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AN ALTERNATIVE METHOD OF EVALUATING 1540NM EXPOSURE LASER DAMAGE USING AN OPTICAL TISSUE PHANTOM

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14. ABSTRACT
An optical phantom was designed to physically and optically resemble human tissue, in an effort to provide an alternative for detecting visual damage resulting from inadvertent exposure to infrared lasers. The phantom was exposed to a 1540-nm, Erbium:Glass, Q-switched laser with a beam diameter of 5 mm for 30 ns at varying power levels. Various materials were tested for use in the phantom; including agar, ballistic media, and silicone rubber. The samples were analyzed for damage lesions immediately after exposure and the Minimum Visible Lesion – Estimated Dose 50% (MVL-ED50) thresholds were determined from the data. In addition, any visible damage was evaluated for similarity to human tissue damage to determine if the phantom tissue would be a suitable substitute for in vivo exposures.

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Phantom, Laser, Er:Glass, epoxy resin, ballistic media, agar, ED50, skin damage, laser damage

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1. INTRODUCTION

Tissue phantoms are becoming a widely used method of evaluating various laser applications. Not only do they reduce the need for human and animal test subjects, phantoms also provide a uniform sample material without the variables introduced by biological subjects. The objective of this experiment was to create a low-cost material that would be easily reproduced and that closely resembled the optical and physical characteristics of human or porcine skin. In addition, it must be able to meet the rigorous requirements of both field and laboratory testing environments; such as sunlight and high temperatures. The materials must be available in bulk sizes due to the possible requirement of a life-size model. This phantom will be used primarily to study the effects of laser exposures for near- and mid-infrared wavelengths.

Lasers that operate at 1540 nm are widely used by both government and civilian organizations. Military and law enforcement agencies[1] use this wavelength for range finders as well as laser designators. In addition, due to the non-ablative aspects of this wavelength on human skin, the medical field utilizes these infrared lasers for skin remodeling treatments[2]. In this procedure, an Erbium:Glass laser stimulates collagen shrinkage and dermal wound healing while leaving the epidermis mostly intact. The result is smoother and tighter skin, while minimizing the possibility of scarring or permanent damage. This wavelength is considered "eye safe" because the exposure limits are larger than any other wavelength regime, but this nomenclature is discouraged in the ANSI Z136.1-2000 laser safety standard[3]. The standard for 1540 nm Maximum Permissible Exposure (MPE) for skin is 1 J/cm^2. Even though this wavelength has relatively large MPEs, this radiant exposure is commonly accessible with today's higher-energy pulsed laser systems. Due to the various applications involving long-distance use of lasers at this wavelength, it is necessary to evaluate the risks of accidental exposure to the skin from reflections and eye.

Despite the many uses of lasers at the 1540 nm wavelength, there is relatively little data on the effects to human tissues. Skin is the largest organ in the body, and as such has more surface area which can be exposed to laser damage. It is composed of three layers; the epidermis, dermis and subcutaneous layers respectively. The average thickness of these three layers[4] combined is approximately 2 mm, beyond the 1-mm depth[4] of 1540 nm infrared laser penetration. Human skin optical and thermal properties have been widely modeled, but there are surprisingly few references available for experimentation at this wavelength. Most experiments have been done using Yucatan and Yorkshire pig skin since it is very similar to human skin. Alexei Lukashev, et al[5, 6] and Cain, et al[7, 8] have done some work in this area using porcine (*Sus scrofa domestica*) test subjects, but they used a different spot size or duration parameters than this experiment. Pocock et al[9] used the same parameters as this paper with hairless guinea pig (*Cavia porcellus*) subjects to find an MVL threshold. When creating this phantom, the Effective Dose (ED$_{50}$) levels determined by Cain, Lukashev and Pocock were used as the phantom objective [Table 2]

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2. METHODS AND MATERIALS

2.1 Materials

Because of the unique field condition requirements that this phantom must endure, several materials were tested in order to find one that would give the best results. The first substance tested for the phantom was a two-part epoxy resin mixture called Poly-Sil 73 (Poly-Tek Develop. Corp., PA). It is a silicone rubber often used in the creation of molds and casts. The Poly-Sil provided a stable material that was the same density as human tissue. [Table 1] It had very low absorbance and scattering properties which allowed us to manipulate those properties as desired through the use of additional materials. The resin is formed by mixing two epoxy substances; Part A and Part B. The resin combination cures within six minutes to a semi-opaque finish. Resin can be purchased inexpensively in large quantities and has a long shelf-life, making it a preferred candidate for use in this phantom. One thing to consider when adding pigment or other substances is that both components of the rubber are hydrophobic. This will make incorporating any material with a water base very difficult.

Agar (Sigma Aldrich, MO) is another material that is used for creating phantoms. It is a dry powder comprised of seaweed polysaccharides and mixes with water to form a gel-like matrix. The amount of agar powder can be varied to alter the density of the material. It is readily available and can be easily stored since it comes in a powder form. However, it is fairly expensive compared to some of the other materials tested in this project.

The third substance tested was an animal protein gel (SIM-TEST™, Corbin Mfg., OR) that closely mimics the density of human tissue [Table 1]. SIM-TEST is most often used as a ballistic media in which studies are conducted on the ballistic effects of projectiles on human tissue. The gel can be prepared with almost no bubbles or aberrations being formed, and dries a translucent amber color. It has a high water content that facilitates the mixing of dyes and solutions into the gel, as well as helping to closely mimic the damage to human tissue. The medium is also fairly inexpensive and will remain viable for long periods of time if stored appropriately.

India Ink (KOH-I-NOOR Inc., NJ) is a water soluble dye used extensively in visible wavelength phantoms to increase photon absorbance rates. The absorption properties of the ink act as a substitute for melanin. It has a refractive index similar to melanin [Table 1] but it is a spherical shape where melanin is ovoid. While this ink is mainly used as an absorbing agent, it also has scattering properties due to its size and shape.

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Table 1. Physical and optical properties.

	Thickness (mm)	Density (g/cm^3)	MP (°C)	Thermal Conductivity	Refractive Index
Human Epidermis	.08[10]	1.2[10]	NA	.26[11]	1.34[12]
Human Dermis	2.08[10]	1.2[10]	NA	.53[11]	1.41[12]
Cured Resin	2.0	1.12	>340	.017[13] (W/cm·s°C)	1.453
Pig Dermis (flank)	3.848[14]	--	NA	.511 (W/m°C)	1.361[15]
Pig Epidermis	.0795[14]	--	NA	--	--
Agar 4%	2.0	.995	93.4	.625[16]	1.333
SIMTEST	2.0	1.25	36-42	--	1.706
India Ink	.254[17]	1.03	NA	--	1.365 (500:1)
Melanin	.002[18]	1.4[18]	NA	.105[19]	1.4[18]

2.2 Procedures

To prepare the epoxy resin phantom, the ink concentration is mixed into Part B making sure that it was well incorporated. An equal amount of Part A was then added, using the weight for measurement as opposed to volume (per product instructions). The mixture was again well mixed, then poured into 6 inch wide hexagonal mold, leaving a 2 cm thick sample. The samples were covered to prevent any debris from settling on them, and then allowed to harden.

To prepare the SIM-TEST phantom, large chunks were weighed and then cut into small pieces. The cubes were placed in a beaker over low heat, stirred until melted, and then immediately poured into a mold and allowed to solidify before adding a cover. Any additives were mixed in immediately after being poured to a 1-cm depth into the sample mold, which was 8 cm x 11 cm in size. This same mold was used for the agar samples also.

The agar mixture was made to form a 4% agar concentration. The desired amount of agar powder was added to water and heated until boiling, stirring constantly to avoid burning. In an effort to maximize the benefits of both materials, there were also several samples made that combined the agar and ballistic media together. For these items, the gel was melted and thoroughly mixed with the water media before adding the powder. The powder was added so that a ratio of two parts ballistic media to one part agar was formed. The India Ink was added immediately after the mixture was poured into the mold.

India Ink was added in various concentrations to each of the materials, and the samples were then placed in a spectrometer (Cary 6000i, Varian Inc., CA) to measure the

percentage of light transmitted through. The purpose of this was to test whether there was a relationship between the concentration of pigment and the optical properties of these phantoms at this wavelength. The samples were created by first cutting 1 mm thick microscope slides into four sections. These pieces were then affixed between two more microscope slides to act as spacers; forming 1-mm, 2-mm, and 3-mm deep holders. Tape was placed along the bottom edge of the slides, and the phantom material was poured into this space. Once the material had solidified, another piece of tape was placed along the top to completely enclose the material. This reduced the chances of dehydration or material loss. A graph depicting the relationship between absorbance of the epoxy phantom and India Ink concentration can be found in the Appendix, Figure 12.

2.3 Measurements

Physical and optical properties of each material were obtained using standard laboratory techniques. Measurements were determined for both density and melting points. The refractive indexes of our materials were found using a 632 nm Nd:YAG laser and goniometer. (Physics Apparatus Research Inc.). The samples were placed between two microscope slides, 100 cm from a target and the refractive distance was marked on a white board. Sardar[18] describes this as the same method for testing the refractive index that is used in several of his papers. This data was then used with equation 1 to determine the index of refraction for each sample. Due to its intense color, the India Ink was tested at a diluted strength of five hundred parts water to one part ink.

$$ n = \frac{\sin(\alpha + \varsigma_m)}{\sin(\alpha / 2)} $$

Equation 1. Refractive Index, where α is the apex angle; ς_m is the minimum deviation or tan-1 (refract. distance / 100cm)

Prior to laser exposure, the prepared samples were marked with a grid of 1cm x 1cm squares and placed in the sample holder. Each sample contained 60-70 squares, depending on the surface finish. Any section that had previous damage or aberrations was not exposed. Each exposure was noted for any visible damage and the amount of energy delivered was raised or lowered accordingly. For damage assessment, immediate readings were taken and additional readings were taken anytime after 1 hour of being shot, since the damage did not change beyond that time frame. Readings required at least two out of three readers to confirm a perceptible change in the sample.

2.4 Integrating Spheres

The optical properties of the materials used in this experiment were determined using a double-integrating sphere system. (Figure 1) Two integrating spheres (Oriel Model 70451) were aligned, leaving room in between the two spheres for a sample holder. A 1530-nm laser (NP Photonics) was controlled using a Thorlabs LCD2000 laserdiode

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controller, and monitored via an oscilloscope. (Tektronics TDS-3054B) The beam was directed into the first sphere and measured through two liquid nitrogen cooled detectors. (Judson J16D-M204-RO5M-60). Caps with reflective coating that mirrored the internal coating of the spheres were placed on the exit ports not attached to the detectors. Light was measured at each detector, giving values used in determining the total diffuse reflectance (Equation 2) and total diffuse transmittance (Equation 3).

$$R_d = \frac{X_r - Y}{Z_r - Y}$$

Equation 2: Total diffuse reflectance.

and:

$$T_d = \frac{X_t - Y}{Z_t - Y}$$

Equation 3: Total diffuse transmittance.

Where:

X_r is the reflected intensity at detector 1

Z_r is the incident intensity at detector 1

X_t is the transmitted intensity at detector 2

Z_t is the incident intensity transmitted at detector 2, with no sample and a reflectively coated cap on the far exit port

Y is the correction factor for stray light

(Light measured by both detectors with no sample and no reflective exit port cap)

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An inverse adding-doubling method (IAD) was used to derive the absorption and scattering coefficients, as described by Prahl[#].
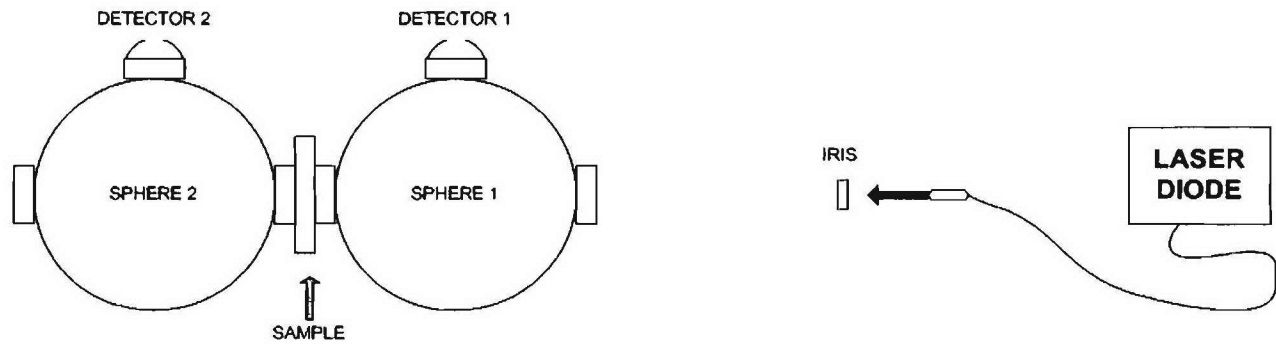

Figure 1. Double integrating sphere set-up used to determine the material optical properties.

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2.5 Laser Set-Up

The Er:Glass Megawatt laser was modified by Dr John Taboada[20] (Taboada Research Inst.) with a rotating Q-switch yielding 30-ns pulses of up to 3.5 joules per pulse at a wavelength of 1540 nm. Pulse duration was measured using an ET-3000 InGaAs Electro-Optics Technology, Inc. photodiode that was connected to a Tektronix TDS 220 Oscilloscope. The beam was split with a 90/10 beam splitter and the Gaussian beam was measured with calibrated Molectron J25 probes. The energy measurements were made using a Molectron JD1000 energy meter. Visual alignment was made using a HeNe laser. (Figure 2) The sample holder was placed 24 inches from the last mirror leaving a 5-mm beam diameter at the tissue phantom surface.
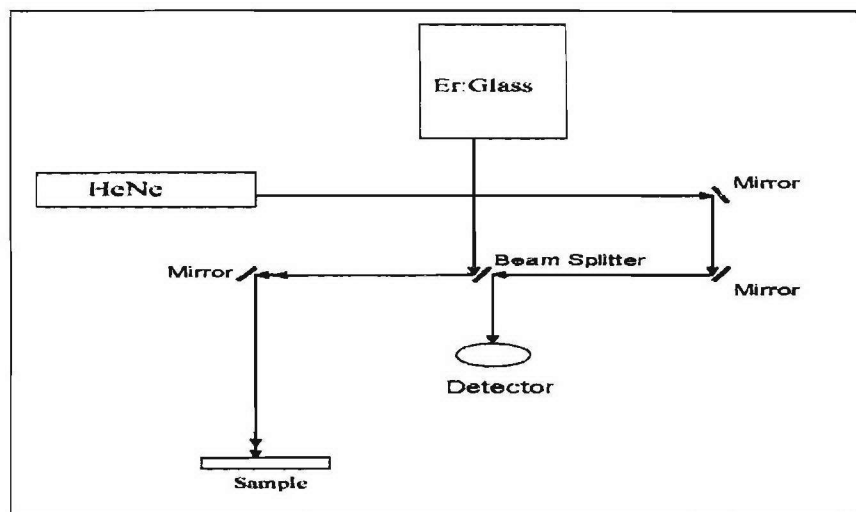

Figure 2. Schematic of laser set-up

3. RESULTS

The SIM-TEST ballistic media was found to be a poor phantom material for the purpose of these laser exposures. Since the material is mostly water, it quickly dries out if left uncovered. Not only did that cause large cracks to form in the material, it altered the physical and optical properties as well. The largest problem associated with this material is its low melting point (36-37°C in these lab experiments) which would reduce its effectiveness during warm field testing conditions and result in lowered MVL values. In an effort to correct these problems, numerous other substances were added to the SIM-TEST; such as agar, glycerol, and dextrose. Dehydrated samples were also made by boiling the gel for an extended period of time before pouring it into the mold, thus reducing the water content by almost one-third. While these additives and procedures did aid in reducing the severity of dehydration and melting, they were not enough to make the gel a viable phantom material. This is unfortunate, since the lesions that formed upon exposure were similar in appearance to those seen in human skin. (Figure 7)

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Agar shared many of the same negative aspects as ballistic media, namely the high water content. In addition, it was not firm enough to withstand the rigors of handling without causing some breakage or tears. (Figure 8) It was found to have a higher melting point than the ballistic gel (92°C).

The varying ink concentrations added to the samples appeared to have little to no effect on the ED_{50}s of agar, ballistic media, or resin. There was a slight increase to the material's absorption seen by the spectrometer; however, it was most likely due to the high water content of the ink rather than any properties of the ink particles.

The epoxy resin appeared to be the best suited for the purposes of this project. The high melting point and low evaporation rate of this substance made it a highly efficient material for this phantom. One drawback of this material is that mixing it incorporates air bubbles into the final product. Mixing the two parts in a vacuum was not feasible because the cure time is so short. Also, the mixture is viscous enough to make the removal of any air bubbles very slow and difficult. The transmission through the resin was approximately 12% and when the India Ink was added, this transmission amount decreased accordingly. One of the other major drawbacks to this material is that it is highly hydrophobic. This made adding anything to the resin very difficult, especially water-based materials.

Upon initial exposure, the material showed a white spot (Figure 3a); the intensity of which increased with energy. The high energy levels caused the material to become slightly raised at the center of the lesion; however this returned to normal after just a few moments. All damage appeared to be internal as there were no divots or abrasions on the surface. Within two minutes, the white marks disappeared, leaving a grey circle instead. Because of the fading properties of exposure damage, all of the immediate readings were taken exactly 5 seconds after being shot. The color of the grey circle also darkened with higher energies and only marks that were still observed more than an hour after exposure were listed as lesions (Figure 3b). This is also evident that the lesions to the left side of the picture are much lighter than those in the center. One other note, as the ink concentration increased there was an additional circle of grey seen in many of the grid squares. The intensity and diameter of this circle increased with energy levels, and these marks were noticeable at levels well below the established ED_{50}s.

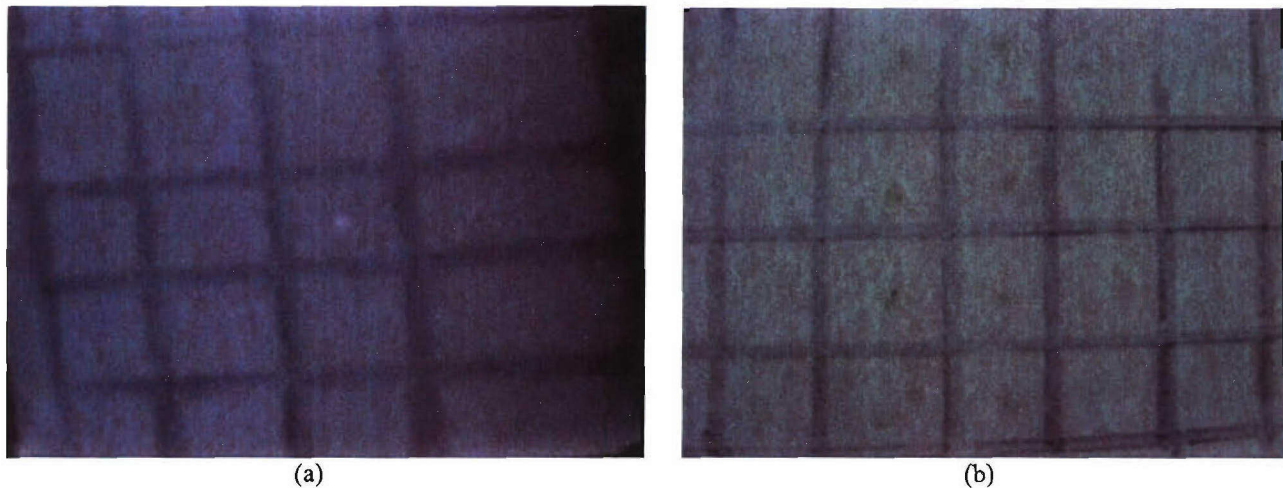**Approved for Public Release; Distribution Unlimited**

Figure 3. Resin damage marks after laser exposure. (a) Immediate (b) After 1 hour.

The damage observed in the epoxy resin phantom was also examined under a microscope. In Figure 5, the target area was magnified at 250x and shows the key components of the phantom. The brown lesion marks seems to be concentrated just below the surface and in the center 2 mm of the 5-mm spot. The air bubbles are visible in the damaged area as well as in the surrounding space. The India Ink particles are shown as the black marks. Figure 6 shows another epoxy resin sample at a magnification of 120x but this time the sample was exposed to 3 pulses to highlight the damage. Again, the brown damage is easily visible in the center 2 mm of the spot but this time the air bubbles are not readily noticeable in the damaged area.

4. DISCUSSION

4.1 Optical Properties

Absorption and scattering coefficients were determined for each of the materials tested in this experiment and then compared to reported values[8] for skin. While none of the materials exactly matched those of the dermis and epidermis, a combination of resin and 100 µL of India Ink did come close. (Table 2) One of the consequences of mixing in absorbing materials was that additional air bubbles were incorporated into the product, thereby increasing the scattering values.

Table 2. Absorption and scattering coefficients for reference and tested materials.

Material	μ_a (1/cm)	μ_s (1/cm)
Agar (4%)	8.790	38.179
Albumin (7%)	19.886	4.189
BM & Resin (1:1)	11.959	97.595
BM (100%)	4.425	21.009
Dermis (PIG)	5.420	8.598
Epidermis (PIG)	6.000	8.602
India Ink (500:1)	20.153	13.788
Intralipid (1%)	13.088	90.261
Resin (100%)	1.570	3.923
Resin + 100 µL Ink	3.252	10.306
Resin + 250 µL Ink	4.259	15.362

It was also noted that none of the materials demonstrated diffuse reflectance values anywhere near those reported for tissue. Numbers derived from a graph in Takata's[25] report (Figure 11) show the percent reflectance of Caucasian human skin to be approximately 25%. In contrast, the ballistic media, resin, and agar samples were all below 2%. (Figure 4) Although these numbers are not ideal, it does show that by mixing different materials into the resin, it is possible to adjust the phantom's optical properties. Further tests will need to be conducted for different additives, or mixtures of the additives, to reach the desired parameter effects.
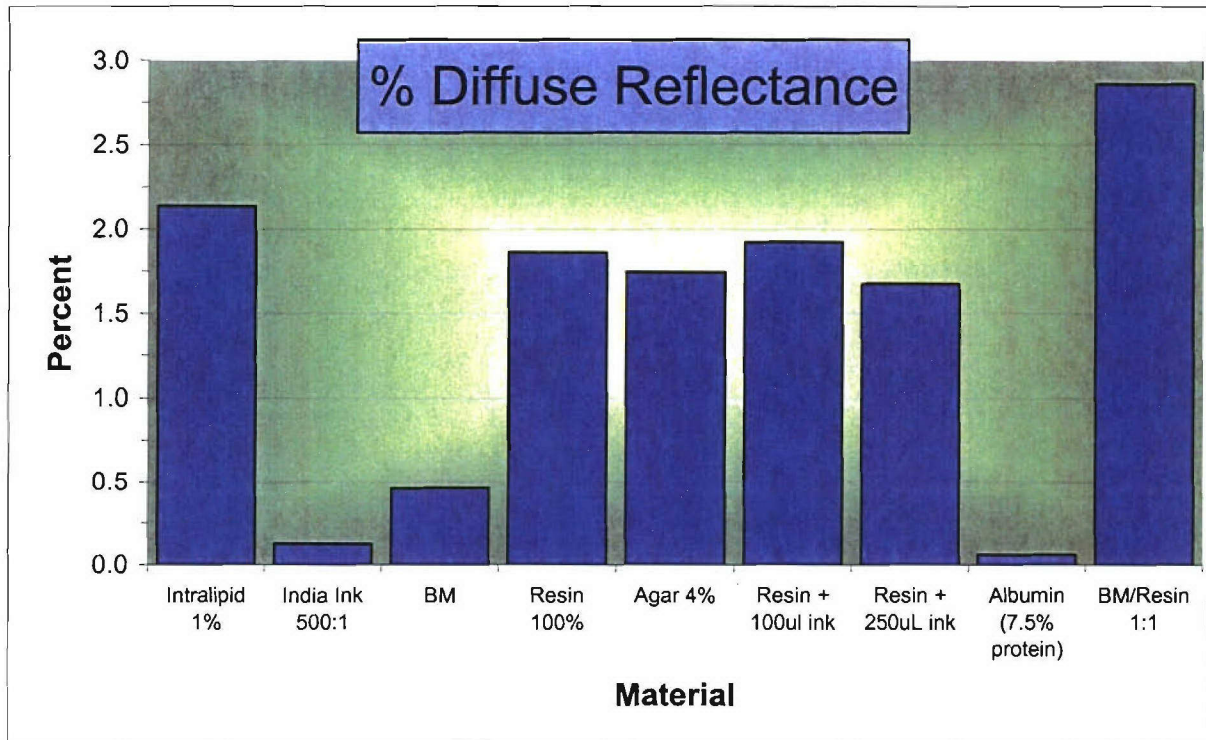
Figure 4. Percent diffuse reflectance for each material.

4.2 Damage $ED_{50}s$

To find the ED_{50} we used Probit Analysis. The ED_{50} is the estimated dose which has a 50% probability of creating a visible lesion. This was computed using the EZ-Probit program designed by Dr. Clarence Cain, Gary Noojin and Capt Lonnie Manning at Brooks City- Base in San Antonio, Texas[21]. It is a C++ program that operates on a personal computer and produces all the same output information as the SAS software. The ED_{50} was computed using a 95% confidence level.

The water-based phantoms were not able to withstand the environment required for this experiment. For all experiments with the Ballistic Media the $ED_{50}s$ were below 2 J/cm^2. This irradiance falls well below $ED_{50}s$ reported in the literature for guinea pigs and porcine studies [Table 3]. The low $ED_{50}s$ are probably due to the high absorbance of water at 1540 nm and the low melting point of the gel.

This experiment found the preferred material of all researchers involved to be the epoxy resin. The ED_{50} for this material fell in between the values reported for other animal studies [Table 3]. This could be beneficial in the field of developing standards for the safe use of lasers since the phantom could be used as an alternative to live animal studies.

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Table 3. Summary of ED_{50} data .

Material	MVL-ED_{50} (J/cm^2)
Ballistic Media (0.1% India Ink)	1.91
Epoxy Resin (0.1% India Ink)	3.82
Guinea Pig [9]	3.0
Domestic Pig – (Lukashev) [5,6]	3.2
Yucatan Mini-Pig (Zohner) [22]	6.1

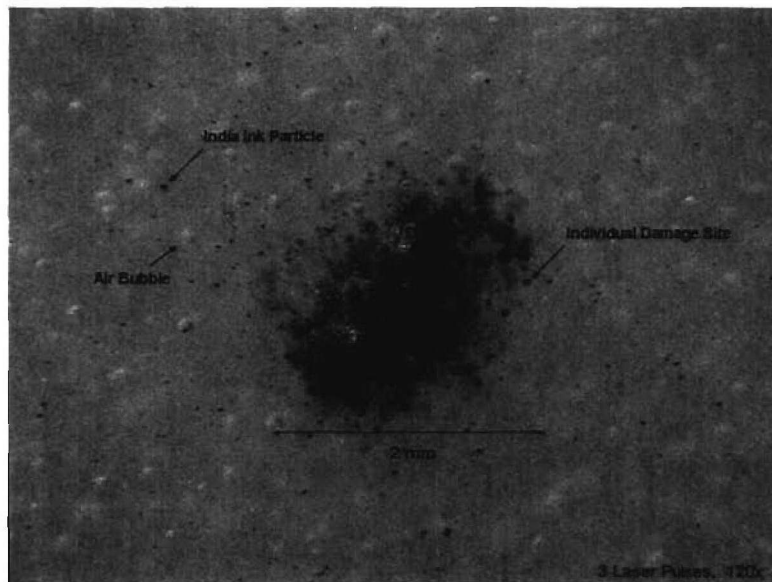Figure 5. Laser exposure damage (8.39 J/cm^2) to resin, viewed at 250x magnification.

Figure 6. Laser exposure damage (6.29 J/cm2) to resin viewed at 120x magnification.
In this case, three pulses were shot into the same spot to emphasize the damage.

4.3 Damage Mechanism

The epoxy resin temperature rise was measured using thermocouples on the surface and was found to be minimal, approximately $0.02°C$ during exposures. This result, and a pulse duration of 30 ns, suggests that the mechanism for the damage observed from these laser exposures is not a thermal process. Additionally, when the damage is viewed under a microscope, no ablation of the resin surface is visible; instead there are brown marks in areas where bubbles were present before exposure. It seems possible then, that there is another mechanism for the damage seen, such as laser induced breakdown (LIB). Future studies can be conducted to determine if the damage occurs to the resin surrounding the air bubbles or to the air itself within the bubbles. The damage may be due to the optical or thermal properties of the phantom material or the focusing of the laser energy by the trapped air. It is interesting to note that while measuring the melting point for the resin there was no discoloration of the material, even in areas of direct contact with the heat source.

According to Walsh[23], plasma is generated when the irradiance exceeds 10^8 - 10^{10} W/cm^2. In our study the irradiance was 1.05×10^8 W/cm^2 at the epoxy resin ED_{50}, which is near the threshold for plasma generation. Furthermore, equation (2) is used to determine the electric field amplitude[24], which is mainly based on the power density and is an indicator of dielectric breakdown when the amplitude reaches 2×10^5 V/cm.

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$$E = \left(\frac{2\Phi}{cn\varepsilon_0} \right)^{1/2}$$

Equation 4: Electric Field Amplitude

Where:

n is the index of refraction of the epoxy resin phantom (1.5)

Φ is the power density (1.05×10^{12} W/m^2)

ε_0 is the permittivity of free space

c is the velocity of light

For the parameters in this study, the electric field intensity was 2.3×10^5 V/cm, which again is right on the limit for dielectric breakdown. This is a sign that during exposures at our ED$_{50}$ or above, the damage in our phantom was caused by LIB. Our result is also similar to Zohner's [22] field intensity of 3.3×10^7 V/m at the surface of porcine skin.

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5. CONCLUSION

Of the three materials tested, the resin appears to be the best substance for this phantom. It has the longest shelf-life, was the most durable, and is easily prepared. The damage is easily visible and occurs at similar irradiances that cause damage in animal models. We suggest that the damage mechanism at this wavelength and pulse duration is not due to thermal effects but rather laser induced breakdown. The ED_{50} for the epoxy resin falls between damage thresholds for porcine and guinea pig studies, which could make the phantom an alternative for damage studies. The phantom still needs to be tested at other infrared wavelengths to see how it compares to animal studies over a range of wavelengths.

The Ballistic Media and Agar samples did not meet the environmental conditions for this study, however, for different conditions a water based sample could be ideal as long as one remembers that water is highly absorbing at 1540 nm and any visible damage would probably be due to the water content and low melting point of the material; not the added absorbers.

6. FUTURE WORK

This project found that the epoxy resin produced results similar to human skin when tested at 1540nm. However, the damage was incurred using nanosecond laser pulses, which may have produced a non-thermal damage mechanism. This study should be broadened to include larger pulse durations and other IR wavelengths to see how closely it resembles human skin in terms of damage thresholds, such as $ED_{50}s$, and MVLs. In addition, priority should be given to finding an appropriate mixture of scattering and absorbing agents, i.e.: Intralipid solution and India Ink respectively, to match the optical properties of skin.

By having suitable absorption and scattering coefficients one could simulate the thermal profile of skin in a tissue phantom and understand what happens inside the tissue as it is exposed. This could be easily done by using a thermal camera to record surface and edge temperature changes as the tissue heats and then cools. Characterizing the thermal profile on the tissue surface would help properly model damage mechanisms in tissue.

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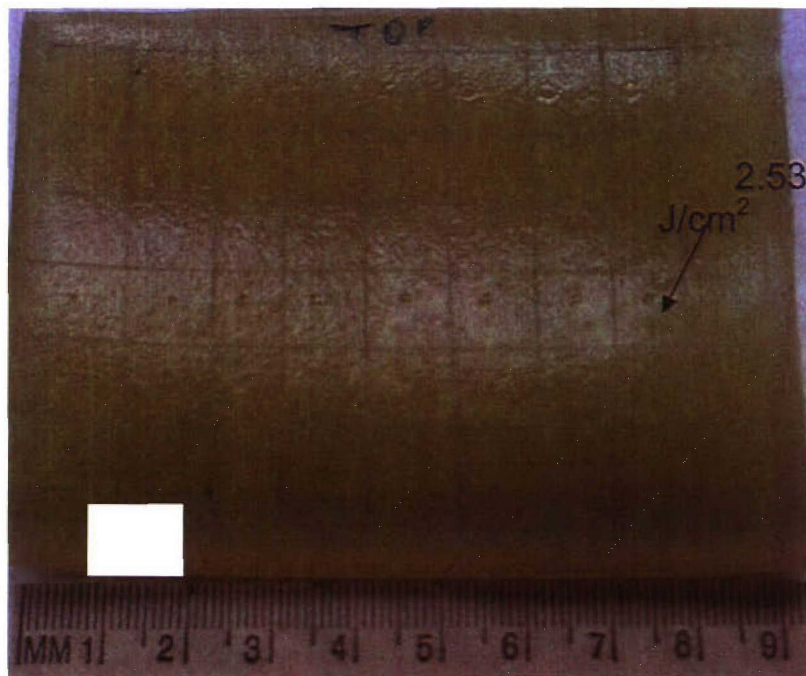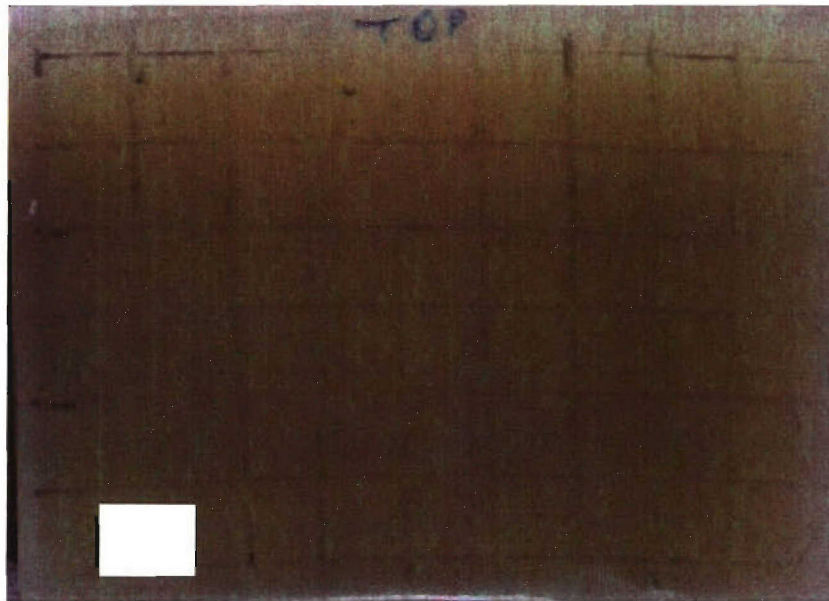
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Figure 7. Ballistic media samples (a) before and (b) post-exposure.
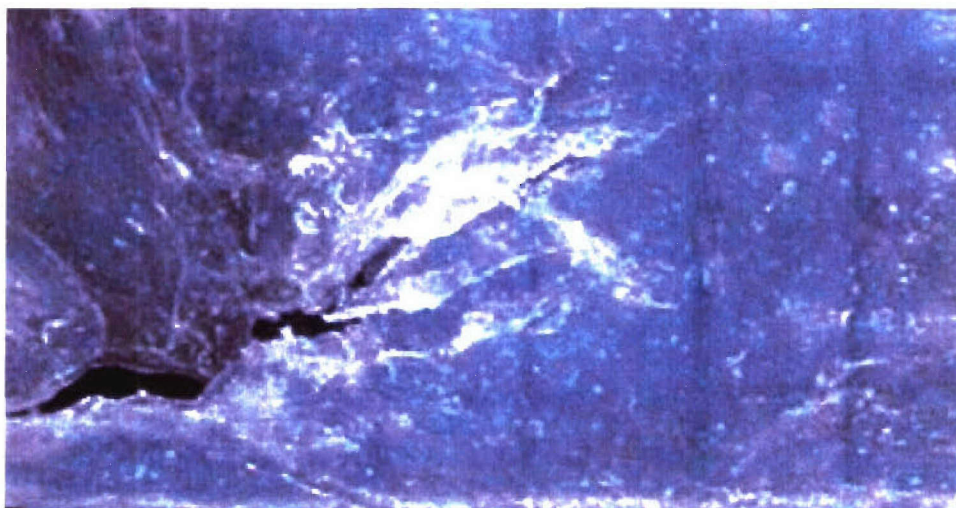
Figure 8. Sample of Agar 4%. Note the large tear and air bubbles.

Table 4. Integrating sphere data obtained for tested materials.

| Sample	n	$R_{diffuse}$			T_{total}		
	632nm	980nm	1310nm	1530nm	980nm	1310nm	1530nm
Air	1.00	0.0059	0.0078	0.0051	0.841	0.844	0.845
Intralipid 1%	1.36	0.1622	0.0916	0.0214	0.118	0.177	0.054
Naphthol 4%	1.39	0.0077	0.0058	0.0021	0.841	0.743	0.157
India Ink 500:1	1.37	0.0061	0.0040	0.0013	0.163	0.225	0.064
BM	1.71	0.0256	0.0211	0.0046	0.621	0.577	0.168
Resin	1.45	0.0253	0.0236	0.0186	0.769	0.767	0.715
Agar 4%	1.33	0.0137	0.0236	0.0174	0.794	0.730	0.249
Resin + 100ul ink	1.50	0.0255	0.0211	0.0192	0.524	0.522	0.489
Resin + 250uL ink	1.49	0.0223	0.0160	0.0168	0.306	0.372	0.372
Water	1.32	0.0021	0.0041	0.0005	0.856	0.762	0.168
Albumin(7.5% protein)	1.29	0.0028	0.0021	0.0006	0.859	0.770	0.181
BM/Resin 1:1	1.32	0.1266	0.0901	0.0286	0.176	0.118	0.062
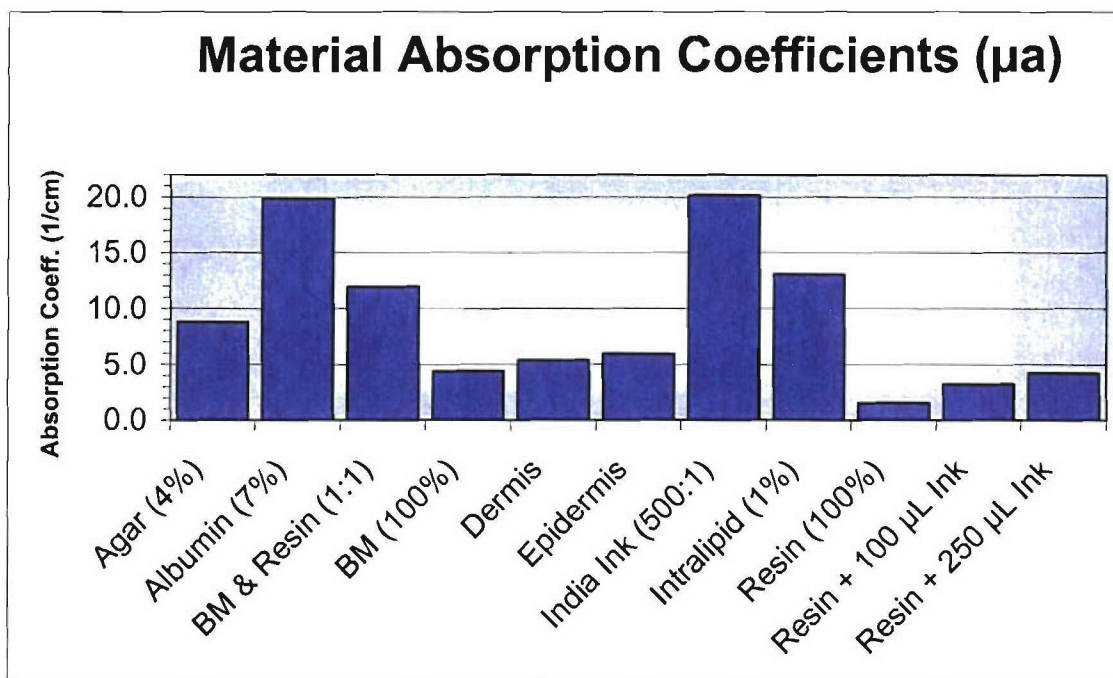
Figure 9. Material absorption coefficients.
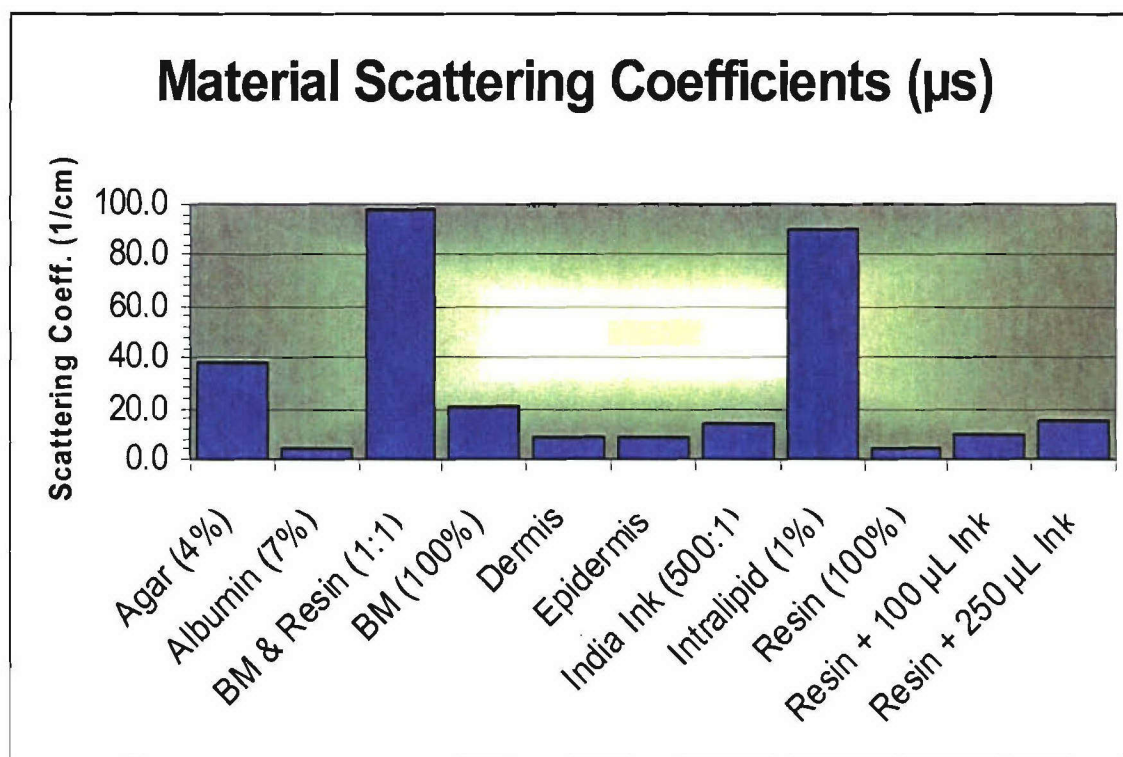
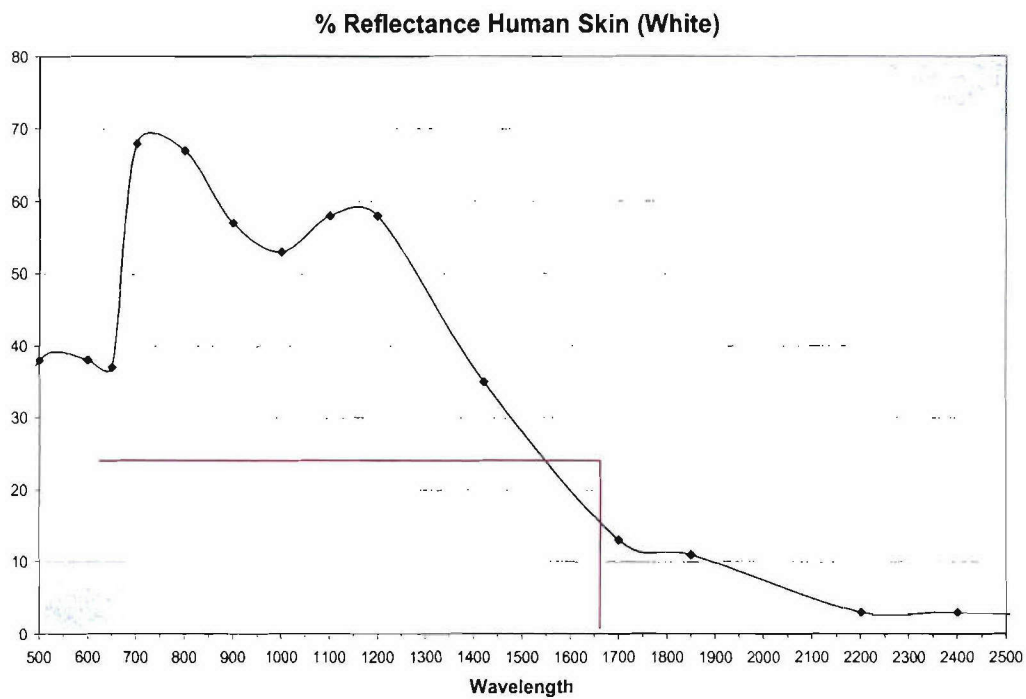Figure 10. Material scattering coefficients.

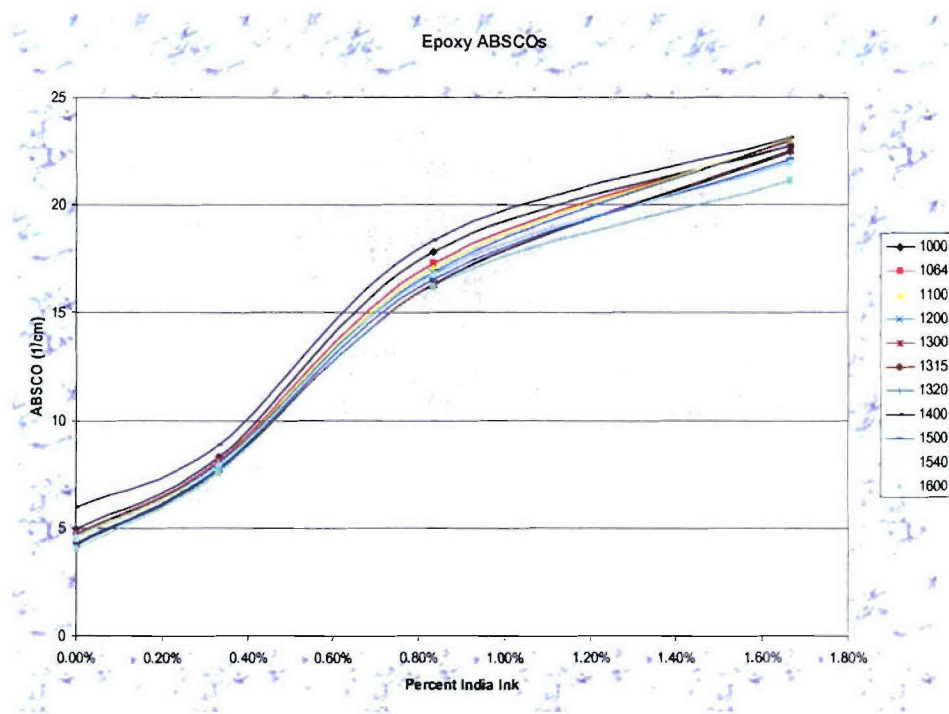Figure 11. Percent reflectance values for Caucasian skin

Figure 12. Absorbance vs. Ink concentration for an epoxy resin tissue phantom for various IR wavelengths.

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