if % is > 50] ^e	Significantly different data distribution sub-pairs, % (n) ^a	Overall exposure variability [Different if % is > 50] ^e
Yallambie	46.4% (13)	Not different	80% (4)	Different
Springvale	80% (24)	Different	100% (5)	Different
Mobile 3.4 GHz (5G-NR)				
Yallambie	NA	NA	NA	NA
Springvale	66.7% (20)	Different	80% (4)	Different
Wi-Fi 5 GHz				
Yallambie	0% (0)	Not different	40% (2)	Not different
Noble Park	NA	NA	NA	NA

^aif at least three compared corresponding percentile values (across the percentiles of P₅, P₂₅, P₅₀, P₇₅, P₉₅) of compared blocks of 1-or 6-min versus 30-min were significantly different (simultaneous quantile regression with Bonferroni correction).

^bn = 30 unique 1-min data blocks.

^cA single 30-min data block.

^dn = 5 unique 6-min data blocks; [×]150 (30 × 5) comparisons of corresponding percentiles; [×]25 (5 × 5) comparisons of corresponding percentiles.

^eOverall exposure variability (in data distribution pairs) was considered different if % value for pair A and pair B were > 50%.

provided separately in the Supporting Information. The simultaneous QR model graphical outputs for the 1800 MHz band measured in Yallambie are shown in Figures 2 and 3, illustrating the comparison between the first 1-min or 6-min blocks and 30-min block, respectively.

Figure 2 shows the regression coefficient value (shown on Y-axis), which is the difference between exposure (in $\mu\text{W}/\text{m}^2$) reported by 1st 1-min and 30-min ATL blocks, plotted across all estimated percentile levels (shown on X-axis). The regression line running fairly flat up to 80th percentile level indicates a little difference in the exposure of the 1st 1-min and 30-min distributions. The value of the coefficient shows a brief, small increase around P_{80} – P_{85} followed by a steady drop at higher percentiles. This indicates that the magnitude of difference, reflected in terms of the value of the regression coefficient, become much lower across higher percentile levels. Figure 3 also shows a similar pattern for the comparison of 1st 6-min block and compared with 30-min block. These trends are also reflected in the estimated exposure difference given in Tables 4 and 5 for the five reported percentile levels.

Of the measurements collected in 15 frequencies bands, only five frequency bands showed consistent outcomes while comparing between 1- or 6- or 6-min and 30-min ATLs across both sites (see Table 3). For example, four frequency bands (AM radio, and mobile bands of 800 MHz, 900 MHz, 1800 MHz) showed overall similar exposure variability, while one (3.4 GHz) frequency band showed overall different exposure variability. The other individual frequency bands, such as mobile 2600 MHz, Wi-Fi, etc. showed inconsistent outcomes across two measurement sites.

i. Comparison between 1-min and 30-min blocks

No difference in the overall outcome of exposure variability was observed for AM radio with the exception of

the 80th to 99th percentiles in both sites; whilst for FM radio and VHF band III showed mixed outcomes (different at Yallambie, but not different at Springvale). Mobile services with < 2 GHz frequency bands (except for mobile 700 MHz) showed inconsistent results. In mobile services with > 2 GHz frequency bands, mobile 2100 MHz and 2300 MHz data distributions showed similar overall exposure variability across both sites; whilst mobile 2600 MHz showed inconsistent outcomes. The comparison of mobile 2300 MHz distributions showed similar exposure variability across both measurement sites. Wi-Fi exposure distributions showed inconsistent variability; except for Noble Park at 2.4 GHz, all exposure distributions demonstrated similar outcomes. ISM showed inconsistent overall exposure variability.

ii. Comparison between 6-min and 30-min blocks

The overall exposure variability for exposure sources (frequency bands) was “not different” for most of the radio and TV frequency bands (except FM radio) and mobile services with < 2 GHz frequency bands. Only 700 MHz band was the exception in both the 1- and 6-min comparisons. All other frequency bands of mobile services (> 2 GHz frequency) showed “different” overall exposure variability. Mobile 2300 MHz distributions resulted in inconsistent outcomes. The overall exposure variability for measurement sites (Yallambie and Springvale) was “not different” while comparing 1-min vs 30-min. However, the 6-min vs 30-min comparison of exposure variability showed “different” for Yallambie but “not different” for Springvale. Wi-Fi (2.4 GHz and 5 GHz) exposure showed inconsistent variability too; Yallambie and Noble Park exposure variability showing overall similar and different outcomes, respectively. ISM showed overall different exposure variability.

TABLE 4 | Estimated difference in measured RF-EMF exposure between the five 6-min blocks and the 30-min block across five different percentile levels for the Mobile 1800 MHz band.

	Estimated difference in measured exposure ($\mu\text{W}/\text{m}^2$) across various compared percentiles (significantly different values in bold)									
	P_5		P_{25}		P_{50}		P_{75}		P_{95}	
	Exposure diff.	p-value	Exposure diff.	p-value	Exposure diff.	p-value	Exposure diff.	p-value	Exposure diff.	p-value
1 st 6-min										
Yallambie	-2.97E-06	0.88	-3.24E-06	0.93	1.32E-04	0.12	1.05E-03	< 0.0001	-3.18E-02	< 0.0001
Springvale	-6.80E-07	0.96	5.74E-06	0.85	-1.07E-04	0.37	7.55E-04	0.03	9.80E-03	< 0.0001
2 nd 6-min										
Yallambie	-1.08E-06	0.95	-3.68E-06	0.93	-6.84E-04	< 0.0001	-8.19E-04	0.0004	-2.20E-02	< 0.0001
Springvale	-3.00E-07	0.98	-2.75E-06	0.92	3.21E-04	0.01	6.32E-04	0.01	-3.66E-03	< 0.0001
3 rd 6-min										
Yallambie	6.00E-07	0.97	-9.90E-07	0.98	1.89E-04	0.01	6.59E-04	0.02	-1.67E-02	0.005
Springvale	-2.70E-07	0.98	-1.46E-06	0.96	-6.28E-04	< 0.0001	-2.02E-03	< 0.0001	-3.80E-03	< 0.0001
4 th 6-min										
Yallambie	1.47E-06	0.94	2.04E-06	0.96	-4.60E-04	< 0.0001	-2.51E-03	< 0.0001	7.50E-03	0.007
Springvale	4.60E-07	0.97	-3.93E-06	0.89	-1.82E-05	0.87	6.32E-05	0.83	-2.10E-03	0.004
5 th 6-min										
Yallambie	2.54E-06	0.90	4.52E-06	0.91	8.16E-04	< 0.0001	1.94E-03	< 0.0001	6.58E-02	< 0.0001
Springvale	8.20E-07	0.95	2.13E-06	0.94	6.30E-04	< 0.0001	9.81E-04	< 0.0001	-2.48E-04	0.70

Note: Each 6-min block was compared with to the 30-min block in terms of difference in exposure level. In each comparison, 6-min block to be compared was excluded from the 30-min block (i.e., comparison of the 6-min block with the rest of 24 min block); p-values were significant at ≤ 0.002 (0.05/25).

TABLE 5 | Estimated difference in measured RF-EMF exposure between the thirty 1-min blocks and the 30-min block across five different percentile levels for the Mobile 1800 MHz band.

Estimated difference in measured exposure ($\mu\text{W}/\text{m}^2$) across various compared percentiles (significantly different values in bold)											
	P_5		P_{25}		P_{50}		P_{75}		P_{95}		
1 st 1-min	Exposure diff.	p-value	Exposure diff.	p-value	Exposure diff.	p-value	Exposure diff.	p-value	Exposure diff.	p-value	
Yallambie	-3.39E-06	0.94	-4.25E-06	0.96	-3.10E-04	0.06	7.22E-04	0.16	-4.36E-02	< 0.0001	
Springvale	-7.70E-07	0.98	5.34E-06	0.93	-1.47E-04	0.62	2.46E-03	0.03	1.89E-02	< 0.0001	
2 nd 1-min											
Yallambie	-2.84E-06	0.95	-2.48E-06	0.97	-1.53E-03	< 0.0001	-3.34E-03	< 0.0001	1.90E-02	< 0.0001	
Springvale	-5.90E-07	0.98	9.99E-06	0.88	2.74E-04	0.36	2.81E-03	0.03	1.02E-02	< 0.0001	
3 rd 1-min											
Yallambie	-2.37E-06	0.95	-2.35E-06	0.98	7.44E-04	0.002	4.27E-05	0.92	-3.16E-02	< 0.0001	
Springvale	-5.10E-07	0.98	-2.56E-06	0.97	1.92E-05	0.94	1.44E-03	0.10	1.30E-02	< 0.0001	
4 th 1-min											
Yallambie	-2.22E-06	0.96	-1.55E-06	0.98	2.24E-03	< 0.0001	2.26E-03	< 0.0001	-6.36E-02	< 0.0001	
Springvale	-3.70E-07	0.99	-1.99E-06	0.97	-7.14E-04	0.0002	-2.57E-03	< 0.0001	-3.38E-03	0.001	
5 th 1-min											
Yallambie	-1.93E-06	0.96	-3.48E-06	0.97	-9.69E-04	< 0.0001	2.51E-04	0.71	2.94E-02	< 0.0001	
Springvale	-5.40E-07	0.98	9.27E-06	0.89	4.16E-05	0.87	-4.60E-04	0.48	1.35E-03	0.33	
6 st 1-min											
Yallambie	-1.26E-06	0.97	1.08E-06	0.99	1.79E-03	< 0.0001	1.82E-03	< 0.0001	1.60E-03	0.57	
Springvale	-4.40E-07	0.98	1.04E-05	0.88	1.38E-04	0.60	1.18E-04	0.88	-3.50E-03	0.0002	
7 th 1-min											
Yallambie	-1.21E-06	0.97	-3.36E-06	0.97	2.27E-04	0.21	-1.47E-03	< 0.0001	-2.44E-02	< 0.0001	
Springvale	2.00E-07	0.99	-3.89E-06	0.95	1.20E-04	0.71	1.55E-03	0.16	4.49E-03	0.0003	
8 th 1-min											
Yallambie	-6.30E-07	0.98	-3.08E-06	0.97	-6.30E-05	0.78	2.37E-03	< 0.0001	-1.09E-02	0.0001	
Springvale	-8.40E-07	0.98	-3.51E-06	0.96	-6.03E-04	0.002	-1.88E-03	0.003	-1.66E-03	0.13	
9 th 1-min											
Yallambie	-9.70E-07	0.98	-8.00E-07	0.99	-5.71E-04	0.01	2.91E-04	0.51	5.46E-02	< 0.0001	
Springvale	-2.00E-08	0.99	7.90E-07	0.99	9.40E-04	0.001	1.44E-03	0.001	-1.05E-02	< 0.0001	
10 th 1-min											
Yallambie	-8.50E-07	0.98	-1.75E-06	0.98	5.92E-05	0.70	-1.88E-04	0.70	3.36E-02	< 0.0001	
Springvale	-8.20E-07	0.97	1.58E-06	0.98	1.02E-03	0.0009	1.67E-03	0.0001	-9.24E-03	< 0.0001	
11 th 1-min											
Yallambie	-7.20E-07	0.98	-3.73E-06	0.96	-1.46E-03	< 0.0001	-2.60E-03	0	-6.14E-02	< 0.0001	
Springvale	-5.90E-07	0.98	-2.79E-06	0.96	-1.57E-04	0.51	-1.53E-03	0.0001	9.17E-04	0.36	
12 th 1-min											
Yallambie	-9.10E-07	0.98	-4.41E-06	0.96	-1.17E-03	< 0.0001	-3.70E-03	< 0.0001	-2.89E-02	< 0.0001	
Springvale	2.50E-07	0.99	-2.90E-06	0.96	6.05E-04	0.05	8.98E-04	0.14	-4.81E-03	< 0.0001	
13 th 1-min											
Yallambie	-3.40E-07	0.99	1.32E-06	0.98	7.45E-04	0.0001	2.41E-03	< 0.0001	8.90E-03	0.0002	
Springvale	-3.80E-07	0.99	-2.10E-06	0.97	-8.26E-04	< 0.0001	-2.83E-03	< 0.0001	1.40E-03	0.27	

(Continues)

TABLE 5 | (Continued)

Estimated difference in measured exposure ($\mu\text{W}/\text{m}^2$) across various compared percentiles (significantly different values in bold)											
	P_5		P_{25}		P_{50}		P_{75}		P_{95}		
14 th 1-min											
Yallambie	8.00E-08	0.99	-1.22E-06	0.98	8.15E-04	< 0.0001	-7.90E-04	0.07	2.06E-02	< 0.0001	
Springvale	3.30E-07	0.99	1.90E-06	0.97	4.49E-04	0.17	2.67E-05	0.94	6.37E-03	< 0.0001	
15 th 1-min											
Yallambie	-2.10E-07	0.99	-3.04E-06	0.97	4.18E-04	0.03	3.89E-03	< 0.0001	-6.61E-02	< 0.0001	
Springvale	-6.20E-07	0.98	2.68E-06	0.96	-7.59E-04	0.0007	-3.24E-03	< 0.0001	6.93E-03	< 0.0001	
16 th 1-min											
Yallambie	1.28E-06	0.97	1.29E-06	0.98	-5.14E-05	0.75	2.43E-03	0.0007	3.59E-02	< 0.0001	
Springvale	7.00E-08	0.99	-5.53E-06	0.93	-7.61E-04	0.0004	-2.85E-03	< 0.0001	-1.94E-02	< 0.0001	
17 th 1-min											
Yallambie	1.10E-06	0.98	-4.69E-06	0.96	-1.37E-03	< 0.0001	-2.74E-03	< 0.0001	1.43E-02	0.002	
Springvale	1.00E-07	0.99	-2.00E-07	0.99	-5.93E-04	0.01	-2.91E-03	< 0.0001	-1.31E-02	< 0.0001	
18 th 1-min											
Yallambie	9.80E-07	0.98	3.74E-06	0.96	2.70E-04	0.04	-3.03E-03	< 0.0001	-7.07E-02	< 0.0001	
Springvale	-9.00E-07	0.97	-2.10E-06	0.97	7.49E-04	0.007	-1.09E-04	0.76	-9.78E-03	< 0.0001	
19 th 1-min											
Yallambie	8.40E-07	0.98	1.61E-06	0.98	1.08E-05	0.93	-2.48E-03	< 0.0001	2.72E-02	< 0.0001	
Springvale	2.20E-07	0.99	-4.06E-06	0.95	6.96E-04	0.04	5.01E-04	0.12	-9.86E-03	< 0.0001	
20 th 1-min											
Yallambie	8.10E-07	0.98	-8.60E-07	0.99	-1.88E-03	< 0.0001	-4.20E-03	< 0.0001	-3.94E-02	< 0.0001	
Springvale	3.70E-07	0.99	-3.81E-06	0.95	8.44E-05	0.75	-1.02E-03	0.05	6.28E-03	< 0.0001	
21 st 1-min											
Yallambie	1.51E-06	0.97	1.90E-07	0.99	-1.01E-04	0.61	-3.11E-04	0.39	-6.72E-02	< 0.0001	
Springvale	1.70E-07	0.99	3.00E-07	0.99	-1.77E-04	0.45	-1.25E-03	0.05	6.97E-03	< 0.0001	
22 nd 1-min											
Yallambie	2.27E-06	0.96	1.55E-06	0.98	-9.30E-04	< 0.0001	-3.84E-03	< 0.0001	2.97E-02	< 0.0001	
Springvale	5.20E-07	0.98	-4.49E-06	0.94	-5.41E-04	0.005	-1.95E-03	0.002	5.13E-03	0.0001	
23 rd 1-min											
Yallambie	6.10E-07	0.98	4.08E-06	0.96	1.31E-03	< 0.0001	-7.58E-04	0.01	1.00E-01	< 0.0001	
Springvale	6.50E-07	0.98	-5.22E-06	0.93	-6.06E-04	0.003	-2.68E-03	< 0.0001	-1.15E-02	< 0.0001	
24 th 1-min											
Yallambie	1.22E-06	0.97	2.45E-06	0.97	-5.29E-04	< 0.0001	-3.62E-03	< 0.0001	-2.80E-03	0.31	
Springvale	3.70E-07	0.99	-1.90E-06	0.97	1.34E-03	0.0007	4.85E-03	< 0.0001	-1.34E-02	< 0.0001	
25 th 1-min											
Yallambie	1.74E-06	0.97	3.10E-06	0.97	9.36E-04	< 0.0001	-1.03E-03	0.02	-3.92E-02	< 0.0001	
Springvale	9.40E-07	0.97	-4.36E-06	0.94	-2.45E-04	0.30	-1.49E-03	0.007	-1.00E-02	< 0.0001	
26 th 1-min											
Yallambie	2.32E-06	0.96	3.80E-06	0.96	3.10E-04	0.03	-4.42E-04	0.36	4.93E-02	< 0.0001	
Springvale	3.60E-07	0.99	-2.83E-06	0.96	-6.40E-04	0.003	-2.43E-03	< 0.0001	-1.29E-02	< 0.0001	
27 th 1-min											
Yallambie	2.20E-06	0.96	0.00E + 00	1	5.80E-04	0.0001	-1.03E-03	0.008	6.49E-02	< 0.0001	

(Continues)

TABLE 5 | (Continued)

Estimated difference in measured exposure ($\mu\text{W}/\text{m}^2$) across various compared percentiles (significantly different values in bold)										
	P_5		P_{25}		P_{50}		P_{75}		P_{95}	
Springvale	7.00E-07	0.98	-6.50E-07	0.99	6.79E-04	0.01	1.42E-04	0.81	1.19E-02	< 0.0001
28 th 1-min										
Yallambie	1.82E-06	0.96	2.36E-06	0.98	-3.29E-04	0.03	1.00E-03	0.11	-8.50E-03	0.0002
Springvale	9.00E-08	0.99	4.86E-06	0.94	1.92E-03	< 0.0001	2.92E-03	0.0001	7.19E-03	< 0.0001
29 th 1-min										
Yallambie	2.82E-06	0.95	5.11E-06	0.95	1.34E-03	< 0.0001	5.41E-03	< 0.0001	1.46E-01	< 0.0001
Springvale	6.90E-07	0.98	2.06E-05	0.75	1.59E-03	< 0.0001	2.46E-03	0.0001	3.79E-03	0.007
30 th 1-min										
Yallambie	2.28E-06	0.96	6.19E-06	0.94	1.95E-03	< 0.0001	5.32E-03	< 0.0001	1.75E-01	< 0.0001
Springvale	1.13E-06	0.97	4.58E-06	0.94	1.26E-03	0.0006	1.26E-03	0.0003	-9.02E-03	< 0.0001

Note: Each 1-min block was compared with to the 30-min block in terms of difference in exposure level. In each comparison, 1-min block to be compared was excluded from the 30-min block (i.e., comparison of the 1-min block with the rest of 29 min block); p-values were significant at ≤ 0.0003 (0.05/150).

4 | Discussion

This study assessed measurement variability associated with different ATLS employed in environmental RF-EMF exposure monitoring, specifically 1-min and 6-min, compared to 30-min ATL. This was undertaken by employing both nonstatistical and statistical approaches to data analysis. In addition, it also compared RF-EMF exposure variability across multiple percentile levels by comparing the exposure distributions of 1-min and 6-min to that of 30-min. The findings of these comparisons on exposure variability obtained through two different approaches indicate that 1-min and 6-min ATLS provide comparable results across majority of the measured frequency bands.

The relative variability (or relative deviation in dB) values reported in our study were consistent across multiple measured frequency bands and measurement sites. In fact, the measurement variabilities of both ATLS (1-min and 6-min) largely remained within ± 3 dB. This is consistent with the RF-EMF exposure variability associated with different averaging time lengths in monitoring human exposures to mobile base station (The International Telecommunication Union 2024a). For example, ATLS of 1- and 6-min have been shown to provide exposure variability of less than 1 dB (The International Telecommunication Union 2024a). A broadband measurement (420 MHz - 6 GHz) survey assessing RF-EMF exposure difference between ATLS of 1-, 6- and 30-min showed that most of the 1-min and 6-min measurements had differences (compared to reference 30-min ATL) less than 1 dB (The International Telecommunication Union 2024b). Evidence therefore largely indicates that exposure variability for different shorter ATLS, including 1-min, are comparable to those obtained from the ATL of 6-min (The International Telecommunication Union 2024a). All this evidence largely supports the validity of environmental RF-EMF exposure assessments obtained using shorter ATLS, including 1-min (Onishi et al. 2021; Henderson et al. 2023; The International Telecommunication Union 2024a). The long-term RF-EMF exposure monitoring data shows much higher exposure variability (Aerts et al. 2018; The

International Telecommunication Union 2024a). For example, the variability of exposure could be about 3 dB over a day long period and up to 10 dB for week-long period (The International Telecommunication Union 2024a). One of the reasons for higher variability in measurements using longer averaging times is mainly due to changes in the mobile phone telecommunication traffic (i.e., changes in output from base station) over time. However, the averaging times applied in long-term measurements are different to those discussed in the current study.

In terms of overall exposure variability, our study showed similar variability of RF-EMF exposure for the exposure distributions of most of the radio and TV frequency bands. This is intuitive since the RF-EMF exposure from the transmission of broadcasting systems typically does not vary greatly with time (The International Telecommunication Union 2018), which means that different ATLS are likely to offer similar overall exposure variation across the RF-EMF exposure distribution. For mobile telecommunications frequencies, overall similar exposure variability was evident mostly in mobile services with < 2 GHz frequency bands; while the variability was inconsistent and much more obvious for mobile services with > 2 GHz frequency bands and Wi-Fi. This was most likely due to the nature of mobile telecommunications systems (e.g., LTE) using adaptive power, where the RF-EMF exposure varies with time depending on different factors such as mobile traffic and dynamic power control (The International Telecommunication Union 2018). A recent study from Greece compared a long-term variability of RF-EMF exposure and found that the variability (in terms of R ratio = $E_{\text{median}}/E_{\text{max}}$) may be different depending on the RF-EMF frequency bands (Iakovidis et al. 2025). For example, it was lowest for the FM radio band and highest for the 3.6 GHz (5G-NR) band (Iakovidis et al. 2025). The Greek study also noted that exposure variability for mobile-telecommunication frequencies increased from 800 MHz to 2600 MHz with the exception of 900 MHz. This infers that higher exposure variability is more likely for higher frequencies. Different frequency bands of mobile phone telecommunication

systems in the current study are associated with various generation of technologies, such as 3 G, 4 G and 5G-NR (Henderson et al. 2023). In Australia, the same frequency band was used by different mobile telecommunication technologies; for example, Mobile 800 MHz was used by 4 G/LTE or 5 G/NR, and Mobile 2100 MHz used by 3 G/WCDMA technologies (Henderson et al. 2023). Therefore, exposure variability observed in different ATLs could also be attributed to the type of mobile technology used in a particular band and the amount of data traffic it carried during the measurements. It has been indicated that RF-EMF exposure variability is likely to differ depending on the type of radio antenna emitting the signals (or frequency), weather or radio propagation conditions, as well as space and time (Iakovidis et al. 2025; The International Telecommunication Union 2024b). The inconsistent findings on different frequency bands and measurement sites also reflect this in the current study. Similarly, Wi-Fi exposure particularly varies depending on Web-browsing data-traffic or duty cycle, which could potentially explain inconsistent overall exposure variability observed in this study (Pachón-García et al. 2015; Verloock et al. 2010). In general, our findings on overall exposure variability showed that RF-EMF exposure associated with 1-min and 6-min ATLs (compared to 30-min) were comparable across a majority of frequency bands. It was clear from the recorded spectra observed in the current study that most of the frequency bands measured in this study contained active services with signals easily detectable above the noise floor.

There have been few studies that have reported comparisons of different ATLs of RF-EMF exposures from several frequency bands (Asadi et al. 2023, 2020; Šuka et al. 2019). Asadi et al. assessed the effect of different ATLs of 30 s, 1 min and 6 min on reporting average RF-EMF exposure levels (average power density) for a wide frequency band of 3 MHz–18 GHz (Asadi et al. 2023, 2020). The overall observed difference between 30-second and 6-minute averaging time length from the reference value was < 3 dB (Asadi et al. 2020). That study concluded shorter ATLs such as 30-second or 60-second provide comparable RF-EMF exposure levels that of 6-min for radio wave signals in both indoor and outdoor human environments. Šuka et al. (2019) measured RF-EMF exposure of mobile frequency bands, including Global System for Mobile Communications 900 MHz, Digital Communication System 1800 MHz, and Universal Mobile Telecommunications System 2100 MHz, compared the variability in measurements associated with shorter averaging time lengths (15 s, 30 s and 1 min) to those of 6-min. That study found the standard variabilities with these ATLs were below 5%. In addition, the relative deviations from 6-min root-mean-square mean for 15 s, 30 s and 1-min ATL were 19%, 16% and 10.5%, respectively. These results demonstrated that shorter ATL can be applied to reduce the total duration of the exposure assessment survey with a reasonably acceptable variability in exposure. A study from Japan showed that measurement variability (E-field strength of Wideband Code Division Multiple Access at 800 MHz) for different shorter and longer ATLs (including of 1- and 6-min) remained within ≤ 3 dB (Watanabe and Hamada 2016). Though these studies used different methods to assess effect of different ATLs on reporting RF-EMF exposure, their results are consistent to each other indicating the justified application of shorter ATLs in RF-EMF exposure monitoring. Since RF-EMF exposure

measurements with longer ATLs are time consuming, application of a lower ATL is a valid approach particularly for the situation where the exposure levels are expected be far below the limits (The International Telecommunication Union 2024b).

Our findings indicate that ATLs of 1-min and 6-min (when compared to 30-min) provide overall similar outcomes. This demonstrates that 1-min ATL can adequately characterise ambient exposure levels in human environments. This is consistent with the suggestion from other studies that short measurement times, such as 1-min, are generally adequate to estimate RF-EMF exposure value representative of longer averaging times (Asadi et al. 2023, 2020; The International Telecommunication Union 2020; Pachón-García et al. 2015). However, this is based on the comparison of exposure variability measured at the five reported percentiles. The results could be different if evaluation of the exposure variability involves comparison of the exposure across multiple percentiles. The exposure variability tends to become significantly larger across higher percentile levels (see Figures 2 and 3 – the graphs only available for mobile 1800 MHz band). It is unclear why this occurs; therefore, future research is required to understand this observation.

This study has a few notable strengths. It evaluated RF-EMF exposure variability associated with most of the frequency bands of contemporary telecommunication and broadcast technologies. The exposure variability was studied using a robust statistical approach, enabling simultaneous comparison of exposure levels across multiple percentiles. Further, a convenience (i.e., non-probability) sampling method adopted in this study is an accepted approach to RF-EMF exposure assessment studies, (Röösli et al. 2010) and is regarded as a cost-effective approach despite having less clear generalizability than probability samples (e.g., random sampling) (Speak et al. 2018). The findings of the study, therefore, are likely to support the advancement of evidence on averaging time lengths used in RF-EMF exposure assessments in human environments. The aim of this study was to evaluate the effect of using different ATLs on measured exposures rather than characterise the actual level of exposure. It is acknowledged that the study included measurements for only a limited number of occasions and environments, therefore, the reported exposure levels may not be representative of all exposure situations in Australia. The exposure measurements in this study were undertaken under passive conditions, including no “beam forming” condition for 3.5 GHz (5G-NR) frequency band. Hence the extremely low signal level in this band (particularly in Yallambie) and consequently the exposure variability reported in this particular frequency band does not represent “beamforming” condition. In fact, beamforming antennas of 5G-NR networks could provide additional variability in exposure levels over time (The International Telecommunication Union 2024b).

In conclusion, the study showed that ATLs of 1-min and 6-min used in RF-EMF exposure monitoring provide acceptable and comparable exposure variability (mostly within ± 3 dB) across almost all measured frequency bands. The ATLs 1-min and 6-min (compared with longer ATL of 30-min), for a majority of frequency bands, also tend to provide similar overall exposure variability. These findings, consistent to available evidence

(e.g., Asadi et al. 2023, 2020; The International Telecommunication Union 2020, 2024b) confirm that a shorter ATL such as 1-min can adequately assess environmental RF-EMF exposure levels from most of the broadcast and telecommunication frequencies with acceptable exposure variability. However, as indicated in the current and recent study (Iakovidis et al. 2025), a longer ATL could be more favourable particularly for the fifth-generation mobile phone frequency band (e.g., 3.5 GHz in view of capturing larger exposure variability. Therefore, the selection of ATL should be considered in view of this emerging knowledge, and the trade-off between what is practically achievable and what can still be a fair representative of existing RF-EMF exposure levels of different frequency bands.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data collected for this article could be shared on a reasonable request to the corresponding author.

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