Table 1. Chromosome aberration analysis in 455.7 MHz-exposed human peripheral blood lymphocytes

Donor	Number of cells	Number of cells	Gaps/isogaps		Chromatid breaks		Iso-chromatid breaks & Acentric fragments		Dicentrics	
	control	455.7 MHz	control	455.7 MHz	control	455.7 MHz	control	455.7 MHz	control	455.7 MHz
1	200	200	2		1	4	1		3	
2	200	200		2	1	1	1			1
3	192	169	1	1	3	1	1		1*	
4	200	200	2		3		2	1	1**	
5	130	200		1	1			3		
6	200	200			2	2		1		
7	200	200		1	2	1	1	1		1
8	200	200	1			1	1	1		
9	200	200			3	3				2
10	200	200			1	2	1			2
11	200	200		1		3	1	1		3
12	200	200	1		2	3		1		
13	200	200		1		3	1			
14	200	200				1				
15	64	152								
16	114	200			1					
19	200	200				1	1			2
20	200	200			3	3	1	1		
21	200	200			4		1	1		
22	200	200					2	3		1
30	200	200	2	1	2	2	1	2	1	
31	200	200	1			2	1	2		1
39	128	105			3					
40	200	148	1		1	1	1			
41	169	118			3	1	1			
42	200	200		1		2		1		
45	200	101	1		1	1				
46	200	200	2	1	2	2	1	3		
SUM	5197	5193	14	10	39	40	20	22	6	13

* centric ring chromosome
** acentric ring chromosome

reference number) is given. It can be seen that there is no difference in the frequency of different types of chromosome aberrations between 455.7 MHz-exposed and non-exposed samples. The frequency (%) of cells with dicentric chromosomes is 0.12 (6/5197) in the controls and 0.25 (13/5193) in the microwave-exposed cells. However, despite this doubling in microwave-exposed cells, the difference between both cell populations was statistically not significant.

The possible synergistic effect of MMC and the microwaves was investigated in lymphocytes from 4 donors. The results are summarized in Table 2. They show that using MMC it is, as is well known, possible to increase the frequency of sister chromatid exchanges. However, the situation is less clear with regard to the combined treatment by microwaves and MMC or microwaves alone. In one case the microwave-exposed cells also showed an increased SCE frequency compared to the controls (donor 18). Whereas in some cases the microwaves did not influence the MMC-induced SCE frequency, in others they did. However, this influence corresponded sometimes with an increased SCE frequency and sometimes with a decreased SCE frequency.

Besides the synergy with MMC we also investigated possible synergistic effects with X-rays of different doses. This was again done using a "classical" chromosome aberration analysis. Table 3 summarizes the results (pooled data). As is well known, X-rays were shown to break chromosomes. A statistically significant increase compared to control cells was observed starting from the dose of 10 cGy ($P < 0.001$). Microwave exposure followed by X-irradiation did not reveal an increased aberration frequency compared to X-ray exposure alone.

Table 2. SCE frequency in human peripheral blood cells from 4 donors after in vitro exposure to 455.7 MHz and MMC (paired t-test)

Donor	Mean number of SCE per cell					
	Controls	455.7 MHz alone	0.05 μg/ml MMC alone	455.7 MHz + 0.05 μg/ml MMC	0.1 μg/ml MMC alone	455.7 MHz + 0.1 μg/ml MMC
17	4.56 ± 2.69	5.37 ± 2.06	21.78 ± 5.97*	21.68 ± 6.16	40.28 ± 5.93*	41.44 ± 9.89
18	4.90 ± 2.62	6.50 ± 3.67**	25.58 ± 5.98*	25.22 ± 9.07	43.40 ± 7.34*	51.20 ± 9.80*
23	5.52 ± 2.60	6.26 ± 2.94	46.92 ± 8.79*	**38.90 ± 6.82***	74.96 ± 13.21*	**65.34 ± 12.76***
24	4.93 ± 3.06	5.14 ± 2.46	25.42 ± 6.77*	30.04 ± 9.83*	52.48 ± 11.37*	**43.00 ± 9.84***

Statistics (compared to unexposed controls or, for combined exposures, compared to chemical treatment alone): *P < 0.001; **P < 0.01; bold = statistically significant *decrease*.

Table 3. Chromosome aberration frequencies in human peripheral blood cells from 6 donors after in vitro exposure to 455.7 MHz fields and X-rays. Pooled data.

Exposure conditions	Number of cells analysed	Chromosome aberrations (excluding gaps and isogaps)	
		Chromatid type aberrations/100 cells	Chromosome type aberrations/100 cells
0 cGy	1200	0.50	0.67
5 cGy	400	0.75	0.75
10 cGy	1200	0.92	1.75
20 cGy	400	0.50	3.00
30 cGy	732	1.09	1.50
100 cGy	600	1.00	15.67
455.7 MHz + 0 cGy	1193	0.59	1.09
455.7 MHz + 5 cGy	400	1.25	1.00
455.7 MHz + 10 cGy	1200	1.25	1.58
455.7 MHz + 20 cGy	354	0.56	1.98
455.7 MHz + 30 cGy	753	0.66	2.66
455.7 MHz + 100 cGy	600	1.83	16.67

Discussion

In the present investigation no change in temperature was found after a 2 h exposure (17 ± 1°C), but exposure levels were not well characterized and the approximate SAR evaluation (6.5 W/kg) may yet suggest the presence of a thermal effect at the cellular level. However, no chromosomal effect could be observed resulting from the microwave exposure. We found an increase in the frequency of dicentric chromosomes compared to non-exposed control cells, but this increase was statistically not significant. Furthermore, if the increase in dicentrics/rings was true, one would expect an increase also in chromosome breaks. There was absolutely no difference in other types of chromosome aberrations. Our conclusion therefore should be that the electromagnetic field exposure does not induce chromosome aberrations.

A possible synergistic effect of microwaves and the chemical mutagen MMC was investigated with the sister chromatid exchange test. It is indeed known that MMC is a good inducer of SCE (Evans, 1977); furthermore, we previously already observed a clear and very reproducible increased SCE frequency in 954 MHz- and MMC-exposed cells compared to MMC-exposed cells only (Maes et al., 1996). However, this was less clear in an experiment involving 935.2 MHz fields (Maes et al., 1997) and was not confirmed in a later experiment involving 900 MHz RF fields (Maes et al., 2000). The results of the present investigation also do not point towards RF-induced genetic effects alone, or in combination with X-rays or MMC. It was indeed found that 455.7 MHz fields alone did not increase the SCE frequency in three out of four subjects, and that the combined treatment (microwaves followed by MMC) increased the SCE frequency, compared to MMC alone, in some cases, but