

Absorption of 193- and 213-nm Laser Wavelengths in Sodium Chloride Solution and Balanced Salt Solution

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Objective: To determine absorption coefficients for sodium chloride solution (saline) and balanced salt solution at the 193- and 213-nm laser wavelengths.

Methods: Absorption coefficients were obtained for each of the component species found in balanced salt solution. This was achieved by measuring laser pulse transmission through solutions of varying concentration. The experiments were repeated using the 193-nm excimer and 213-nm solid-state laser wavelengths. Results for each species were then used to obtain an overall absorption coefficient and penetration depth for balanced salt solution and 0.9% sodium chloride solution.

Results: Absorption coefficients in balanced salt solution for the 193- and 213-nm wavelengths were found to be 140 and 6.9 cm^{-1} , respectively. In 0.9% sodium chloride solution, the absorption coefficient was 81 cm^{-1} at 193 nm and 0.05 cm^{-1} at 213 nm. At 193 nm, absorption in balanced salt solution was dominated by sodium

chloride. Sodium citrate emerged as the dominant species of absorption at 213 nm.

Conclusions: For the species investigated, we found reduced absorption for the longer wavelength of 213 nm. While the difference in wavelength between 193 and 213 nm is within about 10%, the respective molar absorption coefficients varied by 1 to 4 orders of magnitude. This indicates that predictions for the wavelength-dependent changes of absorption coefficients of other solutions are unreliable.

Clinical Relevance: Fluid placed on the surface of the cornea during keratorefractive surgery has proved to be a barrier to ablation for the 193-nm wavelength. The increased penetration depth through sodium chloride solution and balanced salt solution for the longer 213-nm laser wavelength may mean that these solutions cannot be used as a masking agent for keratorefractive procedures performed with this wavelength.

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EXCIMER LASERS operating with a wavelength of 193 nm have been used to correct refractive errors in the cornea since the mid-1980s.¹⁻³ In recent years, a solid-state laser with an output wavelength of 213 nm has been investigated as an alternative to excimer lasers.⁴⁻⁷ These investigations have focused largely on establishing the ablation rate behavior with fluence for this longer wavelength. Although the ablation rate has been found to be similar to that achieved with excimer lasers, other factors that may affect ablation rate are yet to be investigated.

The ablation rate of corneal tissue depends primarily on the fluence of the laser. The fluence determines the precision and efficiency with which tissue is removed. Two other related factors that have an effect on the ablation rate (at 193 nm) are corneal hydration^{8,9} and the presence

of surface fluids. Fluid on the cornea can result in a reduction of the ablation rate during refractive surgery procedures with 193-nm laser pulses.¹⁰ This reduction in ablation rate is evidenced by the high degree of absorption of 193-nm light in balanced salt solution (BSS).¹¹ Underlying tissue, therefore, is effectively masked from incident radiation.¹² An unknown reduction of the ablation rate can result in undercorrection of refractive errors or irregular ablations, such as the formation of corneal islands.

During initial patient trials with the 213-nm wavelength solid-state laser in our laboratory, it was observed that the presence of fluid on the corneal surface had little effect on the ablation rate. This suggests that while the fluid is a strong absorber for 193-nm radiation, it may be a weak absorber for 213-nm radiation. The implication is that fluid on the corneal surface during surgery may not have a mask-

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MATERIALS AND METHODS

The transmission characteristics for each component of BSS were investigated for the ultraviolet wavelengths of 193 and 213 nm. Two refractive lasers in clinical use were used for the study. An excimer laser (Telco Medical Technologies, Perth, Australia) with a pulse duration of 20 nanoseconds and repetition rate of 10 Hz was used to supply the 193-nm wavelength. The 213-nm radiation was supplied from the fifth harmonic wavelength of an Nd:YAG laser (Telco Medical Technologies). The pulse duration was 6 nanoseconds and the repetition rate was 20 Hz. The pulse energy of each laser was measured with an energy detector (model ED200; Gentec, Sainte-Foy, Quebec) and monitored on a storage oscilloscope. The energy was obtained from the amplitude of the voltage signal delivered from the detector. To reduce the error arising from pulse-to-pulse variations, 5 pulses obtained randomly were averaged for each measurement.

Figure 1 shows the experimental setup used for obtaining the measurements for each wavelength. Solutions were held in a vessel with a fused silica window at the base to maximize transmission. Above the vessel, a fused silica beam splitter was used to allow simultaneous measurement of the initial and transmitted pulse energies. The splitting ratio of the beam splitter was measured at each wavelength to allow calculation of the pulse energy incident on the solution. The reflection losses at each interface through the vessel were also calculated. This included the air-solution and solution-fused silica and fused silica-air boundaries that are encountered during a single pass through the vessel. For 193 and 213 nm, the refractive index values of the solution were taken to be 1.436 and 1.409, respectively.¹³ The overall reflection losses were 8.0% for 193 nm and 7.4% for 213 nm.

Solutions containing various concentrations of each species were tested for transmission. The depth of solution was maintained at a fixed level of 17.5 mm by placing an equal volume of solution in the vessel for each concentration. This corresponded to the use of 10 mL of solution. Species investigated were based on the recipe used for BSS (Alcon, New South Wales, Australia) and included sodium chloride, potassium chloride, calcium chloride, magnesium chloride, sodium acetate, and sodium citrate. Each solution was prepared by diluting with deionized water. The

range of concentrations used varied between the concentration found in BSS for each species down to a dilution factor of 1/200. A further range was used in the case of the chlorides for 213 nm, which was in excess of the molarities found in BSS. This was necessary for 213 nm because none of these species produced a detectable change in transmission for the concentration range used at 193 nm. Higher concentration ranges were used for sodium chloride (1-5 mol/L), potassium chloride (0.5-4 mol/L), and calcium and magnesium chlorides (0.5-2 mol/L) to produce an appreciable attenuation.

The method of varying concentration was used due to the large degree of absorption observed at 193 nm for sodium chloride solution and BSS. This large absorption made the more conventional method of measuring transmission through varying distances of solution of fixed concentration difficult. By varying the concentration, the requirement of precise and accurate measurement of small distances is circumvented. The method allows calculation of the absorption coefficient for a particular species at other concentrations. Also, insight is provided into the degree of absorption from each species in a mixture such as BSS.

With increasing concentration, incident laser pulses are attenuated in accordance with the Beer-Lambert law for absorption: $E_f = E_i e^{-\alpha_m C d}$, where α_m is the molar absorption coefficient in moles per liter per centimeter ($M^{-1}cm^{-1}$); C , the concentration in moles per liter; d , distance in centimeters; and E_f and E_i , the final and initial pulse energies (in millijoules), respectively.

By plotting transmission against concentration in a log-linear plot yielding a linear relationship, the gradient of the plot was used to obtain the molar absorption coefficient of each species. Multiplication of the molar absorption coefficient (α_m , $M^{-1}cm^{-1}$) with concentration produces the absorption coefficient for a given molarity (α , cm^{-1}). The distance over which 63% of the incident energy is absorbed is defined as the penetration depth and is obtained from the reciprocal of the absorption coefficient.

The absorption coefficient for each species at the molarity occurring in BSS was calculated for each wavelength. By summing the absorption coefficients from each species, an overall absorption coefficient for BSS was obtained. In this way, the penetration depth for each species and BSS was found. The absorption coefficient and penetration depth was also found for 0.9% sodium chloride solution.

ing effect for underlying tissue using the 213-nm wavelength.

The purpose of this study was to quantify the absorption at the 193- and 213-nm laser wavelengths in 2 solutions commonly used during refractive surgery. The transmission characteristics of each wavelength are investigated through the constituent components of BSS and 0.9% sodium chloride solution. Absorption coefficients are then derived from these data.

RESULTS

Transmission was found to decrease exponentially with increasing concentration for all species tested. **Figure 2** shows a log-linear plot of the transmission data for sodium chloride depicting a linear relationship at 193 nm. Similar plots

were created for each species. These data obtained at 213 nm for this range of concentrations are also shown. No attenuation was detected over this range for this wavelength. Data obtained at 213 nm for sodium chloride at the higher concentration range of 1.0 to 5.0 mol/L are shown in **Figure 3**. The gradient of each plot was used to calculate the molar absorption coefficient. **Table 1** presents the results obtained for each species and wavelength. The largest molar absorption coefficient was found to occur in sodium citrate for each of the wavelengths tested. However, for the 193-nm wavelength, the coefficient was larger by an order of magnitude. Similarly, sodium chloride showed the lowest coefficient for each wavelength, although the value for 193 nm was 4 orders of magnitude larger.

Absorption coefficients and molarity for each substance found in BSS are shown in **Table 2**. The penetra-

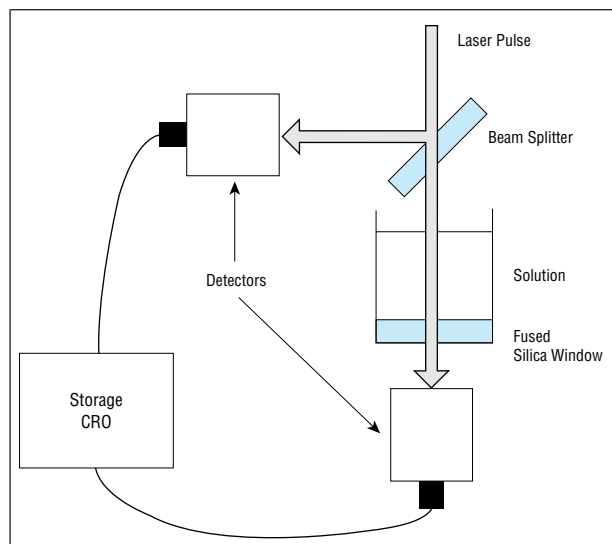


Figure 1. Experimental setup for measuring transmission of 193-nm excimer and 213-nm solid-state laser pulses through various solutions. Reflection losses through the vessel were 8.0% for 193-nm pulses and 7.4% for 213-nm pulses. CRO indicates cathode ray oscilloscope.

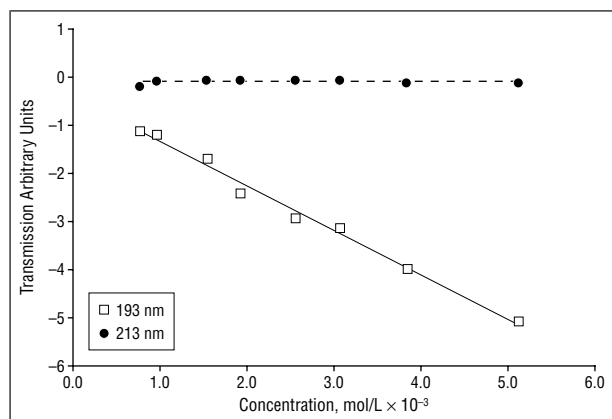


Figure 2. Log-linear plot of transmission in sodium chloride solution vs concentration for 193 nm and 213 nm. Solution path length is 17.5 mm.

tion depth calculated for each component is also presented in Table 2. While sodium chloride has the lowest molar absorption coefficient for 193 nm, the relatively large concentration used in BSS means it has the shortest penetration depth (173 μm). Conversely, magnesium chloride exhibited the longest penetration depth (5010 μm) due to the low value of concentration and despite a molar absorption coefficient comparable to calcium chloride and sodium acetate.

For 213 nm, sodium acetate and in particular sodium citrate were responsible for the observed absorption at this wavelength. The contribution to the absorption from the 4 chloride solutions was negligible by comparison. The absorption due to sodium citrate is relatively weak compared with that of 193 nm, exhibiting a penetration depth of almost 2 mm compared with approximately 0.3 mm for 193 nm.

Table 3 displays results for absorption coefficient and penetration depth in BSS, 0.9% sodium chloride solution, and water. The results for water were included to provide a basis for comparison and were taken from

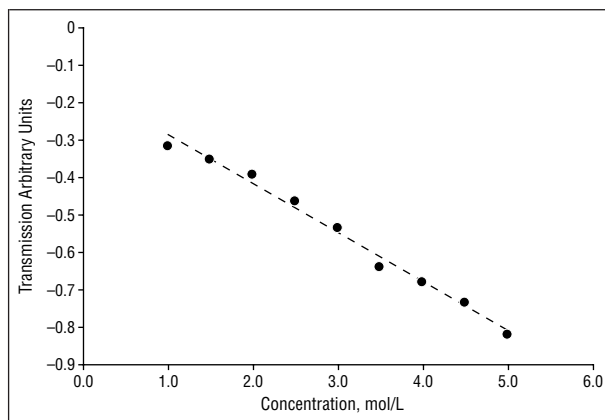


Figure 3. Log-linear plot of transmission in sodium chloride solution vs concentration for 213 nm. Solution path length is 17.5 mm. Note the different units for concentration from that of Figure 2.

Table 1. Molar Absorption Coefficient (α_M) Results

Species	$\alpha_M, \text{M}^{-1}\text{cm}^{-1}$	
	193 nm	213 nm
Sodium chloride	527	0.07
Potassium chloride	673	0.19
Calcium chloride	1588	0.31
Magnesium chloride	1349	0.15
Sodium acetate	1145	58
Sodium citrate	6070	899

the literature.¹⁴ The molarity of 0.9% sodium chloride solution (0.154 mol/L) is approximately 40% higher than the molarity of sodium chloride in BSS (0.11 mol/L). The results show that the penetration depth in BSS for the 213-nm wavelength is longer than 193 nm by a factor of 20. In the 0.9% sodium chloride solution, the penetration depth for 213 nm is 3 orders of magnitude longer than that obtained for 193 nm.

COMMENT

By obtaining the molar absorption coefficient for the various components used in the production of BSS, the penetration depth can be calculated for any concentration of a particular species or for a mixture of species. For sodium chloride, this allows the comparison of penetration depths for solutions of varying molarity. Balanced salt solution contains 0.64% sodium chloride (0.11 mol/L), which is a lower concentration than that of 0.9% sodium chloride solution (0.154 mol/L).

A study by Kornmehl and coworkers¹² on the masking properties of various fluids suggested that 0.9% sodium chloride solution (saline) exhibits significant absorption at 193 nm and negligible absorption for 213 nm. The study did not, however, calculate any absorption coefficients. Absorbance was shown in relative terms over a spectrum of wavelengths between 190 and 240 nm. This trend for the 2 wavelengths investigated in our study is consistent with these results.

Another study by Keates et al¹¹ investigated the absorption coefficient of BSS for 193- and 308-nm wave-

Table 2. Absorption Coefficients (α) and Penetration Depths for Components of Balanced Salt Solution (BSS)

Species	Molarity in BSS, mol/L $\times 10^{-3}$	193 nm		213 nm	
		α , cm^{-1}	Penetration Depth, μm	α , cm^{-1}	Penetration Depth, μm
Sodium chloride	109.51	57.7	173	0.008	1.2×10^6
Potassium chloride	10.06	6.8	1477	0.002	5.2×10^6
Calcium chloride	3.27	5.2	1926	0.001	9.9×10^6
Magnesium chloride	1.48	2.0	5010	0.0002	4.5×10^7
Sodium acetate	28.67	32.8	305	1.7	6019
Sodium citrate	5.78	35.1	285	5.2	1925

Table 3. Absorption Coefficients (α) and Penetration Depths for Various Fluids*

Solution	193 nm		213 nm	
	α , cm^{-1}	Penetration Depth, μm	α , cm^{-1}	Penetration Depth, μm
BSS	140	72	6.9	1450
0.9% Sodium chloride	81	123	0.05	2.0×10^5
Water†	0.12	8.3×10^4	0.04	2.5×10^5

*BSS indicates balanced salt solution.

†Data obtained from Hale and Query.¹⁴

lengths. Experiments were performed by measuring the transmission through an increasing thickness of solution. For 193 nm, the total thickness of solution was 200 μm . These data yielded an absorption coefficient of 145 cm^{-1} for a penetration depth of 69 μm . This value agrees to within 5% for our results in BSS at 193 nm.

For each trial, the transmission through pure water was measured initially corresponding to a concentration of zero. At 193 nm, an average transmission of 75% was observed; for 213 nm, the average transmission was 96%. These transmission values are predicted in data by Hale and Query,¹⁴ who tabulated absorption coefficients for water over a broad spectral range. For 193 nm, an absorption coefficient of approximately 0.12 cm^{-1} was calculated. The depth of solution used in our study of 17.5 mm would produce approximately 80% transmission through pure water based on this value for the absorption coefficient. For 213 nm, Hale and Query calculated an absorption coefficient of 0.04 cm^{-1} , resulting in approximately 93% transmission for our experiments. For each wavelength, our readings corresponded to the findings of Hale and Query.

Our findings may have implications for refractive laser surgery. Corneal hydration has been shown to be an important factor in determining refractive outcome following laser surgery at the 193-nm wavelength. Dougherty et al⁸ showed that ablations carried out on dehydrated cornea resulted in overcorrection of the refractive error. Similarly, superhydration of the cornea produced an undercorrection of the refractive error. More predictable results were achieved with corneas at a physiological level of hydration. In addition to this, work by Campos et al¹⁵ examined the effects of using a nitrogen

gas blower to remove the ablation plume. The study found that the gas acted to dehydrate the cornea and an irregular ablated surface resulted. For ablations performed without the presence of the nitrogen gas, the ablated surface appeared smooth. Subsequent work, however, showed that corneal hydration could be better controlled by using humidified gases to remove the ablation plume.¹⁶ These points suggest that corneal hydration should be closely monitored during refractive surgery. Corneal hydration is often controlled during surgery by the topical application of BSS and removal of excess surface fluid. A possible consequence of the long penetration depth of this fluid at 213 nm compared with 193 nm could be a relaxation of the close monitoring requirement of corneal surface fluid.

The use of BSS or sodium chloride solution also has application for phototherapeutic keratectomy procedures as a masking agent for 193-nm lasers. Phototherapeutic keratectomy is used to treat corneal irregularities and protuberances. The role of a masking fluid is to shield deeper-lying areas of tissue while exposing the corneal irregularities to the incident laser radiation. This results in a smooth and regular postoperative corneal surface. A range of masking fluids have been used for this procedure^{12,17,18} in addition to BSS.¹⁹ Desirable properties of a masking agent for phototherapeutic keratectomy include moderate viscosity and high absorbance.¹² The results of our study show that the solid-state laser wavelength of 213 nm is weakly absorbed in BSS and 0.9% sodium chloride solution compared with the 193-nm excimer laser wavelength. The increased penetration depth of the 213-nm wavelength may affect the suitability of these solutions as masking fluids for phototherapeutic keratectomy procedures.

Results of this study reveal the difference in absorption coefficient for BSS at the 193- and 213-nm laser wavelengths, which could have implications for both refractive and therapeutic laser procedures. For phototherapeutic keratectomy, other solutions used as masking agents at 193 nm should be investigated for suitable absorption before being used at the longer solid-state laser wavelength. In terms of refractive procedures, the possibility that BSS or sodium chloride solution have little effect on the corneal ablation rate may translate to a less stringent monitoring requirement of excess fluid on the cornea. This should, however, be verified with an ablation rate study incorporating known levels of surface fluid on the cornea.

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