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Thermal and Behavioral Effects of Exposure to 30-kW, 95-GHz Millimeter Wave Energy

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14. ABSTRACT

The present research quantified the behavioral effects of a millimeter exposure system developed by the Raytheon Company known as the Silent Guardian™ (SG) system. This system employs a 95-GHz beam that is approximately one-third the area of that found in a similar 95-GHz exposure device, the Active Denial System. Experiment 1 determined the power density necessary to achieve pain intolerability in 90% of the human subject population. In Experiment 2, the SG system operator attempted to disrupt subjects from performing various behavioral tasks including (a) throwing balls, (b) sighting a simulated weapon either while standing erect in the open or while crouching behind a barrier, and (c) burying a simulated improvised explosive device. For all of the tasks, the subject performance was significantly degraded when engaged by the SG system. The degree of degradation was most pronounced during the simulated weapon task in which subjects were called upon to stand erect in the open.

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LIST OF ACRONYMS

711 HPW/RHDR	Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch
ADS	Active Denial System
AFRL	Air Force Research Laboratory
CLT	Carbon-loaded Teflon
IED	Improvised Explosive Device
IR	Infrared
IRB	Institutional Review Board
MMWs	Millimeter Waves
SG	Silent Guardian™

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EXECUTIVE SUMMARY

The present research was designed to quantify the behavioral effects of a millimeter exposure system developed by the Raytheon Company known as the Silent Guardian™ (SG) system. This system employs a 95-GHz beam that is approximately one-third the area of that found in the System 0+ and System 1 95-GHz exposure devices, the Active Denial System. The purpose of Experiment 1 was to determine the power density necessary to achieve pain intolerability (i.e., a behavioral response in which initially stationary individuals are induced to move away from the beam) in 90% of the human subject population (found to be 3.03 W/cm^2). The maximum possible length of all exposures was fixed at a duration (3 s) deemed to be operationally relevant while at the same time minimizing the risk of injuries.

Experiment 2 consisted of a series of sub-studies during which the SG system operator attempted to disrupt subjects from performing various behavioral tasks including (a) throwing balls, (b) sighting a simulated weapon either while standing erect in the open or while crouching behind (and thus partially obscured by) a barrier, and (c) burying a simulated improvised explosive device (IED). The 90% criterion power density established in Experiment 1 (3.03 W/cm^2) was employed as the power density for the ball-throwing task. Because multi-path effects were judged to be more likely in the remaining tasks, somewhat lower power densities were used for the majority of subjects in the simulated weapon task (1.76 W/cm^2 while crouching behind the barrier and 2.55 W/cm^2 while standing in the open) and IED task (1.76 W/cm^2).

For each Experiment 2 task, SG effectiveness was measured as the difference between a subject’s performance during trials when they were targeted by the SG system and that same subject’s performance during “sham” trials (i.e., when they were not targeted). For all of the tasks, the subject performance was significantly degraded when engaged by the SG system. The degree of degradation was most pronounced during the simulated weapon task in which subjects were called upon to stand erect in the open; in this task, the fine motor skills necessary to keep a rifle trained on the target were easily disrupted and the subject did not have a barrier to utilize to his or her advantage.

1.0 INTRODUCTION

Millimeter waves (MMWs), specifically those at the 95-GHz frequency, have been employed as the basis of an anti-personnel, non-lethal weapon system known as the Active Denial System (ADS). This system uses advanced technology to provide a non-lethal capability that has a range greater than that of small arms fire. A focused beam of MMWs, traveling at the speed of light, is directed toward designated personnel. Once the beam reaches the target, MMW energy penetrates the skin to a depth of approximately 0.3 mm (Erwin & Hurt, 1981; Gandhi & Riazi, 1986), resulting in rapid skin heating and an accompanying sensation of intolerable heating that causes the target to reflexively move away from the beam. The sensation immediately ceases when the individual moves out of the beam or when the system's operator turns the beam off. ADS has very low risk of injury because the target's reflexive response causes movement out of the beam before skin heating can reach levels likely to cause thermal damage. In fact, over a decade of research has demonstrated that the desired behavioral response (i.e., rapid escape/repel) can be readily produced at energy levels well below those which cause burns in animals and humans. Of the approximately 10,700 ADS exposures that have occurred to date under human-use protocols, only seven minor injuries (consisting of blistering) have occurred.

The present research was designed to quantify the behavioral effects of a similar 95-GHz MMW exposure system that employs a beam that is approximately one-third the area of that used in the ADS. This MMW system, developed by the Raytheon Company, will hereafter be referred to as the Silent Guardian™ (SG) system. In overview, the research consisted of two studies. The purpose of Experiment 1 was to determine the power density necessary to achieve pain intolerability (i.e., a behavioral response in which initially stationary individuals are induced to move away from the beam) in 90% of the human subject population (found to be 3.03 W/cm^2). The maximum possible length of all exposures was fixed at a duration (3 s) deemed to be operationally relevant while minimizing the risk of injuries.

This criterion power density established in Experiment 1 would then be employed in Experiment 2, a series of sub-studies during which the SG system operator attempted to disrupt subjects from performing various behavioral tasks including (a) throwing balls, (b) sighting a simulated weapon either while standing erect in the open or while crouching behind (and thus partially obscured by) a barrier, and (c) burying a simulated improvised explosive device (IED). For each of the Experiment 2 sub-studies, SG effectiveness was measured as the difference between a subject's performance during trials when they were targeted by the SG system and that same subject's performance during "sham" trials (i.e., when they were not targeted).

2.0 METHODS

Procedures for data collection and treatment of participants were reviewed and approved by the U.S. Air Force Research Laboratory (Wright site) Institutional Review Board (IRB). All applicable rules and regulations were followed.

2.1 Subjects

Prospective human subjects were recruited from among Tri-Care beneficiaries: either active-duty, reserve, or retired military personnel and their dependents. All subjects, male and female, were at least 18 years of age. No incentives were provided to induce participation other than the knowledge that subjects were assisting the Department of Defense to field a non-lethal weapon.

Twenty-one subjects were recruited for Experiment 1, 5 females and 16 males. Of the 21 subjects initially recruited, 8 withdrew prior to completing all phases of the experiment; 3 withdrew due to unforeseen scheduling conflicts; 2 left for reasons relating to health issues; and 3 left because of a mid-study change in the procedures for pregnancy detection.[1] Thirteen subjects (all male) completed Experiment 1.

Table 1 summarizes the number and gender of subjects for each of the Experiment 2 tasks. (Some, but not all, subjects participated in multiple tasks.)

Table 1. Number of subjects (male and female) who participated in each of four tasks in Experiment 2.

Experiment	Task description	Number of subjects	
		Female	Male
2A	ball throwing	1	19
2B1	rifle, in open	2	9[a]
2B2	rifle, behind barrier	1	18
2C	IED[b]	1	18

[a]In addition to these 11 subjects for Experiment 2B1, an additional 5 subjects (all male) participated in a similar sub-study. See below for additional details.
[b]IED = improvised explosive device.

2.2 Facilities and Beam Characterization

All exposures were conducted at the Brooks City-Base Directed Energy Outdoor Test Site (San Antonio, TX) using the SG system.

Prior to conducting Experiment 1, SG beam parameters (size and peak beam power density) were characterized on two separate occasions, once during July 2006 and again during December 2007.[2] Beam parameters were measured at the Brooks Outdoor Test Site at various distances from the transmitter antenna ranging from inside the Fresnel maximum (the location of minimal beam diameter) to the limit of the Brooks Outdoor Test Site, a distance of 325 m.

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[1] At the outset of the study, pregnancy testing was left to the discretion of the experiment's appointed Medical Monitor and the tendency was for subjects to self report their pregnancy status. During the course of Experiment 1 this policy was modified by the IRB such that a negative pregnancy test was required of all female subjects within 36 hr of each MMW exposure.

[2] The SG beam was re-characterized during December 2007 (just prior to data collection for Experiments 1 and 2) in part because Raytheon engineers had modified the SG antenna by tightening the beam's focus following its initial characterization in July of 2006.

Characterization involved use of a carbon-impregnated Teflon® plate (alternately referred to as carbon-loaded Teflon, or CLT). CLT is a homogeneous suspension of carbon powder in Teflon (PolyTetraFluoroEthylene). Prior laboratory and field work has demonstrated that the CLT surface heats at rates similar to skin; therefore, measurement of CLT surface temperature distribution using infrared (IR) thermography allows estimation of the beam parameters and skin heating rates (Durney, Massoudi, & Iskander, 1986; Ross, Allen, Beason, & Johnson, 2011). IR thermography of the exposed CLT was accomplished with an IR camera that was accurate to within 2% of absolute temperature across IR wavelengths from 7.5 to 13 microns (FLIR Systems, Inc., Model ThermaCAM S60, Boston, MA). The IR imagery was captured on a portable computer 30 times per second. Power density was calculated using an empirical model which relates the temperature profile of the exposed CLT (specifically, peak temperatures) with the peak power density of 95-GHz radiation absorbed by the CLT (Ross et al., 2011).

2.3 Experiment 1

A given exposure "session" for a subject typically consisted of two 95-GHz SG exposures at a given power density and duration. During one of the two exposures the subject's back was exposed with the center of the beam focused on the subject's spine midway between waist and neck. During the other exposure, the subject's front was exposed with the center of the beam focused on the subject's sternum.[3] The order of the two exposures (front versus back) was counterbalanced across subjects. During each of the two session exposures male subjects were stripped to the waist; female subjects were allowed to wear a sports bra or a similar piece of apparel. This was necessary to facilitate recording of subject skin temperature using one of two IR cameras that were accurate to within 2% of absolute temperature across IR wavelengths from 7.5 to 13 microns (FLIR Systems, Inc., Models ThermaCAM S60 and S65, Boston, MA). The IR imagery was captured on a portable computer 30 times per second. Subjects were instructed to remain motionless in the beam until they felt that the sensation induced by the MMW energy reached a point of "intolerability" at which time they were to move laterally out of the beam.

During the first round of exposure sessions, all subjects were exposed to a power density (1.6 W/cm^2) that was estimated[4] to cause a repel response in approximately 50%-70% of the Experiment 1 subject population (i.e., less than the 90% level that the study was designed to detect). Once it was established that a power density used in a given round was insufficient to achieve the 90% repel rate, subjects participated in successive rounds which employed increasingly higher power densities. The power densities assigned to successive rounds were incremented by a fixed amount, 0.17 W/cm^2. Testing continued until subjects participated in a round where the assigned power density caused 90% of the subjects to exit the beam before the beam was turned off (i.e., when the maximum duration was reached). The calculation of the 90% criterion power density was determined separately for front and back. Therefore, if the 90% criterion determined for one side was not sufficient to induce a repel response in 90% of the subjects for the other side, testing continued separately for the other side until the 90% criterion

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[3] The choice of beam location for Experiment 1 was dictated in part by the desire to compare data in the present study with that collected during prior ADS studies that had employed a similar methodology (including shot location).

[4] The estimate was based both on prior studies using the ADS along with considerations that effective power density would likely vary as a function of the smaller SG system spot size.

for the other side was reached. The duration of the exposures (3 s) was identical for each of the power densities used.

All Experiment 1 exposures were conducted 238 m from the transmitter on the Brooks Outdoor Test Site (see Figure 7). This distance was chosen because the beam characterization results indicated that the SG minimal and maximal power densities at this range likely bracket the estimated 90% criterion power density.

2.4 Experiment 2

Subject behavior in each of the Experiment 2 sub-studies was captured using an audiovisual suite that included two digital video cameras (Pelco, Clovis, CA, M/N CC3751H-2) and two HD-DVD recorders (Panasonic, M/N's DMR-ES10 and DMR-T3040, Secaucus, NJ). One of the two cameras was situated relatively close to the subject (approximately 4-7 m, depending upon the task) while the other was positioned further away, typically close to either the target at which the subject was aiming (for the ball-throwing and rifle tasks) or to the goal point (for the IED task). Additionally, the SG system had both a digital video and IR camera bore-sighted to the antenna; the output of these signals was also captured (HD-DVD recorder, Panasonic, M/N DMR-ES10), allowing examination of subject responses from the SG operator's perspective. Timestamps for the three captured signals were synchronized using a GPS-based time code generator (ESE Products, Model ES-103U, El Segundo, CA).

2.4.1 Experiment 2A (Ball Throwing)

Subjects were given a bucket of 30 tennis balls and instructed to throw as many balls as possible during a 30-s period into a designated target. The target, constructed from PVC pipe and netting, measured 1.5 m high x 0.9 m wide x 1.2 m deep (see Figure 1). The target was located 7.6 m in front of the subject and approximately 20° degrees to the left of the SG beam path. A 0.3 m wide x 2.4 m high x 0.02 m thick plywood barrier, impervious to the 95-GHz beam, was situated 1.6 m to the left of the center of the subject throwing location. The subject throwing location consisted of a rectangular area (demarcated by bright orange spray paint on the ground) measuring 0.9 m x 1.5 m. For each of 4 30-s trials, subjects were instructed to throw as many of the 30 balls into the target as possible. They were instructed that quantity was more important than accuracy. (By way of example, it would be better to throw 20 balls into the target, missing with the other 10 [accuracy = 20 / 30 = 0.67] than to throw only 10 balls, but have all 10 end up in the target [accuracy = 10 / 10 = 1.00]. In the former [preferred] case accuracy is lower, but the number of balls on target is higher.) Any manner of throwing or moving was acceptable so long as both feet were within the 0.9 m x 1.5 m throwing area at the moment a given ball was thrown at the target. Balls landing in the target, but thrown when one or both of the subject's feet were outside the throwing area, were not counted as being on target.

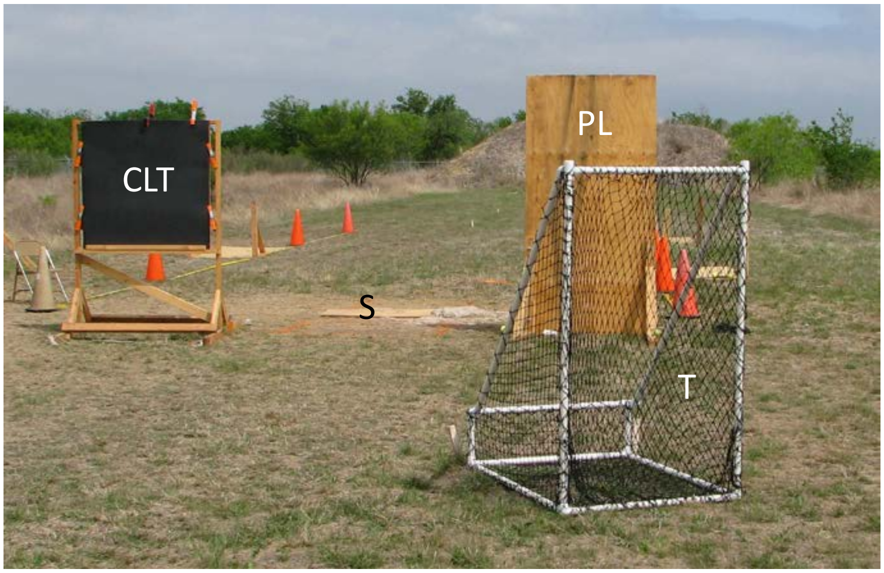

Figure 1. Set-up for Experiment 2A. (CLT=carbon-loaded Teflon used for dosimetry), S = approximate subject location during each trial, PL = plywood barrier behind which subjects could move, T = target.)

During 2 of the 4 trials, the subject was targeted by the 95-GHz SG transmitter operator. The subject was not targeted during the remaining 2 "sham" trials. Order of trial type (exposure vs. sham) was counterbalanced with the constraint that the first trial was always a sham trial. Subjects were not told before a given trial whether it was to be an exposure or a sham trial. Subjects were informed that if they found themselves targeted by the SG transmitter during a trial, and if the resulting sensation reached the point of intolerability, they should move laterally behind the adjacent plywood barrier. Subjects were free to remain behind the barrier for as long as they deemed necessary; they were similarly free to move back into the throwing area and resume throwing balls at the target (providing that the trial had not concluded while they had been behind the barrier).

The timing of the MMW exposures during the 2 30-s exposure trials was controlled by the SG operator. The operator targeted the subject's center-of-mass (chosen in order to be consistent with the Experiment 1 targeting results, to maximize the probability of hitting the target, and to minimize the possibility of ground bounce effects). The operator would attempt to engage the subject at the commencement of an exposure trial. The operator was limited to "shots" of a fixed 3-s duration. Following a given shot, a fixed delay of 2 s was imposed before a succeeding shot could be taken by the operator. The operator was free to fire as many shots as possible during the 30-s trial as long as the 2-s delay between shots was maintained. The durations for both shot length and ensuing delay were based upon estimates from a thermodynamic model that computed the residual heat on human skin generated from multiple MMW exposures and were considered necessary to reduce the risk of injuries to the subjects. The power density for all operator shots was the front-side 90% criterion established during Experiment 1 (3.03 W/cm^2). All Experiment 2A exposures were conducted 238 m from the transmitter on the Brooks Outdoor Test Site (see Figure 7). That is, the edge of the subject throwing area closest to the transmitter was located 238 m away. (This distance corresponded to the location used in Experiment 1 to establish the 90% repel power density.)

Subjects were examined at the conclusion of each trial by a designated medical observer. Observers ensured that any skin redness (or any other heating effect) had resolved before a subject was permitted to participate in a subsequent trial.

Dependent measures recorded for each trial included total number of balls thrown, number of balls on target, number of balls missing the target, and number of “illegal” balls thrown (i.e., balls thrown while the subject was outside the throwing area).

Prior to the first trial of each day, test firings on CLT were conducted to ensure that the transmitter output was stable at 3.03 W/cm^2 and that interference effects from multi-path propagation did not exist. Procedures followed in making these determinations were similar to those utilized during the beam characterization phase of this study and described in Section 2.2, *Facilities and Beam Characterization*. Ground bounce and other interference effects were eliminated in the target area by positioning side-lobe absorbers at appropriate locations between the subject and the SG system (verified by test firings on CLT). In addition, test firings continued at periodic intervals throughout the course of the test day to ensure the transmitter output remained stable.

2.4.2 Experiment 2B1 (Rifle, In Open)

In Experiment 2B1 subjects were given a simulated M16 rifle (Classic Army [Yick Fung Industrial International Ltd.], Tuen Mun, Hong Kong, M/N M15A4) with a 532-nm, green laser (Quarton, Inc., His-Chih, M/N Beamshot Greenbeam 2000) mounted on the end of the rifle barrel. The rifle was modified such that pulling the trigger activated the laser for as long as the trigger was depressed. The size of the laser spot was less than 4.4 cm at a distance of 91 m. The laser was categorized as Class 3A. For a Class 3A laser, direct eye exposure is permissible for 100 s per 24-hr period. No inadvertent eye exposures occurred during the course of the studies.

Subjects were instructed to aim this laser at a target that was 25 m away and approximately 7.5° degrees to the left or right of the SG beam path (see Figure 2). The target consisted of a 10 cm x 10 cm black outline of a square inscribed on a 91.4-cm-wide x 182.9-cm-high piece of white “butcher” paper. Two black lines connected the midpoint of any side of the square with the midpoint of its opposing side. Subjects were instructed to train the laser beam as closely as possible to the intersection of these two lines (i.e., at the center of the square). The 10 cm x 10 cm square was located within the 179.7-cm-tall black outline of a man (also inscribed on the butcher paper). More specifically, the square appeared at the approximate location of the sternum. The paper was mounted on a wooden frame so that it was perpendicular to the ground; the center of the square was located 122.0 cm above the ground.

Subject responses (viz., subject accuracy in aiming and holding the laser beam on target) were recorded using image motion detection hardware and software (M/N Videomex-One, Columbus Instruments, Columbus, OH). The contrast of the green laser spot on the white butcher paper allowed the calculation of that spot’s location relative to the target center over time. That is, a black-and-white CCD camera (M/N VCB-3512T, Sanyo, Chatsworth, CA) was directed at the square target and surrounding area; this video signal was analyzed by the Videomex-One hardware/software (at a digitizing rate of 30 frames/s). The limits of detection by the CCD camera was an area 0.7 m high x 0.9 m wide; that is, if the laser spot fell outside this area it was classified as "missing." The image motion detection hardware and software were recalibrated on a daily basis.

A plywood barrier (same dimensions as that utilized in Experiment 2A), impervious to the 95-GHz beam, was situated 1.6 m to the left of the center of the subject aiming location. The subject aiming location consisted of a rectangular area (same location and dimensions as the subject throwing location for Experiment 2A). For each of 4 65-s trials, subjects were instructed to aim the laser at the designated target as accurately as they could. Subjects were instructed that both feet needed to be within the 0.9 m x 1.5 m aiming area while aiming at the target.

During 2 of the 4 trials, the subject was targeted by the 95-GHz SG transmitter operator. The subject was not targeted during the remaining 2 sham trials. Order of trial type (exposure vs. sham) was counterbalanced with the constraint that the first trial was always a sham trial. Subjects were not told before a given trial whether it was to be an exposure or a sham trial. Subjects were informed that if they found themselves targeted by the SG transmitter during a trial, and if the resulting sensation reached the point of intolerability, they should move laterally behind the adjacent plywood barrier. Subjects were free to remain behind the barrier for as long as they deemed necessary; they were similarly free to move back into the aiming area and re-engage the target (providing that the trial had not concluded while they had been behind the barrier).

The timing of the MMW exposures during the 2 65-s exposure trials was controlled by the SG operator. The operator tactics, including the maximum duration of each shot (3 s) and duration of the delay (2 s) imposed between successive shots, were identical to those described for Experiment 2A. All Experiment 2B1 exposures were conducted at the same location, 238 m from the transmitter on the Brooks Outdoor Test Site (see Figure 7). That is, the edge of the subject aiming area closest to the transmitter was located 238 m away from the transmitter. (This distance corresponded to the location used in Experiment 1 to establish the 90% repel power density.)

For a small number of study participants (n = 5), the position of the target was to the left of the SG main beam path. However, an examination of the medical results for these subjects revealed that this set-up allowed right-handed participants to be subject to multi-path effects from reflections off of the upper receiver and the stock of the rifle. This is illustrated in the left panel of Figure 2. This led to a large blister in the case of one of these 5 subjects; see Section 3.3.5, *Medical Examinations*, for additional details. In order to mitigate the risk of injury, the target was moved to the right side of the beam path for the remaining n = 11 subjects. The right panel of Figure 2 illustrates how for right-handed subjects this alternate set-up allows the shooter's own body to shield against such multi-path effects.[5]

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[5] Because of its size the target could not easily be moved back and forth between its right-side and left-side locations. Hence, the subset of the n = 11 subjects who were left-handed (n = 3) were required to adopt a right-handed stance (i.e., butt of the rifle against the right shoulder) in order to minimize multi-path effects. Other than this requirement, subjects were free to adopt any stance or movement as long as they remained within the confines of the aiming area.

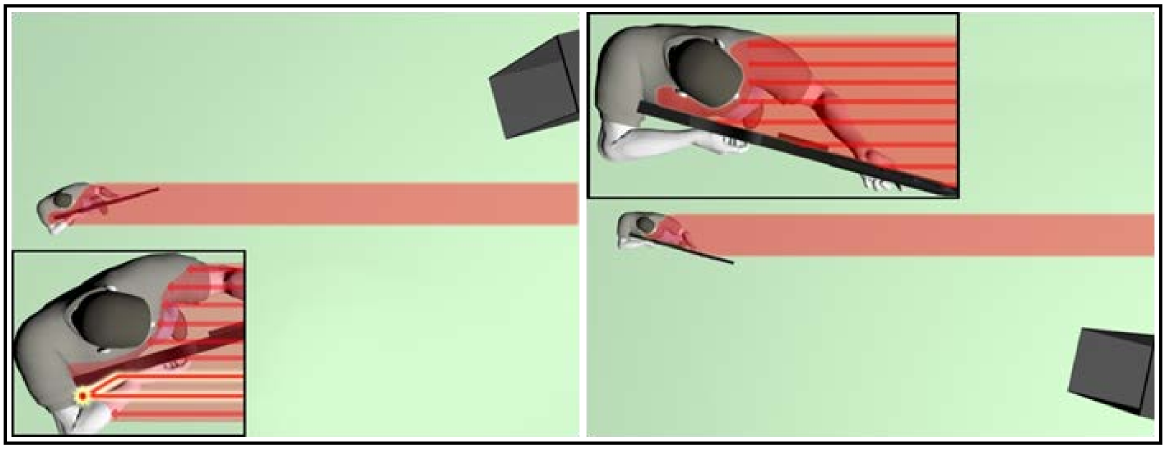

Figure 2. Set-up and orientation of subjects for Experiment 2B1. The left-hand panel shows the set-up for the initial *n* = 5 subjects with the target (grey rectangle) to the left of the main beam path (illustrated in red). The left-side panel inset illustrates the probability of multipath effects in the area of the subject arm. The right-side panel depicts the altered set-up with the target located to the right of the beam path, while the right-side panel inset shows how the subject's body mitigates multi-path effects.

The power density for all operator shots for the initial *n* = 5 subjects was the front-side 90% criterion power density established during Experiment 1 (3.03 W/cm^2). For the remaining *n* = 11 subjects, all exposures were conducted at 2.55 W/cm^2. This reduction followed a number of test exposures with the simulated rifle oriented in different positions that showed that even with the altered set-up, minimal multi-path effects were still a possibility.

Subjects were examined at the conclusion of each trial by a designated medical observer. Observers ensured that any skin redness (or any other heating effect) had resolved before a subject was permitted to participate in a subsequent trial.

Dependent measures recorded for each trial included the percentage of a trial during which the laser was outside the 0.7 m high x 0.9 m wide detection area and the mean distance of the laser dot (when detected) from the target center. Power density at the exposure area was verified over the course of the study as described for Study 2A.

2.4.3 Experiment 2B2 (Rifle, Behind Barrier)

The procedures employed for Experiment 2B2 were identical to those for Experiment 2B1 with the following exceptions. Subjects were instructed to aim the rifle laser at the target while kneeling behind a 0.9 m high x 2.2 m wide x 0.02 m thick plywood barrier that was impervious to the effects of the SG beam. Subjects were further instructed that if the sensation caused by the SG beam reached the point of intolerability, they could crouch down such that their body would be completely obscured by the plywood barrier. Subjects were free to remain completely obscured by the barrier for as long as they deemed necessary; they were similarly free to re-emerge and re-engage the target (providing that the trial had not concluded while they had been behind the barrier). Since this task exposed only a small portion of the individual to the SG beam (primarily the subject's head) and consequently the same area of skin would be consistently reheated, the power level was set to 1.76 W/cm^2 to mitigate possibility of injury.

2.4.4 Experiment 2C (IED)

For Experiment 2C, subjects were tasked with burying a mock IED (actually a modified plastic toolbox, measuring 0.2 m high x 0.4 m wide x 0.2 m deep). More specifically, subjects began each of 4 trials with the mock IED in hand at a starting point that was 20 m from the burial location. They could run or walk from this starting location to the burial location so long as they remained within the "course" boundaries (20 m long x 6.7 m wide, with the long axis parallel to the SG beam path) (see Figure 3). When traversing the course from starting to burial point, subjects were moving toward the SG transmitter location. Burial of the IED was accomplished according to the following rules: The burial location was a pre-excavated hole large enough (0.3 m x 0.6 m) to accommodate the IED. All arming of the IED prior to placing it in the burial location needed to be accomplished in the IED arming area, a 1.2 m x 1.2 m area (demarcated by bright orange spray paint on the ground) immediately in front of the hole. Arming included the following sequence of events: opening the IED, twisting together two pairs of wires located inside the IED, and closing the IED. The subject had to then gently place the armed IED upright in the hole and bury it completely using an adjacent pile of sand. The subject's attempt to conceal the IED was judged by experimenters to be a failure if (a) the IED was improperly armed, (b) the IED, once armed, was dropped or thrown, (c) the IED was not completely buried, or (d) the subject failed to bury the IED within a 3-min period of time.

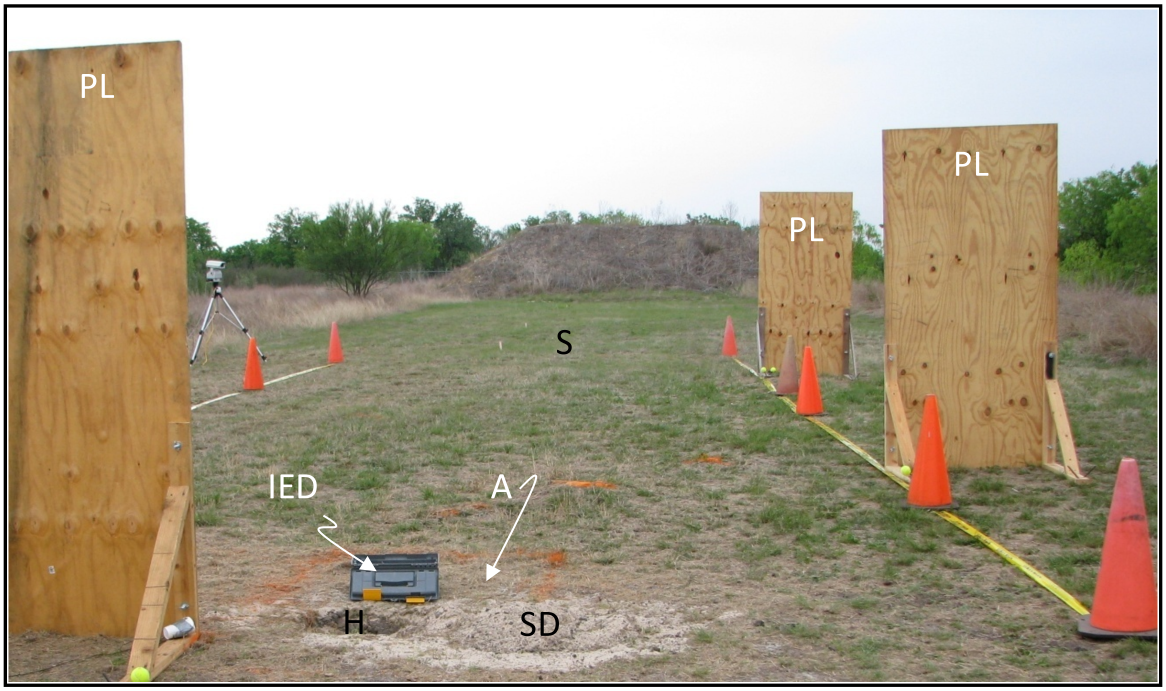

Figure 3. Set-up for Experiment 2C. (H = hole, SD = sand [for filling in hole], S = approximate subject start location for each trial, A = arming area, IED = mock improvised explosive device, PL = plywood barrier. Note that one of the four plywood barriers is hidden from view in this photograph by the plywood barrier in the left foreground. See text for further details.)

Four plywood barriers (same dimensions as those employed in Experiments 2A and 2B1), impervious to the 95-GHz SG beam, were placed at various locations on the course. Two were situated on the far left-hand side of the course (from the subject's perspective), 5 and 15 m from the burial location; a third was located on the far right-hand side of the course, 10 m from the burial local; the fourth was immediately adjacent to the burial location (0.3 m to its right). During 2 of the 4 trials, the subject was targeted by the 95-GHz SG transmitter operator. The subject was not targeted during the remaining 2 sham trials. Order of trial type (exposure vs. sham) was counterbalanced with the constraint that the first trial was always a sham trial. Subjects were not told before a given trial whether it was to be an exposure or a sham trial. Subjects were informed that if they found themselves targeted by the SG transmitter during a trial, and if the resulting sensation reached the point of intolerability, they should move behind any of the four plywood barriers. Subjects were free to remain behind a barrier for as long as they deemed necessary; they were similarly free to move back into the open and continue with their attempt to bury the IED (providing that the trial had not concluded while they had been behind the barrier). As noted above, arming of the IED needed to be accomplished within the 1.2 m x 1.2 m arming area; this specifically required that arming be accomplished in a location where subjects could be targeted by the SG operator. Burial of the IED (placement in hole and covering with sand) also had to be accomplished while subjects were "out in the open" and subject to being targeted by the SG beam.

Because the majority of time during commission of this task would involve exposure of only a limited portion of the individual (as they would presumably be crouching down while attempting to arm and bury the IED) and consequently the same area of skin would be consistently reheated, the power level was set to 1.76 W/cm^2 to mitigate possibility of injury.[6]

Subjects were examined at the conclusion of each trial by a designated medical observer. Observers ensured that any skin redness (or any other heating effect) had resolved before a subject was permitted to participate in a subsequent trial.

Dependent measures recorded for each trial included a determination of whether the burial attempt was or was not a success (e.g., correct vs. incorrect arming of the IED) and the time taken to complete the burial attempt. Power density at the exposure area was verified over the course of the study as described for Experiments 2A, 2B1, and 2B2.

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[6] Because the course was oriented such that the subject start point was 20 m farther from the transmitter than was the burial location, and because the SG power density at the target varied with distance from the antenna, there was an unavoidable variation in the power density received by the subject as he or she traversed the course, with the subject experiencing more intense exposures the closer he or she was to the burial location. Since the primary goal was to ensure subject safety, SG output was set at 1.76 W/cm^2 as measured at the burial location since that position was closest to the transmitter and therefore subject to the highest level of exposure.

3.0 RESULTS

3.1 Beam Characterization

Data collected during the July 2006 and December 2007 characterization sessions indicated a beam profile that is slightly elliptical. Figure 4 depicts an IR image of the beam profile on a CLT sheet.[7]

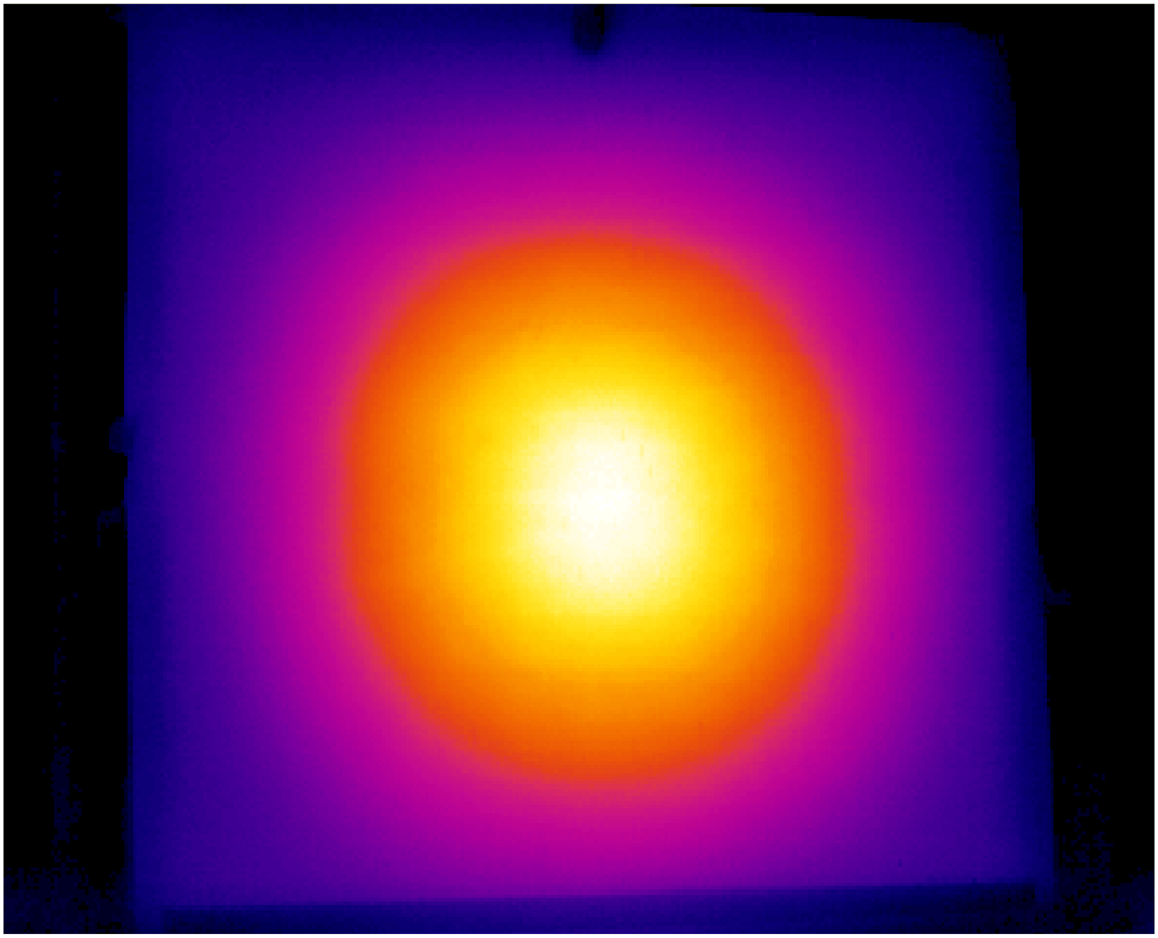

Figure 4. Representative infrared image of the Silent Guardian beam profile on a carbon-impregnated Teflon plate. (Teflon surface temperatures increase as one moves from the plate periphery to its center. For this exposure [image] the change in absolute temperature from the edge to the center of the full width-half maximum spot is 12.0 °C.)

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[7] It should be noted that the beam characterization procedures employed did detect sidelobes. However, because the present experiments were designed to eliminate sidelobe reflections and because the sidelobes detected were sufficiently separated from the main beam such that they did not hit the subject directly, this report refers to the distribution of MMW energy emitted by the SG transmitter as approximately Gaussian with respect to the main beam axis. Further, all references to "spot size" in this paper will indicate the full width-half maximum (FWHM) of the major and minor axes of the two-dimensional Gaussian distribution unless stated otherwise.

Variation in spot size diameter at a fixed distance from the antenna was relatively small. The Figure 5 scatter plot depicts FWHM spot size of the beam's major and minor axes at different distances from the SG transmitter antenna (ranging from inside the Fresnel maximum – approximately 110 m from the antenna – to a point 325 m from the antenna). Figure 6 displays the variation of the FWHM spot area as a function of distance to the antenna where the area of the ellipse (spot) is defined to be:

area = π/4 x FWHM major axis diameter x FWHM minor axis diameter.

Over the measured range, spot size increases by a factor of approximately 8.

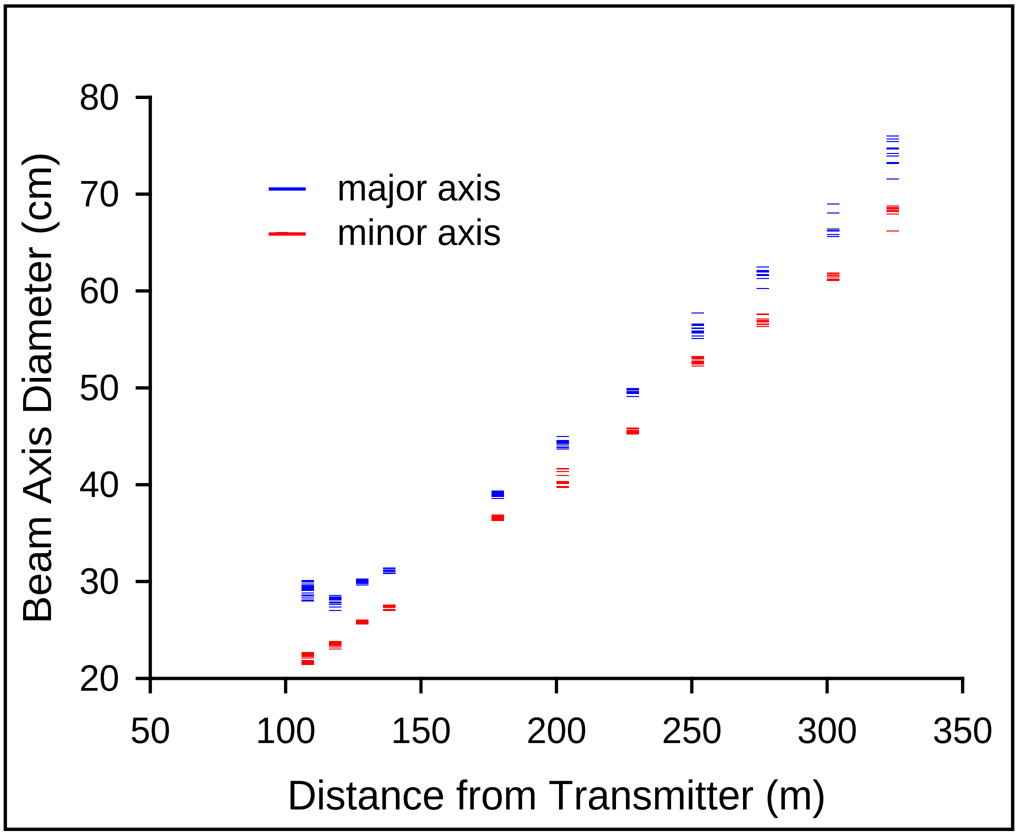

Figure 5. Diameter of the Silent Guardian full width-half maximum spot (both major and minor axes) as a function of distance from the transmitter antenna.

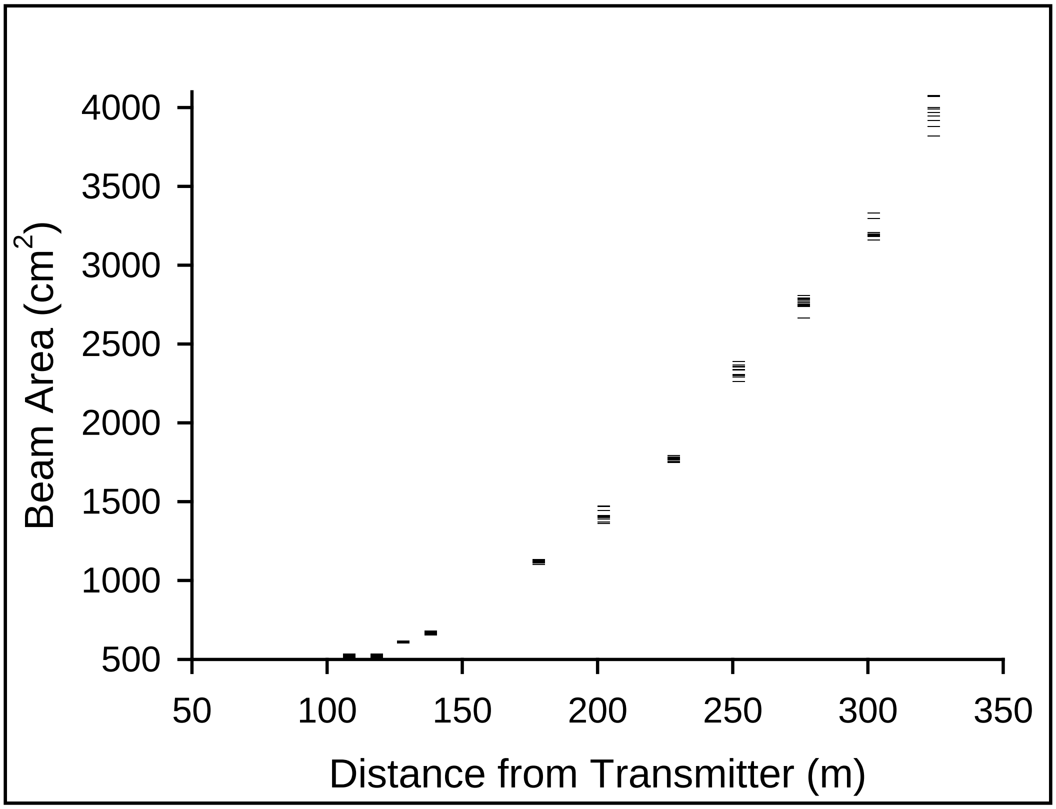

Figure 6. Area of the Silent Guardian full width-half maximum spot as a function of distance from the transmitter antenna.

Figure 7 shows power density measurements as a function of distance from the SG antenna. Again, measurements were obtained at fixed points ranging from the Fresnel maximum to 325 m from the transmitter antenna. The figure includes measurements collected both during the initial (July 2006) and follow-up (December 2007) characterization sessions. The figure summarizes measurements when the SG power output is set at 100% at all distances. Measurements made during the later December 2007 session are noticeably higher than those for the earlier July 2006 session. This is due to interim modifications in the antenna gain made by Raytheon which enabled the system to focus the same total amount of energy into a smaller area (i.e., decreased spot size and increased power per unit).

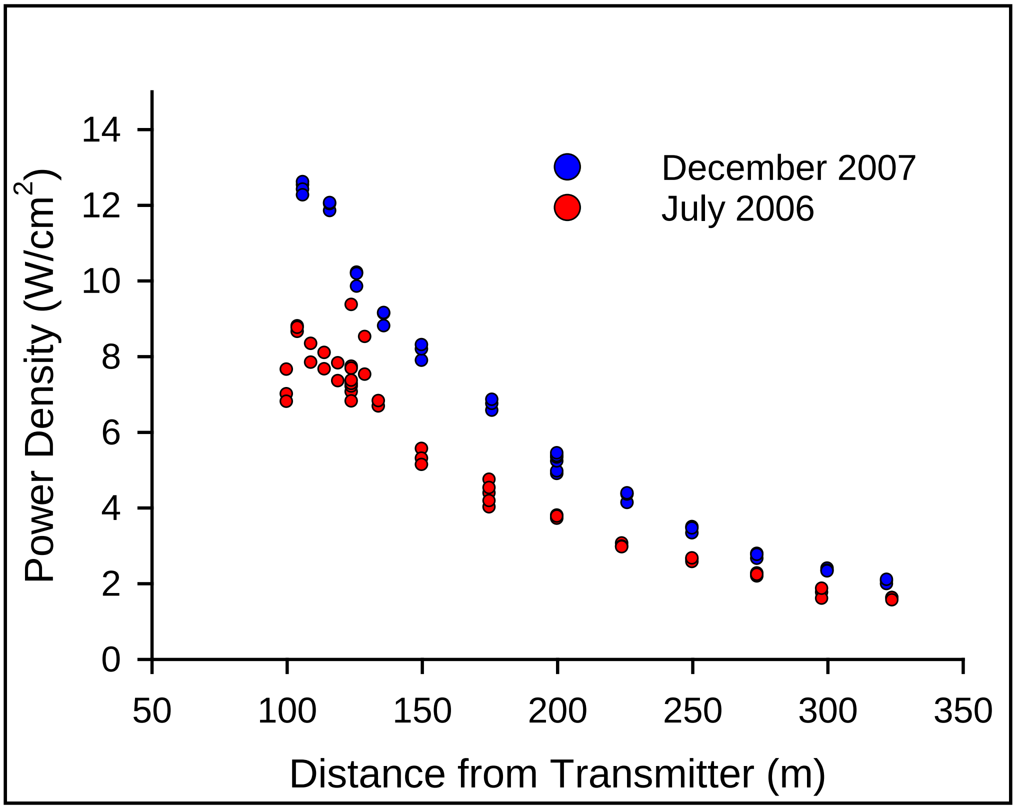

Figure 7. Power density at different distances from the Silent Guardian system with transmitter output set to 100% during two separate characterization (measurement) sessions (July 2006 and December 2007).

3.2 Experiment 1

3.2.1 Behavioral (repel) data

Figure 8 indicates the proportion of subjects repelled by the SG beam for back and front sides separately for the series of power densities employed up to and including the level required to repel 90% of subjects. The 90% criterion level established for both front and back for the SG transmitter (3.03 W/cm^2) is approximately 40% greater than the corresponding levels for the ADS beam (2.2 W/cm^2); the difference is presumably due to the smaller beam size of the SG beam. The figure does not incorporate data from the *n* = 8 subjects who withdrew from the study. (Adding data from the withdrawn subjects would not, however, substantively alter study conclusions. The identical 90% criterion level would be calculated. Further, the mean difference between proportions calculated for all subjects vs. those subjects who completed the study was only 0.01 [*SD* = 0.02]).

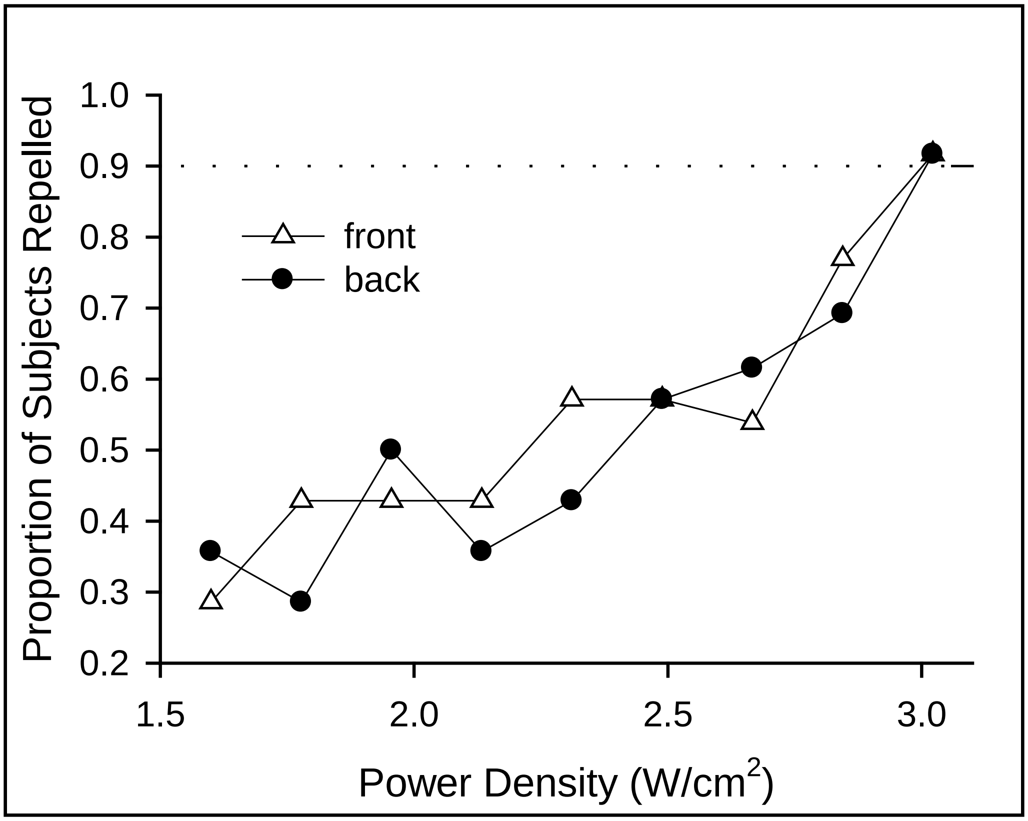

Figure 8. Proportion of subjects repelled by the Silent Guardian beam within 3 s for back and front exposures separately at each power density used during Experiment 1.

3.2.2 Medical Examinations

The Experiment 1 exposures resulted in two blistering incidents, one following a back exposure at a power density of 2.3 W/cm^2, the other after a 3.03 W/cm^2 front exposure. In both cases, the blisters that resulted were less than 5 mm in diameter. The 2.3 W/cm^2 blister formed just above the gluteal fold; the 3.03 W/cm^2 blister formed inside the cavity of the umbilicus. No medical intervention was required for either blister.

3.3 Experiment 2

3.3.1 Experiment 2A (Ball Throwing)

For Experiment 2A, dependent measures (total number of balls thrown during a 30-s trial and the percentage of balls that were accurately thrown [i.e., in the target area]) were analyzed by separate 2 (Trial Type: exposure vs. sham) x 2 (Trial Number: first vs. second trial) repeated-measures ANOVAs. Both analyses revealed significant main effects for trial type, $F(1, 19) = 67.57$, $p < .000001$, $\eta^2 = 0.78$ for number of balls thrown and $F(1, 19) = 16.75$, $p = .0006$, $\eta^2 = 0.47$ for accuracy. Neither analysis yielded a significant effect for trial number or for a Trial Type x Trial Number interaction. For each dependent measure, the significant effect for trial type reflects the degraded performance of subjects throwing tennis balls when targeted by the SG system operator. Specifically, in the case of number of balls thrown, subjects threw on average 22.4 balls during a 30-s sham trial, but were only able to throw 15.1 balls on exposure trials. Similarly, when considering percentage of balls on target, 69% of balls thrown during sham trials were on target; this value decreased to 56% during exposure trials. The results for these two measures are summarized in Figure 9.

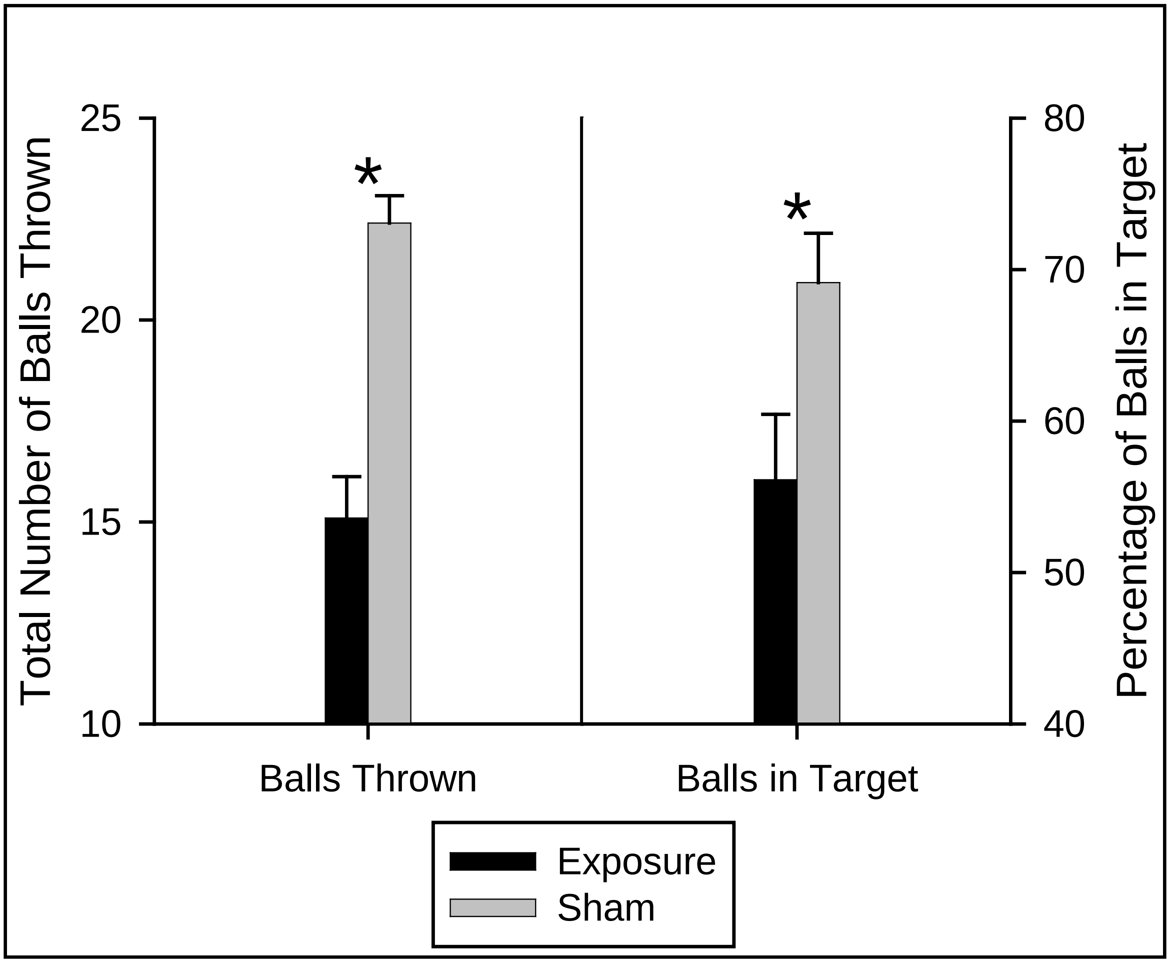

Figure 9. Mean number of balls thrown and percentage of balls thrown that were in the target (+ SEM) for Experiment 2A subjects. Asterisks indicate a statistically significant difference between performance during sham versus exposure trials ($p < .000001$ for balls thrown, and $p = .0006$ for balls in target).

3.3.2 Experiment 2B1 (Rifle, In Open)

For Experiment 2B1, data for mean distance from target center were analyzed by a 2 (Trial Type: exposure vs. sham) x 2 (Trial Number: first vs. second trial) repeated-measures ANOVA. The analysis revealed a significant main effect for trial type, $F(1, 10) = 79.71$, $p = .000004$, $\eta^2 = 0.89$, reflecting the poorer performance of subjects when attempting to aim the rifle during the two 65-s exposure trials. That is, for those rifle laser spots within the 0.7 m high x 0.9 m wide camera detection limits, the mean distance from target center increased from 6.7 cm (during sham trials) to 16.8 cm (during exposure trials). These results are summarized in Figure 10.

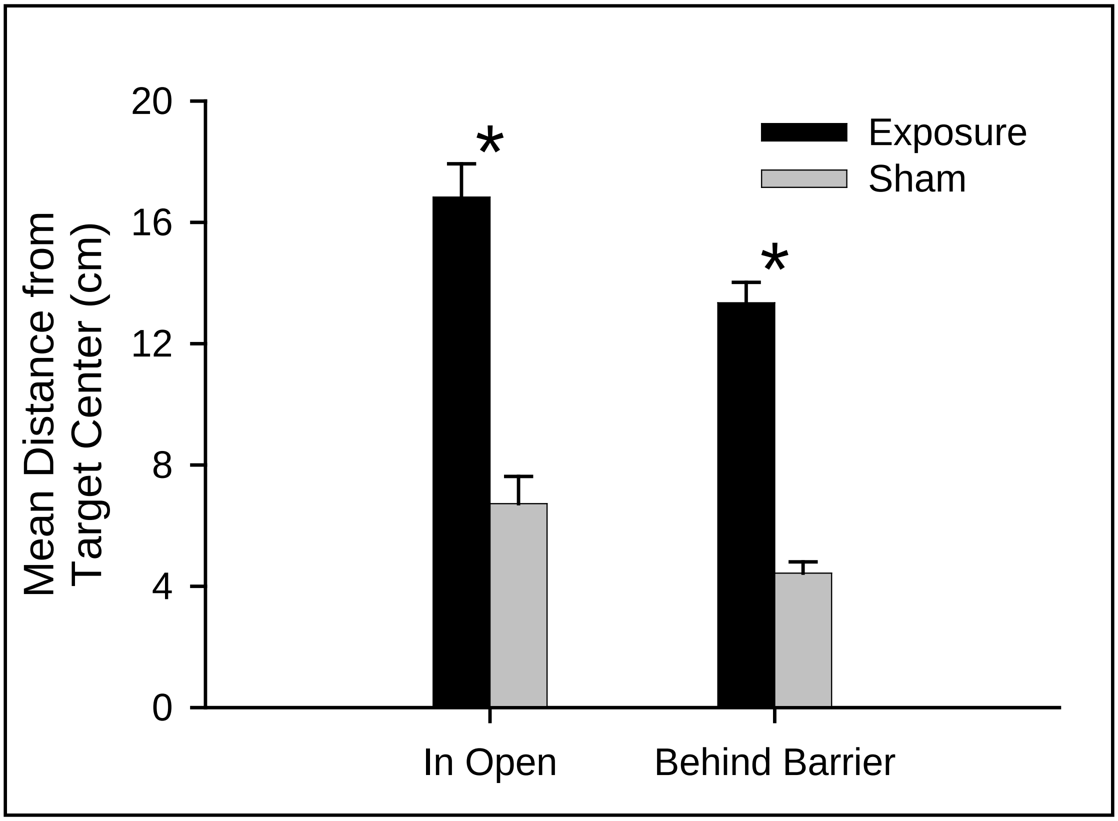

Figure 10. Mean distance of rifle laser spots from target center (+ SEM) for spots within camera detection limits for subjects in Experiment 2B1 (firing at target while in the open) and 2B2 (firing while behind a barrier). Asterisks indicate a statistically significant difference between performance during sham versus exposure trials (*p* = .000004 for subjects in the open, and *p* < .0000001 for subjects behind the barrier).

Data indicating the percentage of time shooters were off target (i.e., percentage of time the laser spot fell completely outside of the camera detection limits) were analyzed by Wilcoxon matched-pair test, T(11) = 0, z = 2.93, $p = .003$, reflecting the substantially poorer performance of subjects when attempting to aim the rifle during the exposure trials. Specifically, during the exposure trials the rifle laser spot was off target (outside of the camera detection limits) for 91% of the two 65-s exposure trials as opposed to only 1% for the sham trials.

3.3.3 Experiment 2B2 (Rifle, Behind Barrier)

Data for this experiment were analyzed identically to data for Experiment 2B1. For the mean distance to target center dependent measure, $F(1, 18) = 97.16$, $p < .0000001$, $\eta^2 = 0.84$, reflecting the poorer performance of subjects when attempting to aim the rifle during exposure trials. That is, when the rifle laser spot was within the camera detection limits, the mean distance from target center increased from 4.4 cm (during sham trials) to 13.3 cm (during exposure trials). This finding is summarized in Figure 10. In addition to this significant main effect for trial type, the ANOVA uncovered a small, but significant trial number main effect, $F(1, 18) = 4.52$, $p = .048$, $\eta^2 = 0.20$. This difference was a consequence of slightly improved performance over the course of testing. Specifically, the mean distance from target center decreased from 9.3 cm during the initial trials (mean of first sham and first exposure trial) to 8.4 cm during the second pair of trials (mean of second sham and second exposure trial). Informal post-study discussions with subjects and viewings of the videotapes led to the tentative conclusion that a subset of subjects was able to improve firing accuracy over the course of the trials by use of a strategy which involved stabilizing the rifle barrel by resting it upon the top of the barrier. Some subjects utilized this strategy from the outset of testing, whereas many others only adopted it after initially employing approaches in which the rifle was not resting on the barrier. (It should be noted that this strategy could be — and frequently was — employed during exposure as well as during sham trials.) The Trial Type x Trial Number interaction was not significant.

For the percentage of time shooters were off target, T(19) = 0, z = 3.82, $p = .0001$, reflecting the substantially poorer performance of the subjects when attempting to aim the rifle during the exposure trials. That is, during the exposure trials the rifle laser spot was off target for 41% of the two exposure trials as opposed to less than 1% for the sham trials.

3.3.4 Experiment 2C (IED)

For Experiment 2C, data for time to bury the mock IED were analyzed by a 2 (Trial Type: exposure vs. sham) x 2 (Trial Number: first vs. second trial) repeated-measures ANOVA. The analysis revealed significant main effects for trial type, $F(1, 18) = 14.54$, $p = .001$, $\eta^2 = 0.45$ (reflecting the fact that subjects took on average 23.6 more seconds to bury the IED during exposure as opposed to sham trials) and for trial number, $F(1, 18) = 5.73$, $p = .028$, $\eta^2 = 0.24$ (reflecting a practice effect, whereby subjects were on average 9.0 s quicker during the last 2 trials [mean of second exposure and second sham trial] than during the first 2 trials [mean of first exposure and first sham trial]). Informal post-study discussions with subjects led to the tentative conclusion that this practice effect was largely due to increased proficiency in arming the mock IED as opposed, for example, to quicker transit times from starting point to the arming location. The Trial Type x Trial Number interaction was not significant. Figure 11 summarizes the main effect for trial type.

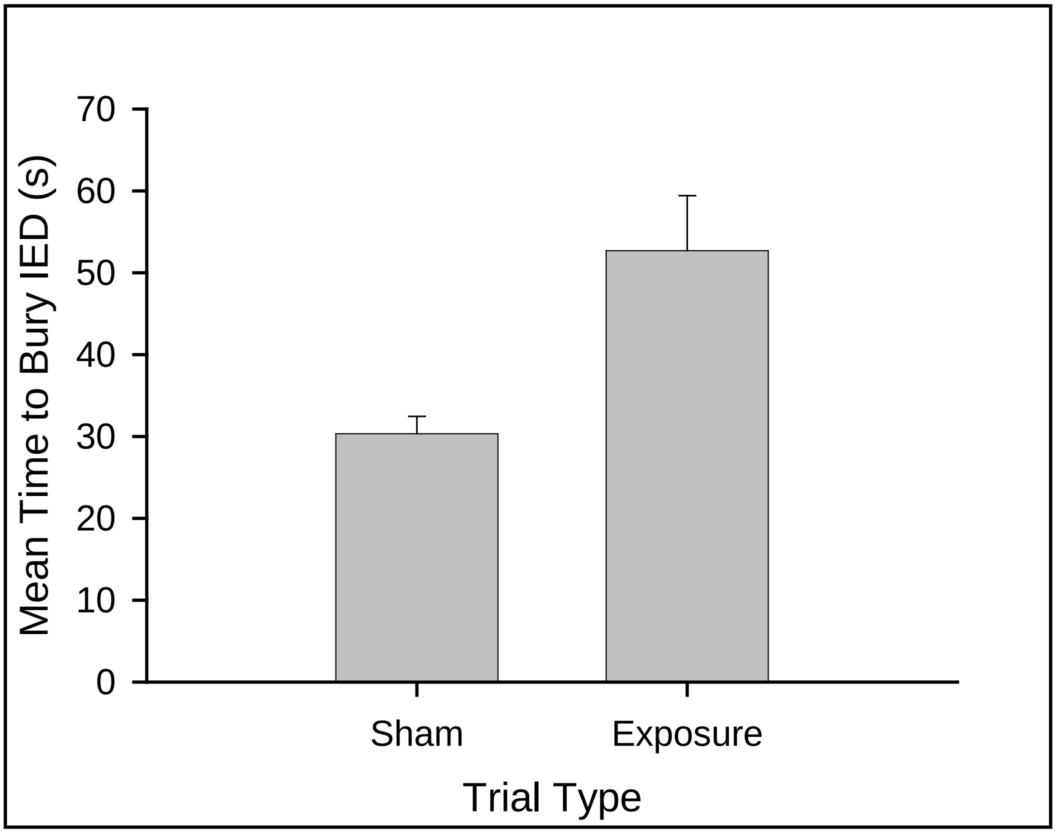

Figure 11. Mean time to bury mock improvised explosive device (IED) (+ SEM) for Experiment 2C subjects. The difference between performance during sham versus exposure trials was statistically significant, *p* = .001.

The foregoing analysis contrasts subject performance (i.e., time to bury the mock IED) regardless of the status of the burials (successful vs. unsuccessful). One might argue (particularly in the case of exposure trials) that trials which end in unsuccessful burials ought to be excluded from analysis. That is, if a subject hurries the arming and burial process as a consequence of being targeted by the SG system, resulting in a short burial time but a failed IED, this short time is not functionally the same as a comparably short time coupled with a successful burial (i.e., a working IED). Thus, an additional analysis examined time to bury the IED only for those trials on which IEDs were judged to be correctly armed and buried. The results largely mirrored those of the preceding analysis: That is, subjects were significantly quicker during sham as opposed to exposure trials (mean difference = 25.5 s compared to the 23.6 s difference found in the foregoing analysis).

As noted, following each trial a determination was made as to whether the burial attempt was or was not a success (e.g., correct vs. incorrect arming, complete burial, etc.). The results are summarized in Table 2. For this 2 (trial type: exposure vs. sham) x 2 (burial outcome: success vs. failure), χ^2 (1, N = 76) = 7.12, *p* = .40, indicating no significant difference in distribution of burial outcome for the two types of trial, exposure and sham. The fact that failure rates were comparable for the two trial types was somewhat unexpected. Informal post-study interviews showed that, in spite of experimenter instructions stressing the importance of *correctly* arming and burying the IED, subjects were highly motivated to perform the task quickly during both types of trials, occasionally leading to errors due to carelessness. (For example, the color of the IED cover/lid was similar to that of the sand used to bury it, making it relatively easy for a rushed subject to leave a small portion of the IED uncovered.)

Table 2. Number of successes and failures in burying mock improvised explosive device during sham and exposure trials for Experiment 2C.

		Trial Type	
		Sham	Exposure
Burial Outcome	Failure	6	10
	Success	32	28

3.3.5 Medical Examinations

The Experiment 2 exposures resulted in one incident of blistering; this occurred during Experiment 2B1 at a power density of 3.03 W/cm^2. After the conclusion of the final trial, the medical observer noticed that a blister had started to develop on the subject's right medial bicep at the juncture of the rifle butt and armpit. Upon initial examination, the blister measured 3 cm in length and 1.5 cm in width. The area of erythema around the wound was about 3 cm; for edema it was about 1 cm. The subject reported the area was negative for pain. Upon re-examination, the size of the blister remained approximately the same (3 cm in length, 1.5 cm in width) as did the degree of erythema and edema. The area still remained negative for pain. The subject was provided with supplies and standard first aid instructions for the care of blisters. The blister resolved in two weeks.

A blister of this size was defined by the governing protocol as an adverse event; therefore, after the blister was noted, the study was immediately halted and the IRB Chair and the Medical Monitor were notified. Further, following consultations with the IRB, the procedures for the relevant study (Experiment 2B1) were modified as described in Section 2.4.2, *Experiment 2B1 (Rifle, In* Open*).*

4.0 CONCLUSIONS

4.1 Effectiveness of SG

The SG system was successful in causing statistically significant degradations in the ability of subjects to complete assigned tasks during each of the Experiment 2 sub-studies when compared to baseline performance during the sham trials. The most significant degradation — if one measures this in terms of statistical effect size (η^2 was the measure employed in this report) — was noted during the standing rifle experiment (Experiment 2B1) where the fine motor skills necessary to continually aim the rifle at the target were disrupted by the MMW beam and the subject was unable to hide behind a barrier while attempting to engage the target as was possible in Experiment 2B2. During Experiment 2B1, the SG system reduced aiming ability such that the laser spot was within the target limits only 9% of the time. Because of safety-imposed restrictions on shot duration, the SG beam could be on a subject for at most 60% of a trial; thus, the system suppressed the individual's ability to train the laser spot within the target limits for (on average) at least 31% of the trial without even being on. Rank-ordering the remaining tasks, from most to least impacted by the SG: the rifle behind a barrier exercise (Experiment 2B2), the ball throwing exercise (Experiment 2A), and lastly the IED exercise (Experiment 2C). For Experiment 2B2, shooters were within target limits 59% of the time. Since, as previously noted, the system could engage a subject for at most 60% of a trial, this implies that shooters were disrupted whenever engaged by the system, but quickly recovered when the beam was off. It should be noted that statistical differences do not necessarily translate to operational effectiveness. The data presented here are necessary for setting parameters for future military utility assessments and system optimization, but should not be considered to represent a complete and final assessment of operational effectiveness.

4.2 Safety Concerns

The SG system spot size is smaller than that for the ADS and requires higher power densities to achieve the same robust repel response as the ADS. The SG system required 9.1 J/cm^2 (3.03 W/cm^2 for 3 s) to repel 90% of a target population compared to 6.6 J/cm^2 (2.2 W/cm^2 for 3 s) for the ADS. The higher energy densities required by the SG system puts the target at increased risk for injury resulting from multi-path effects. Multipath exposures act to multiply the baseline exposure. Increases are typically in the neighborhood of 10 to 50% with 100% increases possible. Thus, an individual shot by SG in a multipath environment might receive 18.2 J/cm^2, putting him or her relatively close to the threshold for injury. (The threshold for a second degree burn is 20-30 J/cm^2.) In contrast, the ADS-targeted individual receives only 13.2 J/cm^2 and remains uninjured. This increased safety risk was noted during Experiment 1 and 2A1 trials where individuals received burns from multipath exposures at a rate that exceeded that found with the ADS.

An increase in the power density required to attain a sufficiently robust repel effect (compared to ADS) also impacts the operationally useful range over which the SG system can be employed. This manifests in two major effects. The first is the reduction in the maximum range at which the SG is effective. This effect can be illustrated by reference to Figure 7. If one were to assume that it required only 2.2 W/cm^2 for SG to effectively repel (i.e., similar to the effective power density for ADS), then the system would be effective out to a distance of approximately 300 m. However, given the finding that it takes 3.03 W/cm^2 to achieve the desired repel response, the maximum range at which SG is effective is only about 250 m.

The second effect is a reduction in the “operational window” over which the SG is both safe and effective. The operational window may be defined as the difference between the maximally effective range (just discussed) and some minimum range. If a target moves closer to the transmitter than this minimum range, he or she is at increased risk for injury unless the operator compensates by reducing the power density. If one were to consider a function relating power density to distance from transmitter for the ADS (that is analogous to the one shown in Figure 7 for the SG), it would be apparent that the ADS is effective over a lengthy “flat” portion of its function; that is, for a fixed output from the system, the target would have to move a relatively long distance from the maximally effective range towards the transmitter before the power density on target would begin to increase to the point where injuries would start to become a concern. This is less true in case of SG. Again, referring to Figure 7, as one moves from a distance of 250 m towards the antenna, the power density on the target increases comparatively quickly. Given a targeted individual who starts 250 m away and is moving towards the SG at 6 m/s, the individual will cover a distance of 60 m in 10 seconds which will cause the power density to change from 3.03 W/cm^2 to 5.0 W/cm^2 which would exceed a 12-J safety limit; that is, he or she might quickly move from a distance where the system was effective to one where injuries were likely unless, as noted, the operator compensated by reducing the output from the system. Thus, more so than with the ADS, the SG requires that the operator constantly know the range to target so that the device output can be updated accordingly.

4.3 Future Military Assessment

This experiment was constrained by the need to ensure the safety of the participants given that these exposures constituted the first-time use of the SG system against human targets. Now that the relevant safe exposure parameters are known, we suggest conducting a scenario-based, live-fire military utility assessment of the SG system to determine whether it will be successful in deterring targets (both individuals and groups) whose behaviors are relatively unconstrained. The participants should be free to develop strategies and counter-measures to defeat the system, and free to roam the entire operational range over which the SG system is expected to be useful. Of concern throughout the design of this assessment will be the safety issues outlined in Section 4.2, *Safety Concerns*.

4.4 Selective Targeting

During the present studies, the operator was instructed to aim for the target's center of mass if possible. During the static exposures of Experiment 1, this aim-point was chosen in order to facilitate comparisons between SG and ADS power levels required for repel. That is, any differences would be related to spot size because other exposure parameters (radiation frequency, exposure duration, and target location) were identical. Changing the spot size affects the amount of skin surface area covered by the beam which impacts the number of nerve fibers excited by the MMW heating. Choosing a different aim-point during this study would have complicated the comparative analysis because the density of nerve endings varies over the body.

Previous work supports the hypothesis that repel responses occur at lower power densities when the face as opposed to the torso is targeted (e.g., Handler et al., 2010). This is possibly a consequence of the significantly greater number of nerve endings in the face (Schmidt, Schmelz, Ringkamp, Handwerker, & Torebjork, 1997). However, because the spot size of both SG and the ADS are larger than the human head, it is unlikely that a statistically significant difference in system effectiveness would be uncovered at that location. However, a systematic study of repel response, power density, and spot size for locations over the body is necessary to provide quantitative answers that would enable the design of an optimal MMW weapon. Previous research has provided the safety thresholds for MMW exposures and indications of trends in effectiveness, and current studies (Parker, Nelson, Beason, & Cook, 2011) should provide some of those answers, but additional research examining both small spots and targeting locations is warranted.

One concern regarding the specific targeting of the face is that in an operational setting the weapon operator is often only able to aim at and track the center of mass when presented with a moving target. Thus, if a system is designed to repel by targeting the face at a relatively low power density, then when the target is free to move and the operator cannot reliably target the face, that same low power density will probably not repel the individual in the designed timeframe, if at all. A system designed to repel 90% of the population when targeting the center of mass is more likely to be successful when the target is moving because it reduces the aiming burden on the operator.

One possible means to improve targeting is the integration of an autotracking capability. At present, it is unclear what behavioral responses will be seen when targeted individuals are no longer able to self-limit their exposure. Before heading too far down this path, we would recommend investigating this behavior. Furthermore, this type of change will necessitate a re-assessment by legal and policy decision-makers.

4.5 Tradespace

When Raytheon tightened the focus of the SG MMW beam, they increased the power density on target at all ranges. However, they may have simultaneously reduced the ability of the system to repel individuals because the increases in power density were achieved by reducing the spot size at all ranges. Since no human tests were conducted with the larger SG spot size and we await the results of other spot size experiments, the hypothesized reduction in effectiveness is only conjectural at this time. However, the hypothesis is supported by the significant difference (a 40% increase) in power required by the SG to repel a static target as compared to that required by the larger-spot ADS. The reduction in SG beam size from July 2006 to December 2007 indicates that the designers are capable of making significant changes in the antenna output. Increasing the beam size should enable a tradeoff in required power density. Until additional spot size data are collected, we cannot at present specify the exact relationship between spot size and power density, but such a systematic study would provide valuable design parameters to system engineers.

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