Health Physics Pergamon Press 1972. Vol. 22 (March), pp. 217–224. Printed in Northern Ireland

EFFECTS OF 2450 MHz MICROWAVE RADIATION ON HUMAN BLOOD COAGULATION PROCESSES

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(*Received* 13 *May* 1971)

Abstract—A relatively inexpensive and compact free-space microwave exposure system was designed and fabricated for irradiating *in vitro* platelet-rich human blood plasma to 2450 MHz CW radiation at varying power densities of up to 280 mW/cm² and 75 mW of absorbed power. Investigation of the non-thermal effects, with temperatures remaining below normal body temperature of 37°C, shows that no significant changes occur to platelet count, coagulation time or clot strength at power densities up to 280 mW/cm² for exposure times as high as 24 hr. Microwave heating to temperatures between 37 and 42°C produced little significant change in coagulation time and clot strength, whereas conventional heating to equivalent temperatures produced an expected and observed increase in coagulation time and corresponding decrease in clot strength.

INTRODUCTION

As EARLY as 1890, D'Arsonval demonstrated that electromagnetic radiation could produce a significant heating effect on humans. Since that time members of the medical profession and others have been investigating the results of, and developing new applications for, this thermal characteristic of electromagnetic waves on matter. One of the early applications was for medical therapy.

As scientific knowledge in this area increased, higher frequencies were studied so that by 1935 frequencies of up to 10 MHz were being utilized. However, it was not until World War II and the development of techniques which used higher frequencies and much higher power levels, that the problems of biological damage received significant attention. At this time, the effectiveness of a new portion of the electromagnetic spectrum which is now referred to as the microwave region was demonstrated. While the exact limits are not specifically defined it is generally accepted that microwaves constitute that portion of the spectrum from 300 to 300,000 MHz.

Following World War II, radar systems that were capable of emitting average power levels in excess of 1 kW were developed. It was noted that the high power densities produced were capable of heating the skin of individuals several hundred feet from the radiating antenna. It was further noted that there appeared to be a unique relationship between certain frequencies and the depth of penetration which resulted in selective heating in matter.

The potential for biological damage from devices emitting microwave radiation and the possible associated health hazards were recognized shortly after the development of the military applications of radar. Some of the first studies were conducted by Daily on U.S. Navy personnel employed in the testing and operation of relatively low powered radar.[1] Although this first study produced no evidence of radar-induced pathology in humans, animal studies during the 15 yr following World War II showed that cataracts, corneal opacities and testicular degeneration could be produced by exposure to microwaves.[2–4] During this same period cataracts were first observed in a

technician operating a microwave generator.[5]

The medical profession, as well as military and industrial organizations, soon developed an awareness of the potential biological hazards from microwaves. It was recognized that the principal effect resulted from the heating of tissue. In 1956, a Tri-Service Committee was formed in the U.S. of representatives from the Army, Navy and Air Force to investigate the biological hazards and to establish recommended levels of exposure to microwaves for military personnel. As a result of several Tri-Service Conferences which evaluated research conducted with experimental animals and information on human exposures, the Committee proposed an average power density limit of 10 mW/cm^2 as the maximum acceptable limit for continuous exposure.[6–9]

This limit was based on two main conclusions: First, it had been theoretically and experimentally determined that continuous whole body exposure of a human to this power density would result in a maximum equilibrium body temperature rise of 1°C—a level considered tolerable on a long term basis without risk of irreversible damage.[10,11] Secondly, several investigations showed that animals exposed to power densities of as low as 100 mW/cm^2 exhibited irreversible tissue damage. Therefore, by applying a safety factor of 10, the level of 10 mW/cm^2 was proposed. MOORE[12] and SCHWAN[13] have reviewed many of the animal and human investigations which have, in most cases, evaluated the thermal effects of microwave radiation.

CLEARY[14] also has reviewed in detail past research on the biological effects of microwave radiation. There is general agreement that much more needs to be done to further investigate low-level or non-thermal effects, to better understand and describe the microwave parameters used for such research, and finally to develop effective dosimetric techniques to properly determine the actual power absorbed within the system or specimens being evaluated.

It has been recognized for some time that platelets are extremely sensitive to whole body exposures from ionizing radiation and that this seriously affects coagulation. It is also a well known fact that platelets are relatively "radioresistant" to ionizing radiation when irradiated outside of the body, since the parent megakaryocytes have already produced the platelets. Disintegration of 1 mature megakaryocyte results in the production of 3000–4000 platelets and as with other hematopoietic cells, the platelets then pass through the walls of the bone marrow to enter the circulatory system.

RICHARDSON[15] reports from studies on non-ionizing radiation effects that blood coagulation time of dogs was altered after exposure to 2450 MHz microwave radiation. He states that the coagulation time may be significantly increased, or decreased, depending on the exposure dosage, and that a correct explanation may require a better delineated knowledge of the blood coagulation mechanism and the biologic effects of microwaves.

It was the purpose of this study to investigate non-thermal effects to *in vitro* platelet-rich human blood plasma.

METHODS

The microwave exposure system consisted of a compact, free-space, focused beam system. Details of the system have been reported by BASSETT *et al.*[16] and BOGGS.[17] However, to summarize, a compact and relatively inexpensive microwave exposure system was designed and fabricated which circumvented the need for an anechoic chamber while yielding a uniform field area. The system utilized a continuous wave 2450 MHz magnetron, with a three phase full-wave rectified power supply, a variable directional coupler, a choked antenna feed and a 1.17 m diameter focused prolate-spheroid antenna.

A focal area with a diameter of approximately $\frac{1}{2}$ wavelength (6 cm) could be illuminated with 1.0 dB uniformity and an area with a diameter of approximately one wavelength could be illuminated within 3.0 dB uniformity. Power densities of up to 1.1 W/cm^2 in the free field were obtained, and about 24 % of the power incident upon the plasma sample container was absorbed within the plasma. The absorbed power was determined after finding the dielectric constant and loss tangent of the platelet-rich plasma using techniques presented by ALTSCHULER.[18] With this information, plus the physical geometry and dimensions of the plasma and rectangular sample container (2.0 cm on each side

and 5.9 cm in height), the absorbed power was calculated with a multilayer computer program based upon work performed by RICHMOND[19] and BREEDEN.[20]

Human blood was collected just prior to each run by drawing the blood into a siliconized vacutainer tube containing the anticoagulant sodium citrate. The blood was centrifuged at 1000 rpm for 5 min to obtain the platelet-rich plasma. Two ml of the plasma was placed into siliconized glass vials for irradiation.

Following irradiation, the platelet-rich plasma was gently mixed and drawn into disposable blood diluting pipettes. These pipettes concontained a given amount of ammonium oxalate to produce a dilution ratio of 1:100. After gently agitating the pipette, several drops were discarded and a drop of plasma placed on the surface of a counting chamber. The diluted plasma was drawn rapidly by capillary action into the space between the cover glass and the ruled area of the chamber, then left for 20 min to allow the platelets to settle. After placing the chamber on the phase microscope stage, the number of platelets per cubic millimeter was determined by counting the platelets in 1 mm^2 on both sides of the chamber, dividing by 2 and multiplying the number by 1000. A thrombelastograph was used to determine coagulation time and clot strength.

This technique utilizes the optical registration of clot formation on the basis of the developing elastic properties of the plasma clot. It permits a simultaneous and continuous visual, as well as photographic, observation of up to 3 plasma specimens during all phases of coagulation, at a controlled temperature of 37°C and with complete exclusion of air. Figure 1 is a diagram of a typical thrombelastogram showing the coagulation time (*r* value), the rate at which the elasticity of the clot increases (*k* value) and the clot strength (*ma* value).

Blood was drawn from 9 individuals over a period of about 4 months. Thirty-seven runs were made with a total of 162 samples being used in the irradiations. The amount of blood drawn per run averaged about 25 ml and in all cases was drawn from individuals within 1 hr of the start of the irradiation.

For each run, at least one control sample was maintained at the same temperature as the irradiated samples. The thermometers used to register any temperature changes were intercalibrated to ±1°C over a temperature range of 0–100°C both with and without the effects of a microwave field, and placed in separate vials.

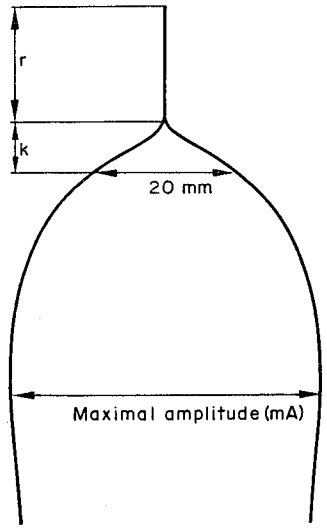

FIG. 1. Diagram of a normal thrombelastogram.

RESULTS

In those samples where a significant temperature rise was observed, it was noted that the rise above the ambient room temperature (about 23°C) occurred within 30–45 min followed by a "leveling off" and a resulting equilibrium temperature.

While the reported data is always related to a relative value of 1.0 assigned to the platelet count of the control for each run, the number of platelets per cubic millimeter averaged about 400,000 immediately after being drawn and showed a counting accuracy of about ±7%. The number of platelets per cubic millimeter varied from a minimum of 94,000 to a maximum of 475,000 for all the runs. Average coagulation time and clot strength were determined from the thrombelastograms. The number of samples run at the various conditions was arbitrarily chosen. Using the description as shown in Fig. 1, typical coagulation times of 10.0 min (20.0 mm on the thrombelastogram) and clot strengths of 60 mm were observed.

Statistical analysis of all data included linear regression analysis with means, RMS values, variances, correlation coefficient and *t*-distribution at the 95% confidence limits.

The data in Table 1 and illustrated in Fig. 2 show that there is no significant effect on the platelet count for incident power densities between 10 and 280 mW/cm². This corresponds to absorbed power levels of 2.7–77 mW. The exposure time was held constant at 5.5 hr and in all cases the plasma temperature was maintained below 37°C, the normal body temperature.

Table 1. *Incident power density and relative platelet count for* 5.5 hr *exposure times and temperatures remaining below* 37°C

Power density incident on sample container (mW/cm²)	Relative platelet count
10	1.11
10	0.97
10	1.05
10	0.78
10	1.16
25	1.09
25	1.08
25	0.90
25	0.92
50	0.96
50	0.97
50	0.88
60	0.99
60	0.95
100	1.24
100	1.18
100	0.99
100	0.84
100	0.88
100	0.99
100	0.92
100	0.94
280	1.04
280	0.95
280	1.18
280	1.09

Table 2 and Fig. 3 present data showing that no significant effect is apparent on coagulation time as a function of power density between 10 and 280 mW/cm², or (for the experimental conditions in this research), absorbed power between 2.7 and 77 mW. As before, the exposure

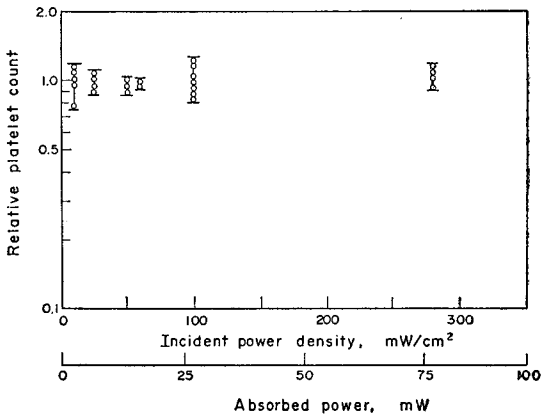

FIG. 2. Relative platelet count vs. incident power density and absorbed power for 5.5 hr exposures and temperatures remaining below 37°C.

time was held constant at 5.5 hr and in all cases the plasma temperature was maintained below 37°C.

Similar results were obtained when comparing changes in the clot strength as a function of power densities between 10 and 280 mW/cm² (absorbed power of 2.7–77 mW). (See Table 3 and Fig. 4.) No significant changes were noted.

Table 2. *Incident power density and relative coagulation time for* 5.5 hr *exposure times and temperatures remaining below* 37°C

Power density incident on sample container (mW/cm²)	Relative coagulation time
10	0.92
10	0.92
25	1.20
25	1.10
25	0.85
25	0.85
50	0.95
50	0.98
50	1.00
100	0.95
100	1.05
100	0.91
100	0.87
280	0.94
280	1.12
280	1.00
280	1.04

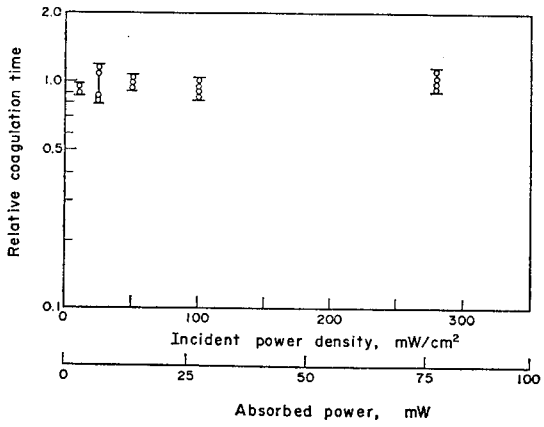

FIG. 3. Relative coagulation time vs. incident power density and absorbed power for 5.5 hr exposures and temperature remaining below 37°C.

The exposure time was again constant at 5.5 hr and temperatures in the plasma remained below 37°C.

The previous results show that for constant exposure times of 5.5 hr, there is no significant change in platelet count, coagulation time and clot strength with *in vitro* exposures to microwave power densities between 10 and 280 mW/cm² when the plasma temperature remains at or below normal body temperature (37°C).

Table 3. *Incident power density and relative clot strength for* 5.5 hr *exposure times and temperatures remaining below* 37°C

Power density incident on sample container (mW/cm²)	Relative clot strength
10	1.16
10	1.16
25	0.94
25	0.88
25	0.94
50	1.09
50	0.97
50	1.16
100	1.03
100	1.57
100	0.94
100	0.86
280	1.00
280	0.80
280	0.87
280	0.87

An investigation was conducted to determine the effect of varying exposure rates on the platelet count at relatively low incident power densities. The first exposures were made at 10 mW/cm² with the exposure times varying from 0.5 to 24 hr. The 24 hr maximum time was chosen since the normal platelet count begins to decrease significantly as time after removal from the body increases beyond 24 hr. As an example, a platelet count on a sample of plasma counted immediately after being drawn was 445,000 per mm³. After 24 hr at 23°C, the platelet count was 293,000 per mm³.

Table 4 and Fig. 5 show the results of relative platelet count vs. exposure times of 0.5–24 hr for a constant power density of 10 mW/cm²

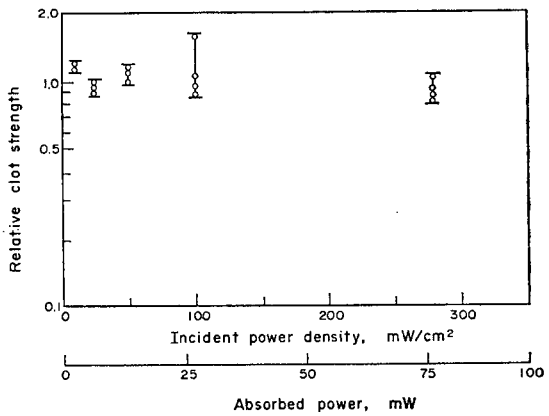

FIG. 4. Relative clot strength vs. incident power density and absorbed power for 5.5 hr exposures and temperatures remaining below 37°C.

with temperatures remaining below normal body temperature. The tests employed show that there is no significant change in the platelet count over a 24 hr exposure time. The larger deviation in the 24 hr data results from the difficulty in maintaining a constant temperature of ±1°C in both the control sample and irradiated sample over a full 24 hr.

Similarly, with the temperature below 37°C and exposure times of 0.5–24 hr, the relative platelet count was observed for considerably higher and varying power densities of 100–280 mW/cm². Again, when tested, the data as shown in Table 5 and Fig. 6, showed no significant change.

Table 4. Exposure time and relative platelet count at 10 mW/cm² and temperatures remaining below 37°C

Exposure time (hr)	Relative platelet count
0.5	0.99
0.5	1.03
0.5	0.98
2.0	0.90
2.0	1.08
2.0	1.05
3.0	1.02
3.0	1.01
3.0	1.02
5.5	1.11
5.5	0.97
5.5	1.05
5.5	0.78
5.5	0.96
24.0	0.87
24.0	0.71
24.0	0.70
24.0	0.77
24.0	1.17
24.0	1.15
24.0	1.25

Although it was not the expressed purpose of this research to investigate any thermal effects, an unusual observation was noted in that, at temperatures above 37°C, microwave heating produced no significant change in either coagulation time or clot strength, whereas external radiant heating produced, as expected, an increase in coagulation time and a decrease in clot strength.

Table 5. Exposure time and relative platelet count at power densities between 100 and 280 mW/cm² and temperatures remaining below 37°C

Exposure time (hr)	Relative platelet count
0.5	1.18
0.5	1.09
0.5	1.06
0.5	0.96
0.5	1.03
3.0	1.05
3.0	0.93
5.5	1.24
5.5	1.18
5.5	1.04
5.5	0.96
5.5	0.99
5.5	0.84
5.5	0.88
5.5	0.99
5.5	0.92
5.5	0.94
24.0	0.47
24.0	0.40
24.0	0.40
24.0	0.56
24.0	1.32
24.0	1.26
24.0	1.50

To study this observation, samples were normalized to that of a control sample maintained at 23°C. A second sample was carefully maintained at a temperature rise and final temperature of that of the irradiated sample

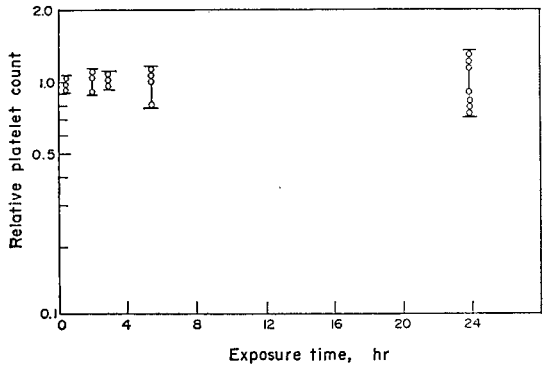

FIG. 5. Relative platelet count vs. exposure time at 10 mW/cm² and temperatures remaining below 37°C.

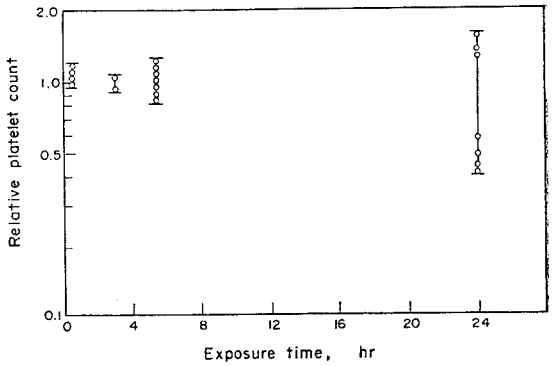

FIG. 6. Relative platelet count vs. exposure time at power densities between 100 and 280 mW/cm² and temperatures remaining below 37°C.

(as previously described). The irradiated (third) sample was exposed to varying power densities selected to obtain a given maximum temperature rise. As previously noted, the maximum temperature was usually reached in 30–45 min. The reported data is based upon total exposure times of 5.5 hr, however, shorter exposure times showed similar, but less significant changes. Table 6 and Fig. 7 show the results of coagulation time vs. maximum temperature rise and Table 7 and Fig. 8 show similar results of clot strength vs. maximum temperature rise. In each case a comparison is made at given temperatures with the relative count of the control sample to which no additional heat above room temperature (23°C) was provided.

Table 6. Maximum temperature rise and relative coagulation time for exposure times of 5.5 hr *and independent of power density*

Maximum temperature rise (°C)	Relative coagulation time	
	Radiant heating only	Microwave heating
34	1.11	1.16
34	1.28	1.11
34	1.00	1.00
37	0.95	1.16
37	0.76	0.76
39	1.84	1.44
39	1.69	1.10
39	1.22	1.04
42	1.70	1.10
42	2.53	1.16
42	1.87	0.96

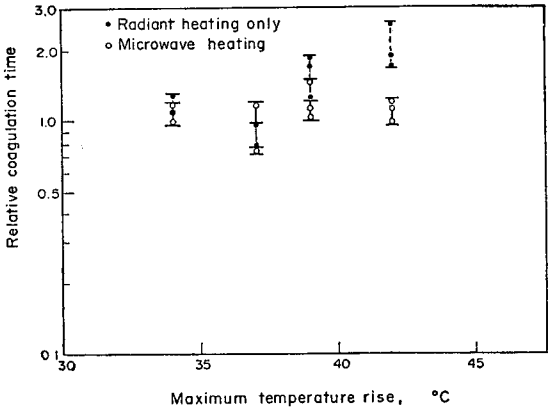

FIG. 7. Relative coagulation time vs. maximum temperature rise for exposure times of 5.5 hr and independent of power density.

Table 7. Maximum temperature rise and relative clot strength for exposure times of 5.5 hr *and independent of power density*

Maximum temperature rise (°C)	Relative clot strength	
	Radiant heating only	Microwave heating
34	0.80	0.89
37	0.86	0.70
37	0.94	0.84
39	0.71	1.00
39	1.15	1.10
39	0.53	0.57
42	0.29	0.64
42	0.25	0.74
42	0.40	0.83

Observation of the data shows that, above about 37°C the coagulation time of the plasma increases significantly when only heat is applied to the sample. This is to be expected. However, when the same temperature is maintained as a result of microwave heating there is significantly less increase in coagulation time. This becomes more apparent as the temperature increases above 37°C.

The change in clot strength shows a consistently similar but reverse effect. With a controlled temperature rise and no microwave exposure, clot strength decreases with increasing temperature. The decrease in clot strength is less with microwave heating than with the controls.

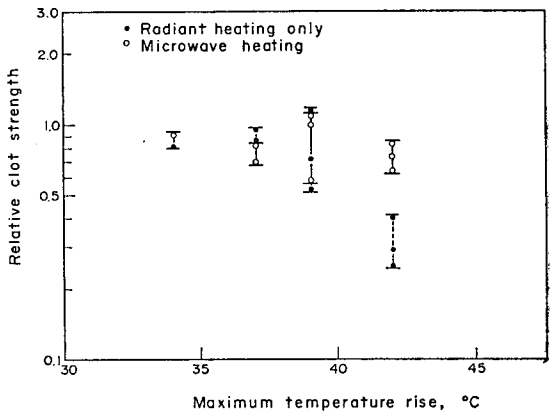

FIG. 8. Relative clot strength vs. maximum temperature rise for exposure times of 5.5 hr—with varying power densities of 10–280 mW/cm^2.

CONCLUSIONS

Investigation of the non-thermal effects of microwaves to human blood plasma shows that no significant changes occur to *in vitro* platelet count, coagulation time or clot strength for power densities up to 280 mW/cm^2. Similarly, no effect is noted when the exposure rates vary from continuous exposures of 0.5–24 hr at power densities between 10 and 280 mW/cm^2. This conclusion agrees with observed effects to platelets from ionizing radiation where it has been noted that platelets are relatively "radioresistant" to ionizing radiation after they have been separated from the parent megakaryocyte.

An unexplained effect occurs when plasma temperature is raised above normal body temperature. External radiant heating in the temperature range of 37–42°C (98.6–108°F) produces an expected increase in coagulation time and decrease in clot strength, whereas this is not as significantly observed when heated by microwave radiation. Additional studies should be conducted to confirm this phenomenon.

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