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Infrared laser damage thresholds for skin at wavelengths from 0.810 to 1.54 microns for femtosecond to microsecond pulse durations

Clarence P. Cain[1], William P. Roach[2], David J. Stolarski[1], Gary D. Noojin [1], Semih S. Kumru[2], Kevin L. Stockton[1], Justin J. Zohner[2], and Benjamin A. Rockwell[2]

[1]Northrop Grumman, 4241 Woodcock Dr., Ste B-100, San Antonio, TX USA 78228-1330
[2]U.S. Air Force AFRL/HEDO, Brooks City-Base, TX USA 78235-5278

Abstract

In this paper we report on our combined measurements of the visible lesion thresholds for porcine skin for wavelengths in the infrared from 810 nm at 44 fs to 1318 nm at pulse durations of 50 ns and 350 μs to 1540 nm including pulse durations of 31 ns and 600 μs. We also measure thresholds for various spot sizes from less than 1 mm to 5 mm in diameter. All three wavelengths and five pulse durations are used extensively in research and the military. We compare these minimum visible lesion thresholds with ANSI standards set for maximum permissible exposures in the infrared wavelengths. We have measured non-linear effects at the laser-tissue interface for pulse durations below 1 μs and determined that damage at these short pulse durations are usually not thermal effects. Damage at the skin surface may include acoustical effects, laser ablation and/or low-density plasma effects, depending on the wavelength and pulse duration. Also the damage effects may be short-lived and disappear within a few days or may last for much longer time periods including permanent discolorations. For femtosecond pulses at 810 nm, damage was almost instant and at 1 hour had an ED_{50} of 8.2 mJ of pulse energy. After 24 hours, most of the lesions disappeared and the ED_{50} increased by almost a factor of 3 to 21.3 mJ. There was a similar trend for the 1.318 μ laser for spot sizes of 2 mm and 5 mm where the ED_{50} was larger after 24 hours. However, for the 1.54 μ laser with a spot size of 5 mm, the ED_{50} actually decreased by a small amount; from 6.3 Jcm^{-2} to 6.1 Jcm^{-2} after 24 hours. Thresholds also decreased for the 1314 nm laser at 350 μs for spot sizes of 0.7 mm and 1.3 mm diameter after 24 hours. Different results were obtained for the 1540 nm laser at 600 μs pulse durations where the ED_{50} decreased for spot sizes 1 mm and below, but increased slightly for the 5 mm diameter spot size from 6.4 Jcm^{-2} to 7.4 Jcm^{-2}

Keywords: infrared, visible lesions, ED_{50}, skin, pulse durations

1. INTRODUCTION

In this paper we report on our combined measurements of the visible lesion thresholds for porcine skin for wavelengths in the infrared (810, 1315, 1318, and 1540 nm). These wavelengths represent the most common used lasers and those capable of delivering very high energy pulses for various pulse durations and repetition rates. Pulse energies can be from millijoules to hundred of joules per pulse depending on the wavelength and the pulse duration. At a wavelength of 810 nm, with femtosecond pulses, terawatt peak powers are generated routinely with tabletop laser systems. These systems can operate at repetition rates greater than 10 pps. For the 1314-1318 nm wavelengths, joule pulses can be delivered with pulse durations from nanoseconds to milliseconds. These pulses can be generated using several different lasing mediums, including Chemical-Oxygen-Iodide-Lasers (COIL) for very large pulse energies. For the longer pulse durations at 1540 nm, pulse energies of 100 joules or more can be obtained at pulse durations of ~1 ms. For nanosecond pulses at this wavelength, a mechanical Q-switch is generally used to shorten the pulse duration. A system developed in our laboratory[1] can generate ~31 ns pulses. The American National Standards Institute (ANSI)[2] divides the electromagnetic spectrum into bands of wavelength regions. The transition from near-infrared to far-infrared is at 1400 nm (according to ANSI) and above this wavelength is considered far-infrared.

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In these studies we have concentrated on skin effects because of the lack of previously reported data supporting the current ANSI-Z136.1-2000. This standard is used for determining the maximum permissible exposure (MPE) levels (safe levels) to laser radiation. We have previously reported the effects of these infrared laser pulses in live eyes from measurements taken at various wavelengths and pulse durations to determine the MVL-ED_{50} thresholds.[3] These thresholds were measured for femtosecond pulses with and without pulse-chirping to counter the effects of group velocity dispersion (GVD) and we also compared these ocular MVL thresholds to the laser-induced breakdown (LIB) and low-density plasma (LDP) thresholds measured in an artificial eye. There are no skin MPE levels for pulse durations shorter than a nanosecond in the current ANSI standard and only a few experimental data points have been reported in the literature. Only one MVL-ED_{50} threshold has been reported for terawatts.[4] We have reported the skin MVL thresholds using the nanosecond and microsecond pulse durations previously and compared them with the ANSI standards. This paper will be the first combined reporting of so many pulse durations, wavelengths and spot sizes for the skin using Yucatan mini-pigs as the subjects. The animals involved in this study were procured, maintained, and used in accordance with the Federal Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources -- National Research Council. Brooks City-Base, TX has been fully accredited by the Association for Assessment and Accreditation of Laboratory Animal Care, International (AAALAC) since 1967.

We also measured thresholds for various spot sizes from less than 1 mm to 5 mm in diameter (810 nm was 12 mm diameter) for all the wavelengths but not for all conditions. We compare these MVL thresholds with ANSI standards set for maximum permissible exposures in the infrared wavelengths. We have observed non-linear effects at the laser-tissue interface for pulse durations below 1 μs and determined that damage at these short pulse durations are usually non-thermal in nature. Damage at the skin surface may include acoustical effects, laser ablation and/or other plasma effects depending on the wavelength and pulse duration. Also the damage effects may be short lived and disappear within a few days or may last for much longer time periods including permanent discolorations.

An array of laser exposures (with varying pulse energy) was placed on the flanks of Yucatan mini-pigs. Probit analysis was used to determine the ED_{50}s for minimal injury. Yucatan mini-pigs were used because they have been found to have higher anatomical similarity to human skin than the commonly used Yorkshire pig.[5] Yucatan mini-pig skin is melanated and, on the flank, is of similar thickness to that on the human arm, which has a high probability of accidental exposure. The data obtained from this study on porcine skin damage will contribute to the further understanding of laser injury mechanisms. By using this model, the properties of human skin can be more closely approximated to gain a better understanding of the human laser-tissue interaction for these wavelengths. These results will add to the existing data on laser-skin effects, upon which safety standards are based and which affect the employment of these laser systems.

The results discussed in this paper has been reported previously in several publications for individual wavelengths and pulse durations but have not been compared collectively to the ANSI standards as now. The results for the 810 nm wavelength at 44 fs was reported in Lasers in Surgery and Medicine[4] and the methods and procedures are described in that reference and will not be repeated here. Some data for the 1318 nm wavelength at both 350 μs and 50 ns have been reported in the Journal of Biomedical Optics (JBO)[6] and those for the 1540 nm were reported in JBO[7] also. Procedures and raw data were presented in those references cited and will not be discussed herein.

2. REPORTED DATA

Threshold measurements for the minimum visible lesion thresholds at each of the 3 wavelengths and different pulse durations for numerous spot sizes are reported herein and enough data points were taken to provide the ED_{50}s using Probit analysis together with the fiducial limits at the 95% confidence level. Because the 24-hour reading is the one normally used for settings standards, we are showing only these values in Table 1 for all values.

Skin Exposures Single pulse	MVL-ED_{50} 1540 nm 24 hrs	MVL-ED_{50} times MPE	MVL- ED_{50} 1314 nm 24 hrs	MVL-ED_{50} times MPE
Yucatan mini-pigs Flanks	Fluence J cm^{-2}	Ratio at 1540 nm	Fluence J cm^{-2}	Ratio at 1318 nm
0.7-mm dia. spot 350 μs or 600 μs	20 (21 – 18)	20	99 (112 –86)	132
1.3-mm dia. spot 350 μs or 600 μs	8.1 (8.7 – 7.5)	8	83 (85 – 81)	110
5-mm dia. spot 350 μs or 600 μs	7.4 (7.8 – 7.0)	7	No data	-
2.0-mm dia. spot 31 ns or 50 ns	No data	-	38.5 (51–31)	380
5.0-mm dia. spot 31 ns or 50 ns	6.1 (6.5 – 5.5)	6	10.5 (11 – 10)	100
Terawatt laser at 810 nm and 44 fs with a 12 mm diameter spot MVL-ED_{50} = 21 mJ for a Fluence = 19 mJ cm^{-2} at 24 hours				

Table 1. Visible lesion thresholds on Yucatan mini-pig skin at 1540 nm and 1314 nm for different spot diameters and pulse durations

For the 1540-nm wavelength listed above, photos of the lesions at 10 minutes post exposure, 1 hour post exposure and at 24 hours are shown in Photos 1, 2, and 3.

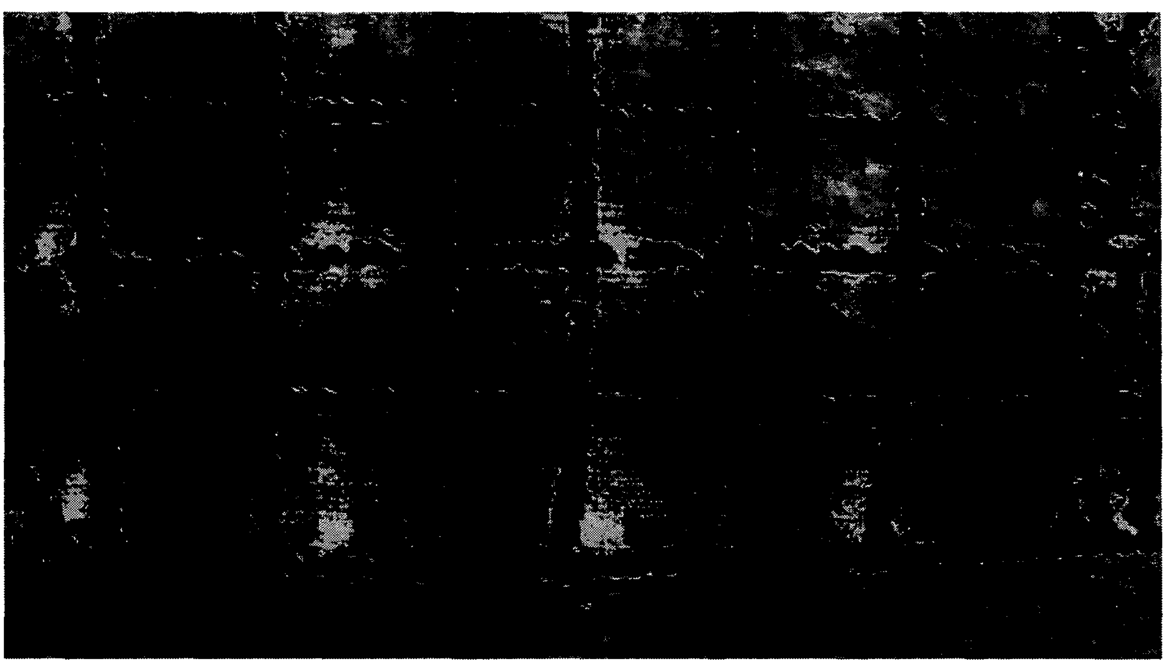

Photo 1. Picture taken at 10 min post exposure for 1540 nm, 600 μs, 5 mm spot size.

The lesions are shown at 3 different times after the exposure because at this wavelength, the skin appears bright red and inflamed. In as little as 1 hour, the lesions shown in Photo 2 are very much lighter and seem to be disappearing.

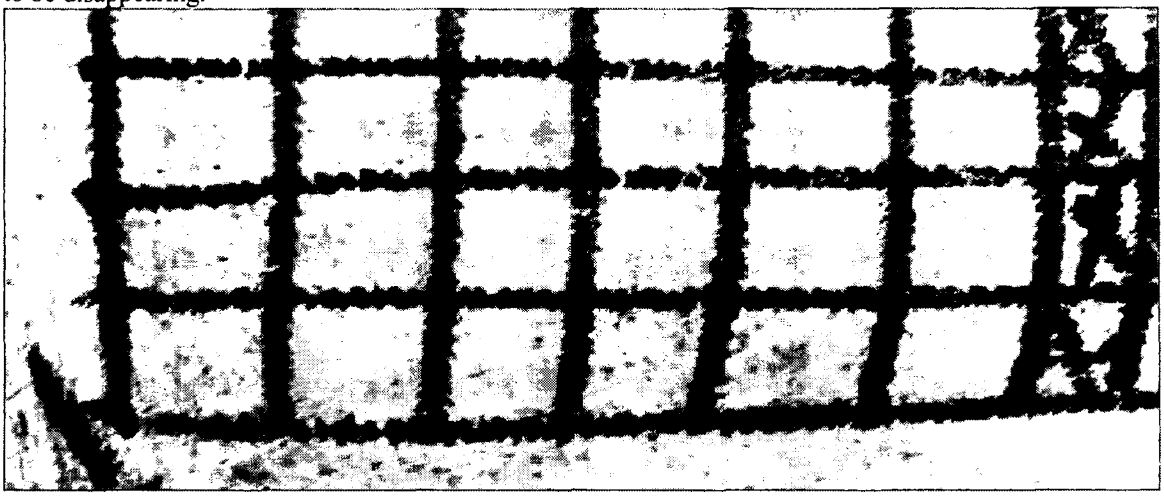

Photo 2. Picture taken at 1 hour post exposure for 1540 nm, 600 μs, 5 mm spot size.

After 24 hours it is difficult to see any of the lesions shown in Photo 1, and the damage appears to be minimal. In fact, the 1-hour threshold was lower at 6.4 J cm^2 because many of the lesions shown in Photo 2 actually disappeared after a few hours.

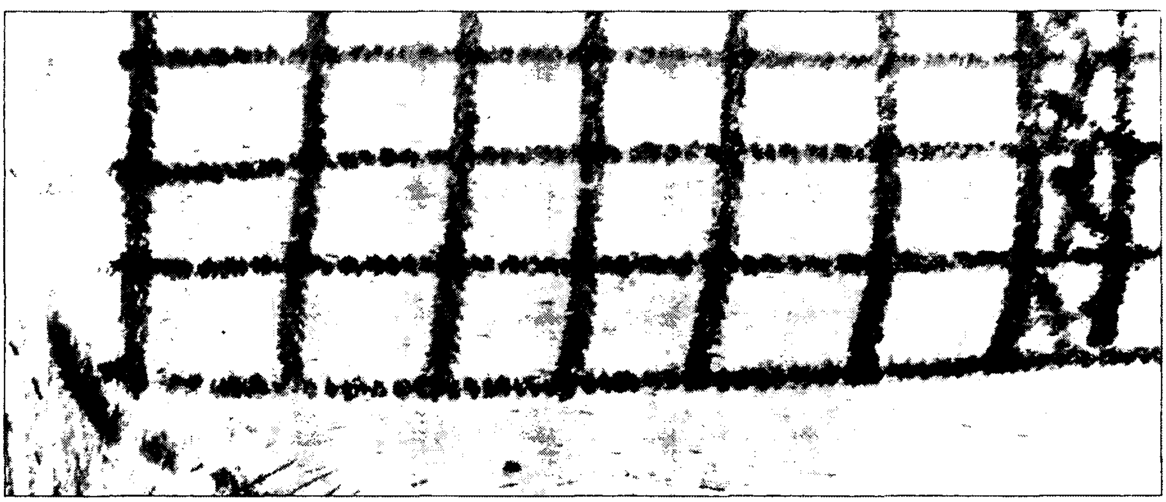

Photo 3. Picture taken at 24 hours post exposure for 1540 nm, 600 μs, 5 mm spot size.

In comparing this wavelength to the 1318-nm, 350-ms laser pulses with a 1.3 mm spot size, the lesions at 1 hour are very much different as shown in Photo 4. In Photo 4, the lesions appear as raised bumps on the skin and did not appear to damage the surface of the skin. These lesions were sub-dermal and it was difficult to discern many of these lesions, even at 1 hour post exposure. The threshold at this wavelength was approximately 10 times the value in fluence as that for the 1540 nm laser.

2.1 Q-switched pulses

Skin damage due Q-switched laser pulses was examined for the two different wavelengths: 1540 nm (31 ns pulse duration) and 1318 nm (50 ns pulse duration). Lesions produced by Q-switched pulses were very different from the long-pulse mode for each wavelength, but were very similar for both wavelengths.

Lesions for 1540 nm at the 1-hour reading are seen in Photo 5 showing different shapes and sizes of lesions depending on the energy of each pulse.

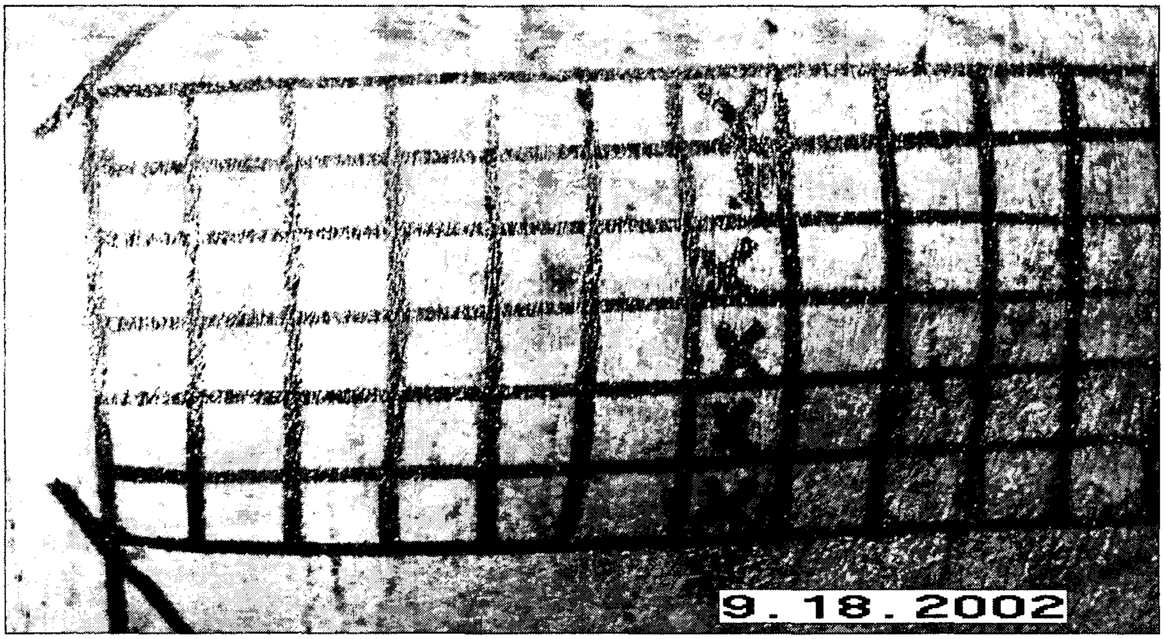

Photo 4. Picture taken at 24 hours post exposure for 1315 nm, 350 μs, 1.3 mm spot size.

In Photo 6, for the same grid position, very few lesions can be discerned either because the lesion itself had healed or the pig had scraped off the skin surface rubbing against the walls of the its holding pen. Very slight discoloration of the skin surface is visible in one or two of the sites.

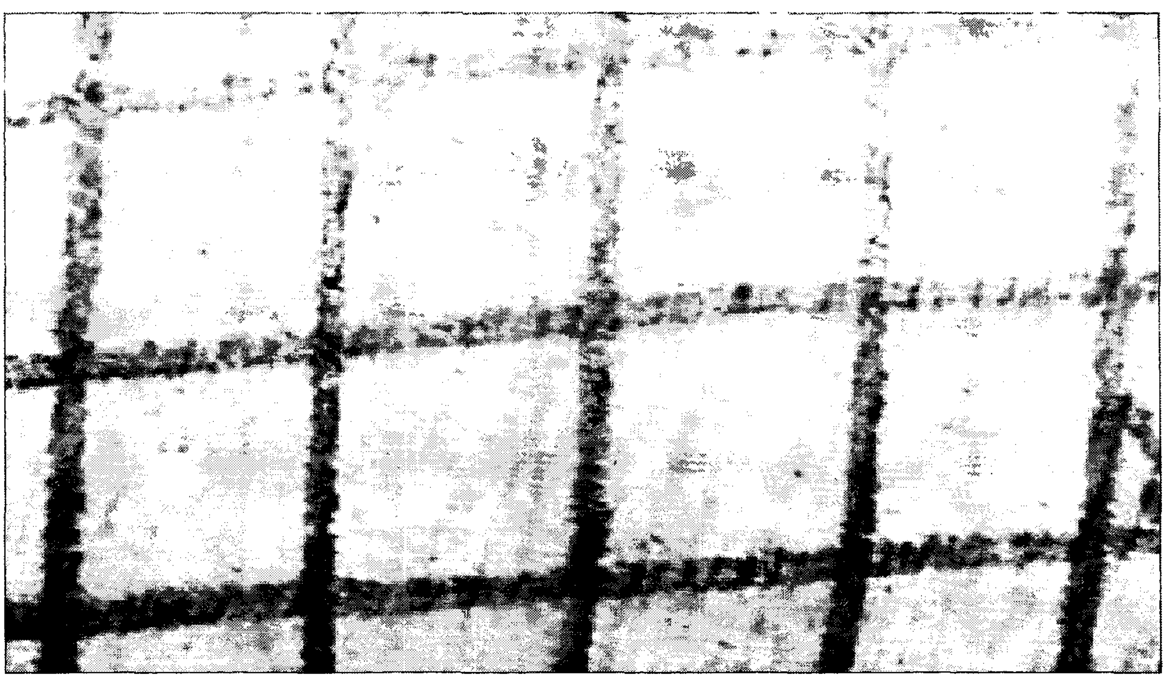

Photo 5, Picture taken at 1 hour post exposure for 1540 nm, 31 ns (Q-switched), 5 mm spot size.

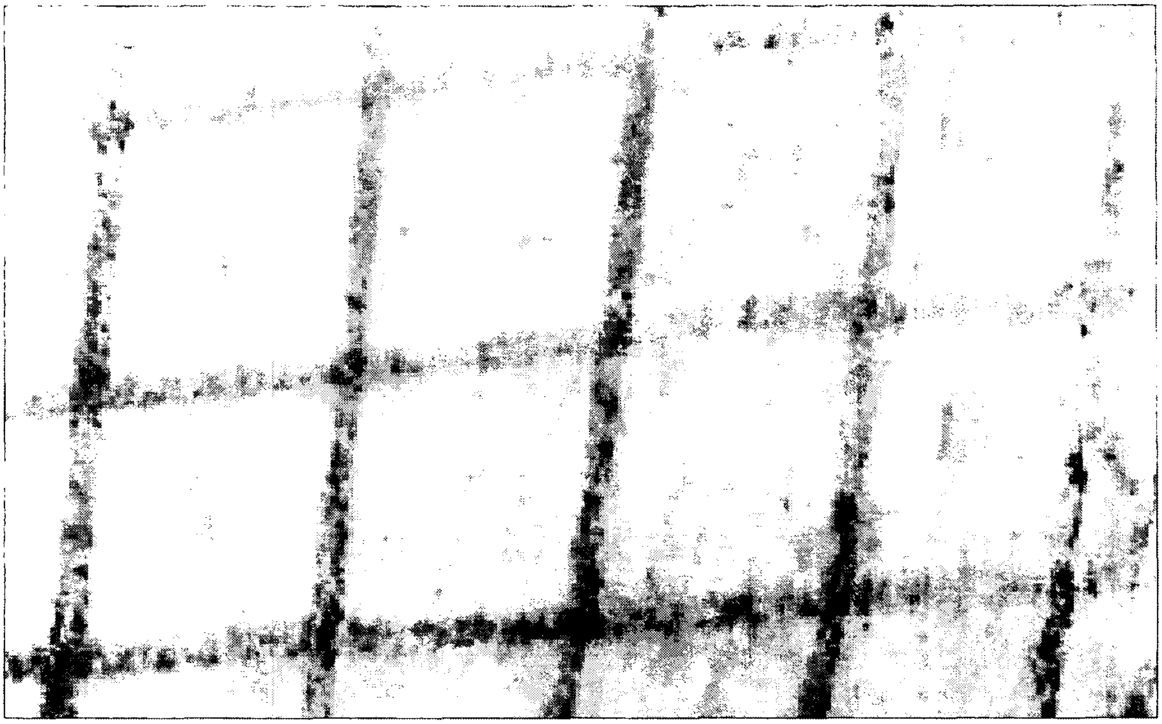

Photo 6. Picture taken at 24 hours post exposure for 1540 nm, 31 ns (Q-switched), 5 mm spot size.

For the 1318 nm, Q-switched pulses, the energy in the pulse did penetrate the skin to a much greater depth than with the 1540 nm pulses, as can be discerned in Photos 7 and 8. In Photo 7, there is redness around the actual white lesion and this redness clearly remains after 24 hours as shown in Photo 8.

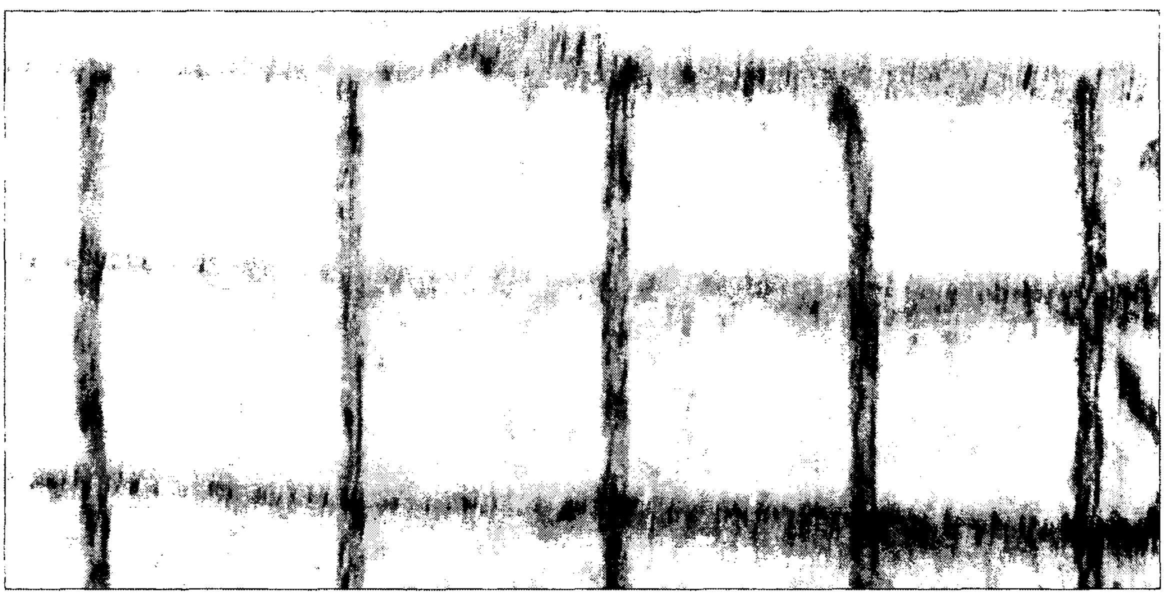

Photo 7. Picture taken at 1 hour post exposure for 1318 nm, 50 ns (Q-switched), 5 mm spot size.

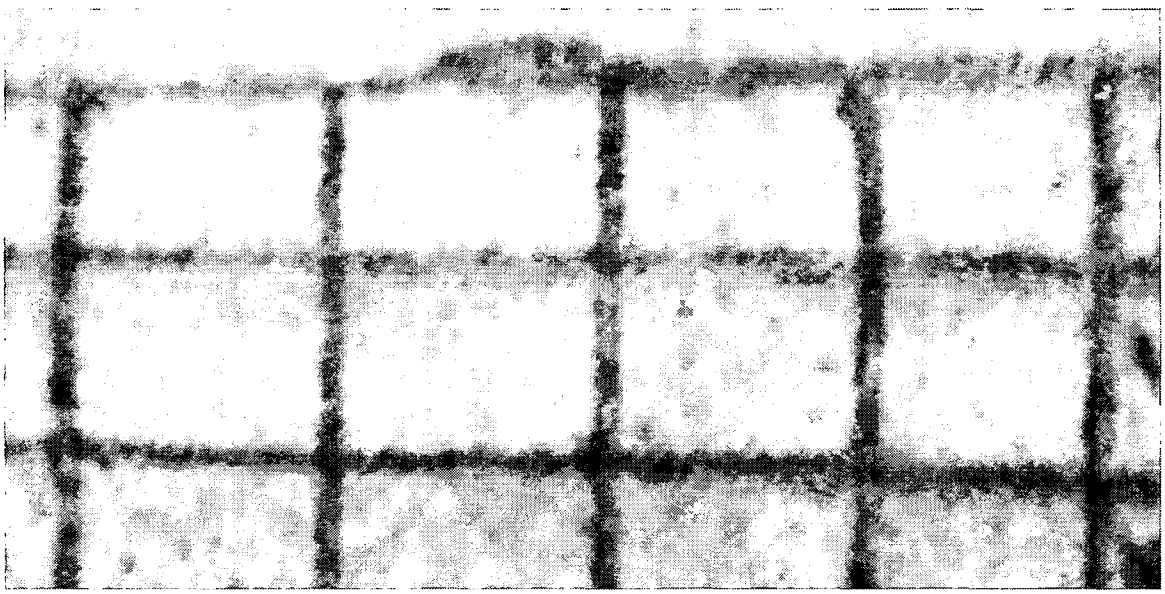

Photo 8. Picture taken at 24 hours post exposure for 1315nm, 50 ns (Q-switched), 5 mm spot size.

2.2 Terawatt laser at 810 nm

The terawatt laser pulse required very much less energy to produce visible lesions for several reasons: shorter wavelength, shorter pulse duration and higher peak powers within the pulse. However, the main reason was that for these peak powers, the beam was able to self-focus as it propagated from the laser to the subject, producing a number of filaments dependent on the pulse energy. Higher-energy pulses produce a number of filaments proportional to the energy contained within the pulse. As can be seen in Photos 9 and 10, some lesions were produced by 6 to 8 filaments while other lower energy pulses produced only 1 visible white spot.

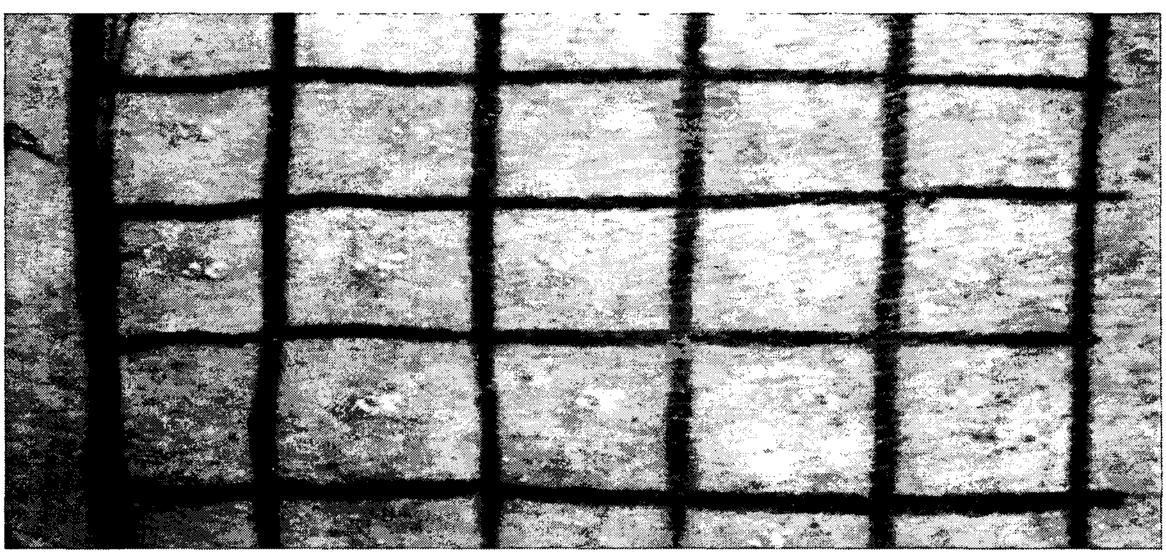

Photo 9. Picture taken at 1 hour post exposure for 810 nm, 44 fs, terawatt laser pulses, 12 mm spot size.

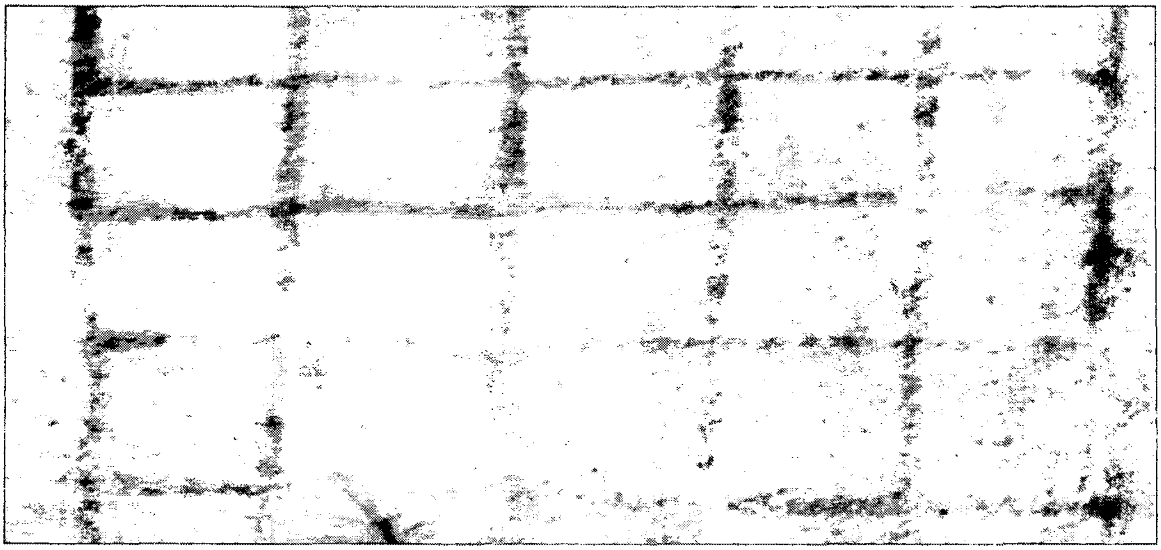

Photo 10. Picture taken at 24 hour post exposure for 810 nm, 44 fs, terawatt laser pulses, 12 mm spot size.

Visible lesion thresholds were determined at both 1 hour and 24 hours post exposure, and are listed in Table 1 for only the 24-hr readings. At 10 minutes post exposure, most of the exposure sites showed edema in the skin and most of this disappeared after 1 hour. Many threshold ED_{50} values observed at 1 hour simply disappeared after 24 hours. Also, some of the observable lesions were probably dead skin that had been blown off by the laser pulse and evidence of this was not visible after 24 hours. Thus the thresholds given after 24 hours represent true damage thresholds for the skin at these pulse durations.

Since Probit analysis (yes/no data) was employed to determine the threshold value, the number of filaments within a pulse was not a consideration in determining whether the energy created a visible lesion. Most of the evidence of a lesion was removed during the 24 hours between the two readings either by the pig rubbing against the walls of its pen or it lying down on the floor. The visible lesions as seen in Figure 10 were the only ones counted in determining the 24-hour threshold.

3. HISTOLOGICAL RESULTS

The histological results from laser exposure sites can aid in identifying the damage mechanism present. While biopsy punches were taken from all laser exposure conditions listed in this review, to this point few of the samples have been analyzed. Detailed histological examinations and analysis has been conducted on the 1.314 μm, 350 μs laser exposures as discussed by Montes De Oca.[8] Results were consistent with second-degree burns for exposures near threshold. Recent work[9] has also analyzed the histological results for 1.54 μm 600 μs laser exposures and found very similar results to the 1.314 μm 350 μs samples. The exposures are within thermal confinement[10] and show many similar signs of thermal injury. Analyses for the 1.54 μm and 1.318 μm, nanosecond exposures have also been conducted.[9] The results of these histological examinations show the possibility of mechanical stress causing some of damage. In addition to mechanical stress related damage, there also appears to be a wavelength dependence on some of the types of damage seen. The damage from the 1.318 μm nanosecond pulse duration exposures is concentrated on the pigmented epithelial cells, sparing the superficial epidermal layers. These findings may be related to the differences in absorption coefficients of the various cellular layers of tissue involved in these interactions.

4. DISCUSSION AND CONCLUSIONS

We have performed MVL threshold measurements on live pigskin and we compare these thresholds with the ANSI safe exposure limits. Since the ANSI safe exposure limits for skin are based on both laser wavelength and exposure time in the near-IR (1318 nm), we have measured thresholds for two different pulse durations on two different laser spot sizes on the skin, as given in Table 1. For the far-IR (1540 nm), ANSI is a function of the wavelength but not of the exposure time for pulses between 1 ns and 10 seconds. We measured these thresholds for three different spot sizes and two pulse durations to determine if there is a spot size dependency and if they vary with time. Since there are no MPE limits for pulses below 1 ns in the ANSI standards, we only discuss the lesion characteristics produced by the terawatt laser for the fs laser pulses and state only the threshold value measured.

Visible lesion threshold measurements at 1540 nm for two pulse durations with three spot sizes are reported herein and enough data points were taken to provide the ED_{50}s and their fiducial limits at the 95% confidence level using Probit analysis. Results for the ED_{50}s using the long pulse (600 µs) are reported for 24-hour post exposure readings in Table 1. Two other threshold measurements have been reported (Rico [11,12] for small spot size and Lukashev[13] for large spot size) for this wavelength. Our data agree with Lukashev's data at the larger spot size but not so well with Rico's data at a smaller spot size. Since our threshold value for the 0.7-mm spot size was so much larger than model predictions, and that we were able to see flashes of light at the delivery site and sometimes hear a pop, we believe that breakdown was occurring at or near the surface of the skin and not all of the pulse energy was penetrating the skin. In analyzing our data, we discovered that there was a large number of zeros or non-lesions at these very large laser pulse energies. In fact, the chi-square term in the Probit analysis was found to be 0.007, showing this distribution was definitely not normal. We determined it prudent to eliminate no-lesion determination above certain thresholds because of the likelihood of generation of plasma that would shield the skin from the laser energy, thereby giving a false negative for the exposure reading. When we eliminated all data points above certain pulse energies, we raised the chi-square term to above 0.6 but did not change the ED_{50} value.

Most lesions initially appeared as a blotched red coloring near the center of the exposure-square, where the laser beam penetrated the skin. These red spots appeared almost immediately and many disappeared before the 1-hour reading. Exposure sites were observed visually after 1 hour and most of the immediate lesions were no longer red splotches but very small discolorations in the skin. At the 24-hour post exposure reading, more lesions could be clearly observed than were visible 1 hour post exposure for the two smaller spot sizes. However, for the 5-mm spot size, fewer lesions were observed at the 24-hour reading and thereby producing a larger ED_{50} at 24 hours than at the 1-hour reading.

Only preliminary data have been reported[14] in the past for the 1318 nm laser, and that was for a spot size of only 0.25 mm in diameter due to laser pulse energy limitations. We had a higher-energy laser and were therefore able to use larger spot diameters of 0.7 mm and 1.3 mm for the long-pulse mode (350 µs). For the 0.7-mm spot, we measured an MVL-ED_{50} threshold of 111 J cm^{-2} at the 1-hour reading, and 99 J cm^{-2} at the 24-hour reading, which indicates that a few more lesions were observable after 24 hours. It was observed but not recorded that during the higher energy exposures, a visible flash was seen and a loud pop was heard due to LIB occurring at the skin surface as reported above for the 1540 nm wavelength. This LIB most likely had some affect on the thresholds and was not noticeable during the larger spot (1.3 mm) exposures. The occurrence of LIB is frequently seen for the large fluences in these exposures.[10] ANSI exposure limits as given in Table 1 for this pulse duration (350 µs) are only 0.75 Jcm^{-2} or slightly more than two orders of magnitude below our 83 J cm^{-2} for the ED_{50} measurement.

MVL threshold measurements at the short pulse duration of 50 ns required special considerations in order to prevent LIB occurring in air even before the laser pulse reached the pigskin. At 50 ns, with pulse energies of 0.4 J/pulse or more, when focused to spot sizes less than 1-mm diameter, we were able to produce irradiances of more than 10^9 W cm^{-2}. Because we were able to expose the skin with energies up to 3.2 J/pulse at 50 ns, we had to utilize spot diameters of at least 2 mm to prevent LIB in the air and shielding of the pulses for the skin exposures. Even for the 2-mm spot diameter, most of the recorded lesions indicated that the observers either saw a flash of light or heard a pop. At a spot diameter of 5 mm, and with the 3.2 J/pulse maximum pulse energy available, the irradiances only reached a value of $3x10^8$ W cm^{-2}; well below the breakdown value for air or on the skin surface. The occurrence of LIB at the skin surface for thresholds lower than in free air is expected, as free-electrons are created at the skin surface by the large fluences from these exposures. The threshold for these phenomena is also reduced by significant linear absorption, up to a factor of 1000 reduction for very absorbing wavelengths in the far-infrared.[10] We believe that LIB at the skin surface was the reason that the MVL-ED_{50} threshold for the 2-mm diameter spot (39 J cm^{-2}, Table 1) was almost 4 times the value for the 5-mm diameter spot (10.5 J cm^{-2}, Table 1). It was interesting to note that the MVL- ED_{50} thresholds at the 1-hour reading were almost identical for both spot sizes. Temperature calculations by models for the 50-ns pulse had a computed temperature rise of a couple of degrees for no scattering and 8 °C rise with scattering for the 5-mm, 2.2-J laser pulse. Thus we believe that the damage should be mechanical and not thermal. Certainly, we could have had LIB and acoustic shock waves without the indicators described above producing this visible skin damage.

For the femtosecond pulses at 810 nm, damage was almost instant and at 1 hour had an ED_{50} of 8.2 mJ of pulse energy. After 24 hours, most of the lesions disappeared and the ED_{50} increased by almost a factor of 3 to 21.3 mJ. There was a similar trend for the 1318-nm laser for spot sizes of 2 mm and 5 mm where the ED_{50} was larger after 24 hours. However for the 1.540-nm laser, for a spot size of 5 mm, the ED_{50} actually decreased by a small amount, from 6.3 J cm^{-2} to 6.1 J cm^{-2},after 24 hours. Thresholds also decreased for the 1.314-nm laser at 350 μs for spot sizes of 0.7 mm and 1.3 mm diameter, after 24 hours. Different results were obtained for the 1.540-nm laser at 600 μs pulse durations where the ED_{50} decreased for spot sizes 1 mm and below but increased slightly for the 5-mm diameter spot size from 6.4 J cm^{-2} to 7.4 J cm^{-2}.

Other femtosecond skin studies have been reported but not with porcine skin. Watanabe, *et al.*[15] performed threshold measurements using red visible laser pulses at 65 fs generated by a tunable dye laser on black and albino guinea pigs. They determined threshold doses required for rupturing melanosomes in the pigmented skin for pulse durations from 65 fs to 35 ns. Another research group, Frederickson, *et al.*,[16] reported ablation thresholds using the same type lasers as our system (Ti:Sapphire), for pulse durations of 120 fs on Sprague-Dawley female rats. Both of these reports relate to our research since the first study produced damage in the melanosomes of the skin (as did our exposures), and the second study also produced ablation of the skin through LIB and plasma generation at the skin surface. A third report, Puliafito, *et al.*,[17] reports on the ablation thresholds and ablation depths in cornea using 65 fs and 100 fs pulses from a dye laser at visible wavelengths.

The higher-energy pulses used in our study generated LIB at the surface of the skin and ablation of the outer layers was clearly evident. We did not measure any ablation effects or rates but we may compare our MVL threshold energies to threshold energies for tissue ablation reported by other researchers for these femtosecond pulses. Ablation thresholds measured by Frederickson, *et al.*,[16] used a Ti:Sapphire laser at 120 fs, 800 nm, with a maximum energy of 37 mJ/pulse and a spot size of 1-mm diameter. The rat skins had no melanosomes and when the tissue was exposed to laser radiation, a small spark of white light, representing the formation of plasma, was visible. Their reported threshold energy for skin tissue ablation was 2 mJ, corresponding to a threshold intensity of 2.5 TW/cm^2, and that sub-threshold pulses produced no plasma and no tissue ablation. Frederickson, *et al.* reported that at a pulse energy of 22 mJ, only one pulse was required to ablate the epidermis, whereas it took 100 pulses to ablate the epidermis with threshold energies of 2 mJ/pulse. They reported that histological examination of the skin-ablative effects of femtosecond, terawatt, pulsed lasers, demonstrated that the depth of ablation was 0.1 micron for above-threshold intensities. Also the collateral damage at threshold was virtually nonexistent, due to the non-thermal tissue ablation mechanism of the plasma generated at the surface. Our value of 21 mJ/pulse for the MVL-ED_{50} threshold compares very favorably with these results for ablating the epidermis.

Our data compared to the ANSI standards for the MPE of skin for two different wavelengths are shown in Figure 1. ANSI-MPE for the 1540-nm wavelength is a constant value for pulse durations from 1 ns to 10 sec as shown in this figure. For the 1318-nm wavelength, it is a function of the pulse durations that changes at 100 ns and again at 10 seconds as shown in Figure 1. At times greater than 10 sec, it is a constant power value or an energy value that is linearly related to pulse duration. All of our data points for all pulse durations are greater that the corresponding MPE values and most are greater than that by a factor of 10. At the 1540-nm wavelength, the MVL thresholds as shown are 6 and 7 times the MPE and may be considered adequate to protect human skin. For instance, the ED_{01} for the 0.6-ms pulses is 4 J cm^{-2} as compared to the ANSI-MPE of 1 J cm^{-2}. Thus, there is only a 1 percent chance of getting a visible lesion even at 4 J cm^{-2} and extremely low at the 1 Jcm^{-2}. For Q-switched pulses, the ED_{01} is 2.6 J cm^{-2}; that is almost 3 times the MPE and, therefore, there is almost no possibility of getting damage to the skin at 1 J cm^{-2}. Thus we conclude that the ANSI standards for the wavelengths and pulse durations as reported herein are adequate to protect the skin and do not require modifications for the 1540-nm wavelength. Since the MVL-ED_{50}s at 1318-nm wavelength are at least two orders in magnitude above the MPEs as stated by ANSI, it is felt that this standard could be relaxed and still provide adequate safety margins.

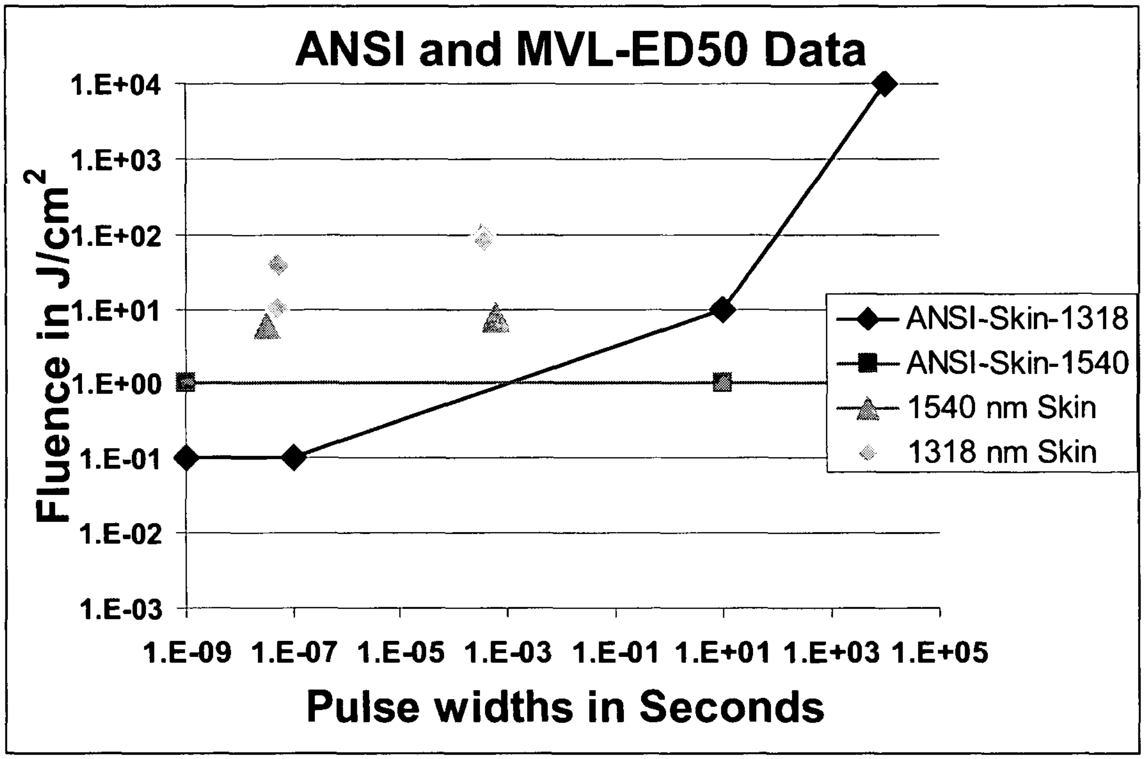

Figure 1. Graphical representation of ANSI MPEs for skin together with experimental data point for two wavelengths and pulse durations.

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