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Photodynamic Cancer Therapy A Study of the Photochemical Properties of meso-Tetra (2,3,4-trifluorophenyl) Porphyrin and meso-Tetra (2,3,5,6-tetrafluorophenyl) Porphyrin

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Photodynamic Cancer Therapy

A Study of the Photochemical Properties of meso-Tetra (2,3,4-trifluorophenyl) Porphyrin and meso-Tetra (2,3,5,6-tetrafluorophenyl) Porphyrin

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in Chemistry

By

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Under the mentorship of Dr.Jim LoBue

Abstract

Photodynamic therapy(PDT) is a type of cancer treatment that utilizes photosensitive molecules that absorb photons and use that energy to create cytotoxic molecules. Porphyrins are photosensitive compounds that can be used selectively at the site of cancerous tumors. Their selectivity is due to the fact the porphyrins are generally not toxic in absence of light; in the presence of light, the drug will be activated to produce the cytotoxic molecule, singlet oxygen($^1O_2$). 9,10 diphenyl anthracene(DPA) was used to simulate the cancer cells and monitor how effective the porphyrin was in creating $^1O_2$, because DPA reacts with $^1O_2$ form diphenyl anthracene-endoperoxide (DPA-EPO). The DPA and two studied porphyrins, meso-Tetra (2,3,4-trifluorophenyl) porphyrin and meso-Tetra (2,3,5,6-tetrafluorophenyl) porphyrin were dissolved in 1,4 dioxane. The solutions were photolyzed with a Coherent I90 Argon laser and absorbance spectra was measured at 15 minute time intervals for 90 minutes. Using these spectra, the reaction order and rate were found with respect to porphyrin and DPA. Carbon-13 NMR spectra was collected that provided critical evidence that DPA-EPO was formed in the photolyzed solution.

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To my fellow researcher, Chris Anderson, thank you for allowing me to use your data(Figure 28) and always letting me bounce ideas off of you.

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Introduction

Porphyrins are biochemically-significant, photoactive compounds that exhibit multiple variations to perform a variety of tasks such as acting as an oxygen transport medium, converting light to energy, hormone synthesis, and iron metabolism.[1] The two most recognized porphyrins are heme and chlorophyll α. The core structure of porphyrins consists of four pyrrole sub-units that are connected by methine bridges. The resulting heterocyclic, square planar compound is very stable due to conjugation throughout the entire structure. Porphyrins have the ability for form metal complexes because the four nitrogen facing the center cavity can bind with metals. They can also be free-base(without metal ligand), and they can be substituted at the four meso- or eight beta positions.[1] In the case of the two free-base porphyrins of this study, they are substituted with fluorophenyl groups at the four meso- positions (Figure 2,3). The conjugated systems of porphyrins yield characteristic UV-Vis spectra with an intense narrow absorption at around 400 nm (known as the Soret band), followed by four weaker bands in the range of 700-450 nm(known as Q bands). [2]

Porphyrins use absorbed energy to that can be transferred to excite oxygen molecules which gives them candidacy for a type of cancer treatment called Photodynamic Therapy (PDT). Photodynamic Therapy works by administering a photosensitive drug and allowing it to absorb throughout the body, including the cancerous tissue .[1,2] Light is then guided to the site of the cancerous tissue, often with the use of optical fibers or light-emitting diodes. The tumor is then hit with light at the necessary wavelength to activate the photosensitive drug. This causes selectively at the sight of the cancerous tumor to hopefully prevent the destruction of healthy cells.

The porphyrin absorbs the photons from the laser and uses that energy to promote an electron from the ground state to the excited singlet state. Their selectivity is due to the fact the drugs are generally not toxic in absence of light; in the presence of light, the drug will be activated to produce singlet oxygen($^1O_2$). Multiple types of reactions can occur once the porphyrin has absorbed energy and promoted an electron to the excited state. The electron can relax from the excited in a variety of processes such as fluorescence, internal conversion, or intersystem crossing. If it decays by intersystem crossing, it will enter a triplet excited state which can phosphoresce or transfer energy by collision to excite the ground state oxygen molecule. If the oxygen molecule is promoted to the singlet state, two types of photoprocesses car occur. Singlet oxygen can react with the biological molecules to hopefully cause apoptosis. Therefore, the amount of singlet oxygen produced is strongly correlated to how much energy gets transferred, the amount of time the photosensitive compound stays in the triplet excited state, and how effective the intersystem crossing was. [3,4]

Since this study will be conducted in vitro, 9,10 diphenyl anthracene (DPA) (Figure 1) was used to simulate the cancer cells. DPA has five characteristic peaks between 270 nm and 400 nm. DPA reacts with $^1O_2$ to form DPA-Endoperoxide(DPA-EPO. Therefore, the presence of DPA Endoperoxide(DPA-EPO) in solution would signal that there was singlet oxygen created by the porphyrin.[3]

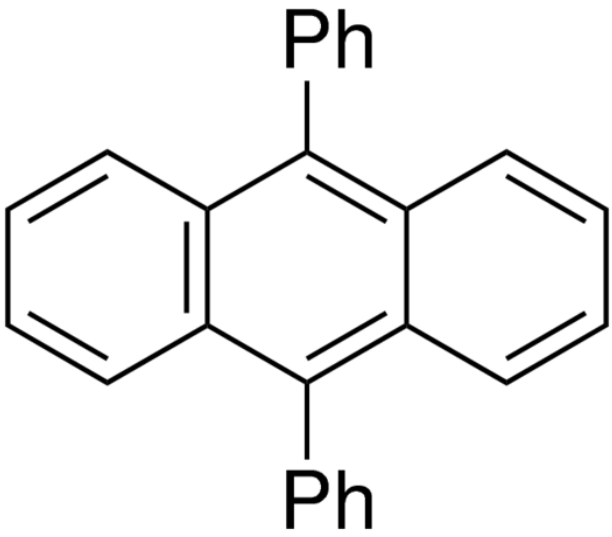

Figure 2 Structure of 9,10 Diphenyl anthracene (DPA)

Experimental

The porphyrins used throughout this research were purchased from Frontier Scientific Inc. The porphyrins and DPA were weighed out on an analytical balance and dissolved in 1,4 dioxane. The solutions were placed into quartz cuvettes because UV quartz has a transmission range of 190-2,500 nm .[5] The photolysis experiments were conducted with a Coherent I90 Argon Ion laser. The laser was set at 514.5nm, 11.9 amps and .050 watts. The quartz cuvette containing the DPA/porphyrin solution was placed in the path of green argon ion laser in the absence of other light sources. At fifteen minute intervals, the solution was taken to record UV-Vis spectra. Each photolysis was performed for 90 minutes.

Absorbance spectra was collected by a double-beam Shimadzu 2401 UV-Vis Spectrophotometer and displayed by UV-Probe software. Once the spectra were collected in the 800-200nm region, the data was transferred into Microsoft Excel 2013 software for further analysis. Once in the Excel software, coefficients were used to scale the to the pure DPA and pure porphyrin spectra obtained prior to mixing and photolyzing. The coefficients were then optimized by using the "Data Solver" function in Excel to fit to the spectra of photolyzed samples. The coefficients at each time interval were then used for kinetic measurements and quantification of the percent decrease of each species throughout the entire photolysis.

For this study, there were a total of six photolysis performed. The first photolysis was conducted on 2.5μM Tetra (2,3,4-trifluorophenyl) Porphyrin(TriF-TPP), 90μM DPA. The second was 2.5μM Tetra (2,3,5,6-tetrafluorophenyl) Porphyrin(TetraF-TPP), 90μM DPA. The third and fourth photolysis were conducted by making solutions of the same

concentrations to determine reproducibility. To be able to perform kinetic measurements, the last two photolyses were conducted by lowering each of the porphyrin concentrations to 1.25μM and keeping DPA constant at 90μM.

Carbon-13 NMR was conducted to provide further evidence of the production of singlet oxygen. An approximately 150μM TriF-TPP, 800μM DPA solution was made in deuterated chloroform. 2.5mL of the solution was photolyzed for 45 minutes, while the other solution was left on the lab table. Portions of the solutions were diluted by a factor of ten and absorbance spectra was collected on both solutions to ensure the solution had been photolyzed. The NMR was collected on the undiluted solutions in Special Optical Glass cuvettes.

To determine the effect of ambient light from the laboratory, a 2.5μM porphyrin, 90μM solution was left on the lab counter for three weeks. To visualize if photodegradation occurred, UV-Vis spectra was collected immediately after mixing the solution and after it was exposed to light from the laboratory environment for three weeks.

Data and Discussion

This section introduces the structures of the porphyrins in this study, contains the spectra from the photolysis experiments performed, illustrates the typical data analysis using Excel, demonstrates how the kinetic parameters resulting in the order with respect to DPA and porphyrin were obtained, and explains how the Carbon-13 NMR spectra provides critical evidence that DPA-EPO was created in solution.

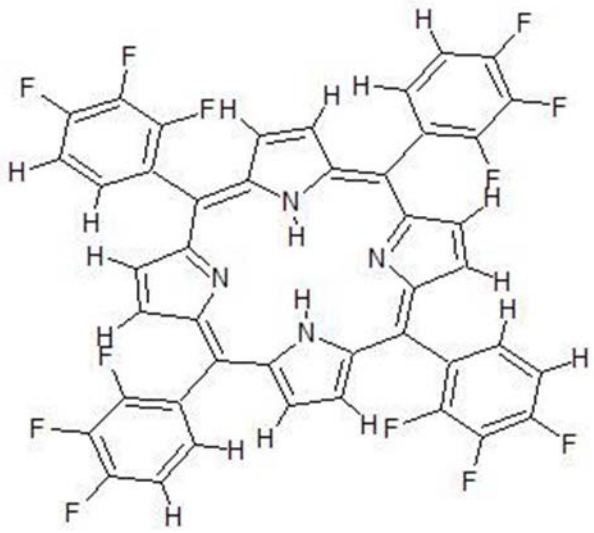

Figure 2 Structure of meso-Tetra (2,3,4-trifluorophenyl) Porphyrin (TriF-TPP)

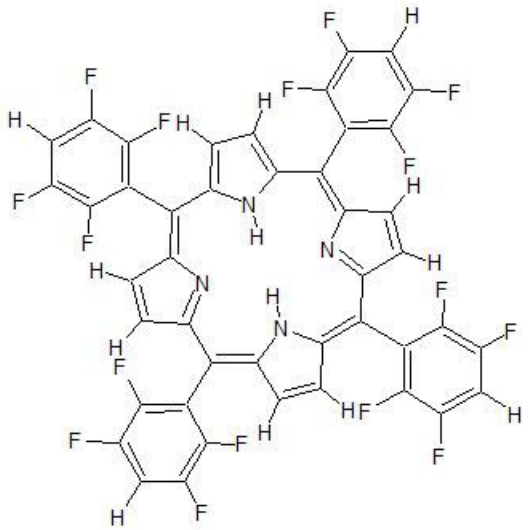

Figure 3 Structure of meso-Tetra (2,3,4-tetrafluorophenyl) Porphyrin (TetraF-TPP)

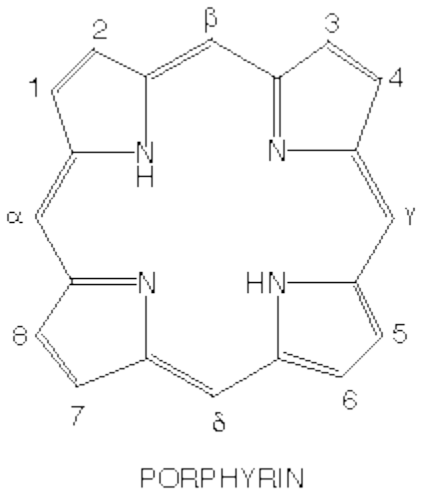

Figure 4: Porphyrin ring without substitution.

Figure 2 shows the structure of TriF-TPP, which shows the four phenyl rings with three fluorines attached to each ring. Figure 4 shows the structure of Tetra F-TPP, which shows the four phenyl rings with four fluorines attached to each ring. Both compounds are substituted at the meso-position. Fluorinated compounds are often used in the medicinal industry because they have prolonged half-lives, which delay metabolism in the body. Therefore, the drug is not eliminated from the body too quickly.[7] The carbon-fluorine bond is hydrophobic, which increases its lipophilicity. The addition of fluorine to medicinal compounds have also shown anti-inflammatory effects. [7] These are characteristics that may increase the ability for fluorinated porphyrins to be effective in combating cancer. Figure 4 demonstrates the porphyrin ring that has not been substituted.

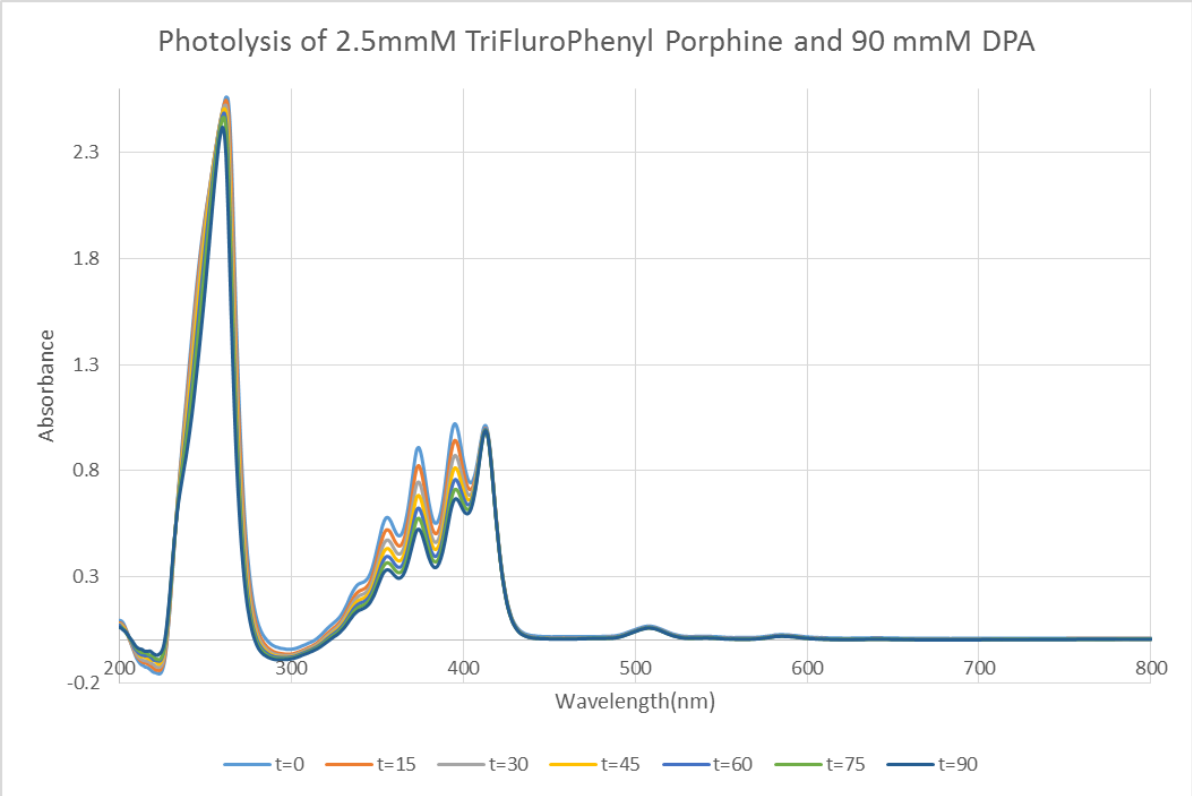

Figure 5: Spectra of 2.5 μM TriF-TPP and 90μM DPA in 1,4 Dioxane

Figure 5 is the UV-Vis absorption spectra of 2.5 μM TriF-TPP and 90μM DPA in 1,4 Dioxane after being photolyzed at 514 nm at fifteen minute time intervals. Figure 6 is a zoomed in view of repeat experiment using the exact same methods to ensure that the results could be duplicated. These specta demonstrate that the peaks at 343nm, 356nm, 374nm, 395nm decreased as the time that the solution was exposed to light increased. However, the peaks at 413nm and 509nm do not show decrease.

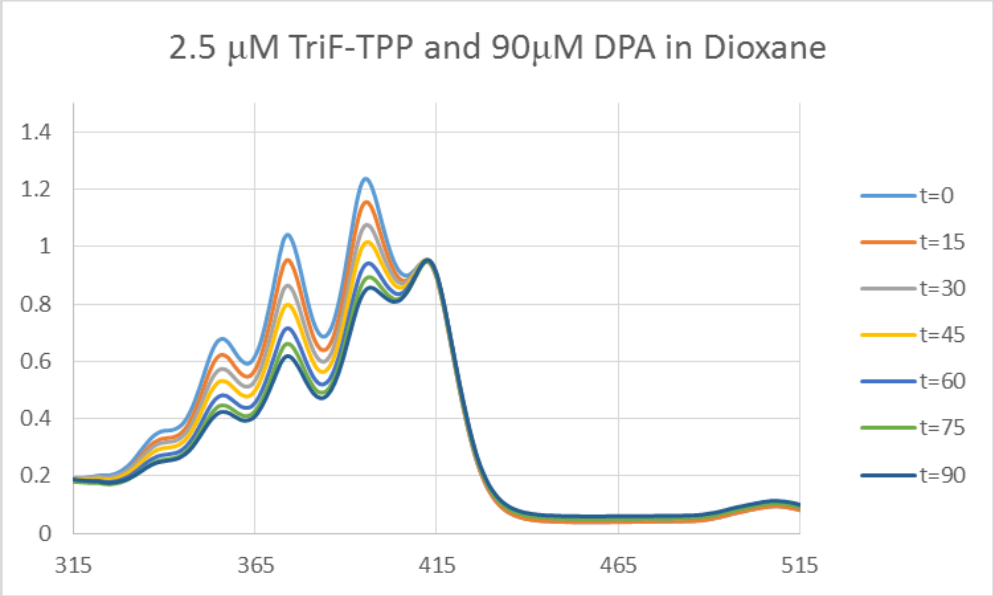

Figure 6: Spectra for Repeat Experiment of 2.5 µM TriF-TPP
and 90µM DPA in 1,4 Dioxane zoomed in to show the decrease in absorption.

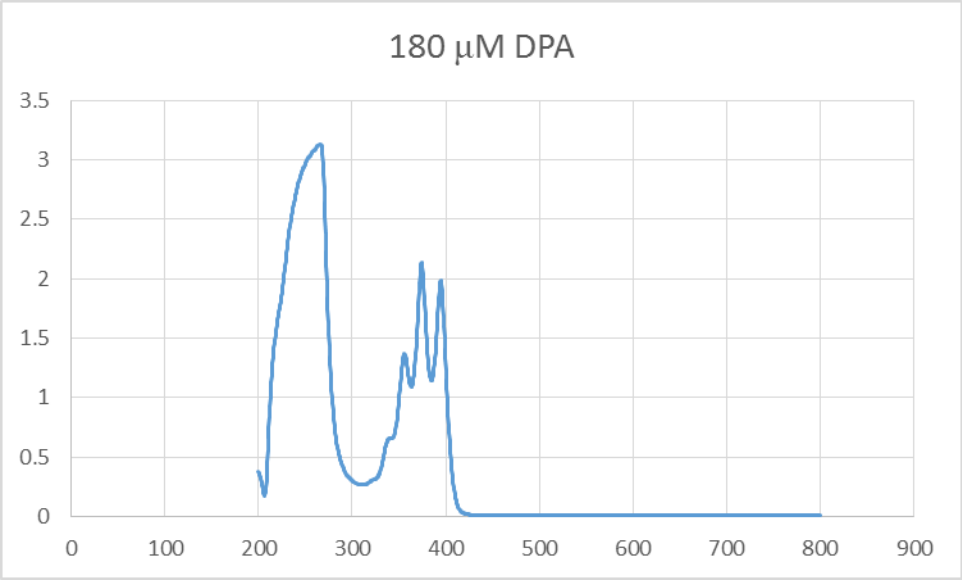

Figure 7: Spectra of 180µM DPA in 1,4 Dioxane

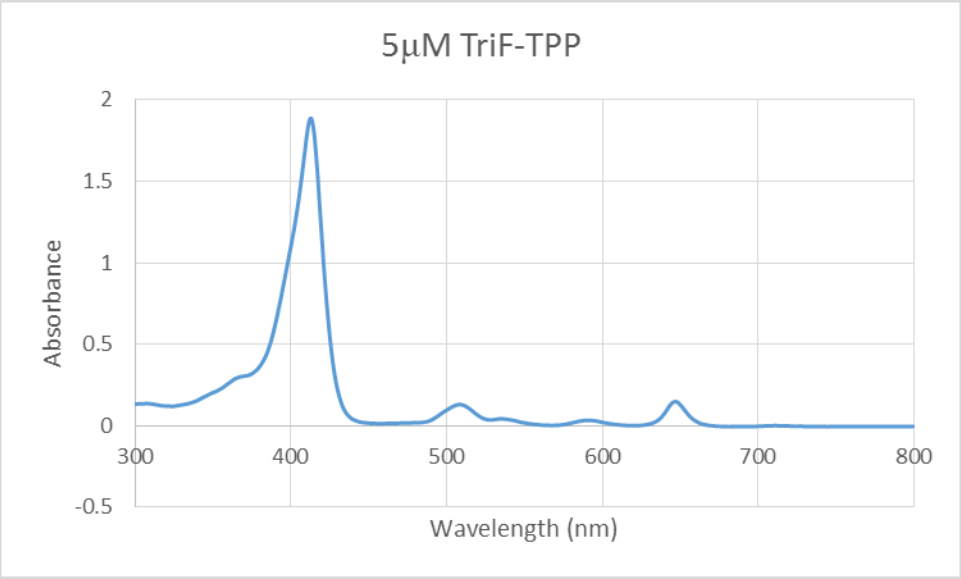

Figure 8: Spectra of 5µM of TriF-TPP in 1,4 Dioxane

Figure 7 and 8 are the absorption curves for the porphyrin and DPA respectively. before the solution was mixed. It should be noted that the DPA and porphyrin are twice as concentrated prior to being mixed because 5mL was of each solution was used to create the solution used in photolysis. Figure 7 shows that DPA has peaks at 343nm, 356nm, 374nm, 395nm. Figure 8 shows that TriF-TPP has a strong peak at 412nm (Soret) followed by weaker peaks such as 509nm and 650nm. This would indicate that the photolysis doesn't affect the porphyrin's concentration but causes DPA to decrease over time. (Figure 5,6).

Table 1: Sample Data Analysis Table showing a small portion of the graph

Wavelength	Pure Porphyrin	Pure DPA	t=0	SMN0	Diff.	Sum of Sq
200	0.111	0.53522	0.226	0.633489	-0.40749	0.452397
201	0.111	0.538152	0.219	0.633489	-0.41449	
202	0.111	0.538152	0.208	0.644036	-0.43604	
203	0.113	0.54695	0.194	0.651362	-0.45736	
204	0.116	0.551349	0.179	0.660105	-0.4811	
205	0.119	0.557215	0.157	0.663962	-0.50696	
206	0.12	0.560148	0.134	0.670403	-0.5364	
207	0.118	0.568946	0.106	0.677092	-0.57109	

Table 1 demonstrates how the data was analyzed for a few sample data points. This same method was used for the entire wavelength range to 800nm. The absorbance values from the pure porphyrin were inserted in column two(Figure 7); pure DPA absorbance values were inserted into column 3(Figure 8). Scaling values were used to multiply the DPA and porphyrin spectra and these scaled spectra were added in column 5. Column 4 contains spectrum of the mixtures of porphyrin and DPA(Figures5&6). The data shown is for an initial spectrum before photolysis. The coefficients were then optimized by minimizing the sum of squares of the residual differences(column 6) between column 4 and column 5. Then, these coefficients were plotted to indicate the effect of the porphyrins in the mixtures(Table 2). Figure 9 demonstrates that the concentration of porphyrin remains unaffected by the photolysis. In this case, a 90 minute photolysis reduces the concentration of DPA by 50%.

Table 2: This table demonstrates how the coefficients were extracted from each time interval and used to perform zero,first,second order tests.

	Porph	DPA
Time (min)	a	b
0	1	1
15	1.01367686	0.962488661
30	1.002867024	0.915318309
45	0.997866083	0.896679989
60	1.031308021	0.879812895
75	1.021115024	0.835634526
90	1.010300669	0.799504751

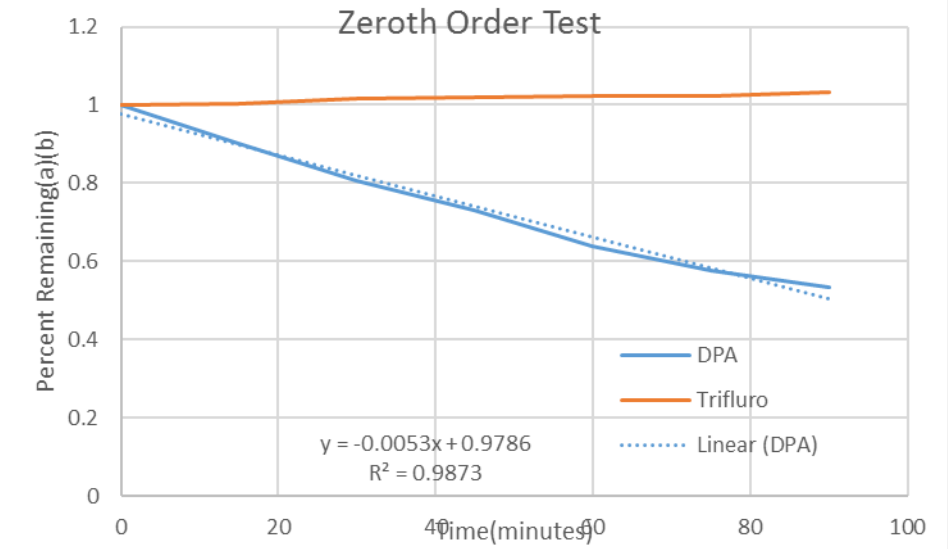

Figure 9: The percent remaining (b) v.s time. The percent A of TriF-TPP l is also shown for comparison. Experiment one 2.5 µM TriF-TPP and 90 µM DPA in 1,4 dioxane.

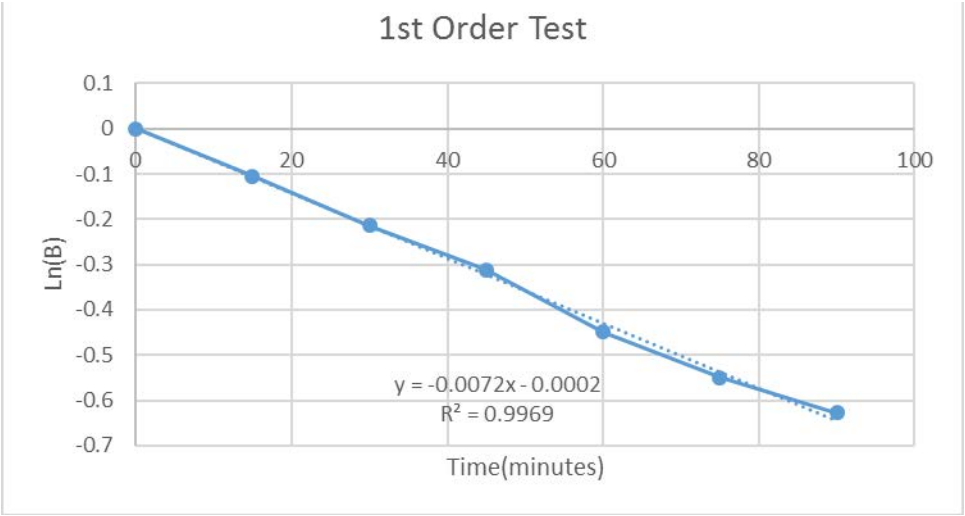

Figure 10: First Order Test, ln(b) v.s time of Experiment One 2.5 µM TriF-TPP and 90 µM DPA

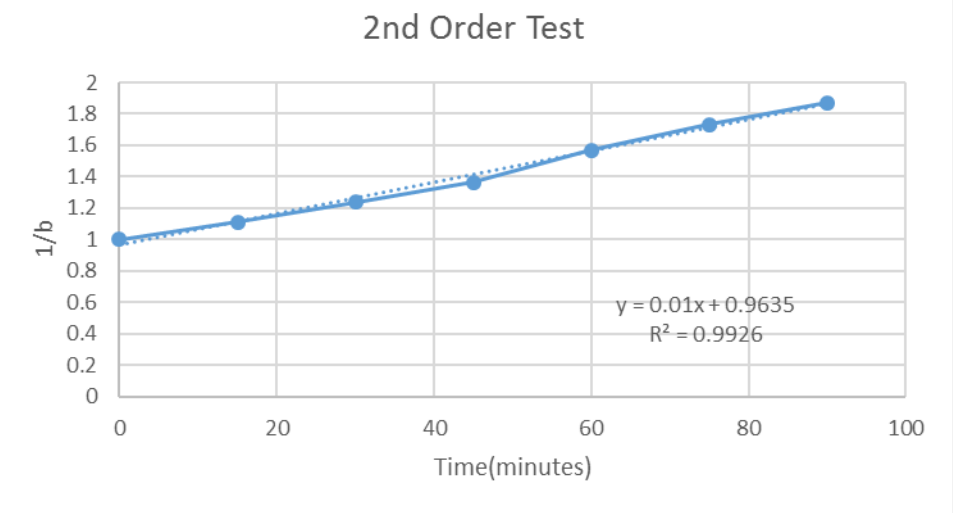

Figure 11: Second Order Test 1/b v.s time of experiment one 2.5 μM TriF-TPP and 90 μM DPA in 1,4 Dioxane.

Figures 9-11 show that DPA is first-order reaction because the natural log of the percent of DPA concentration remaining demonstrates the best linearity. The linearity can be initially visualized by the value of the correlation coeffcient (Figure 10). The other two plots test for zeroth order(Fig9) and second ordr(Fig 11) gave less statistically linear plots. The reaction order of porphyrin had to be determined experimentally by performing a photolysis with a different concentration of porphyrin but the same concentration of DPA (Figure 12).

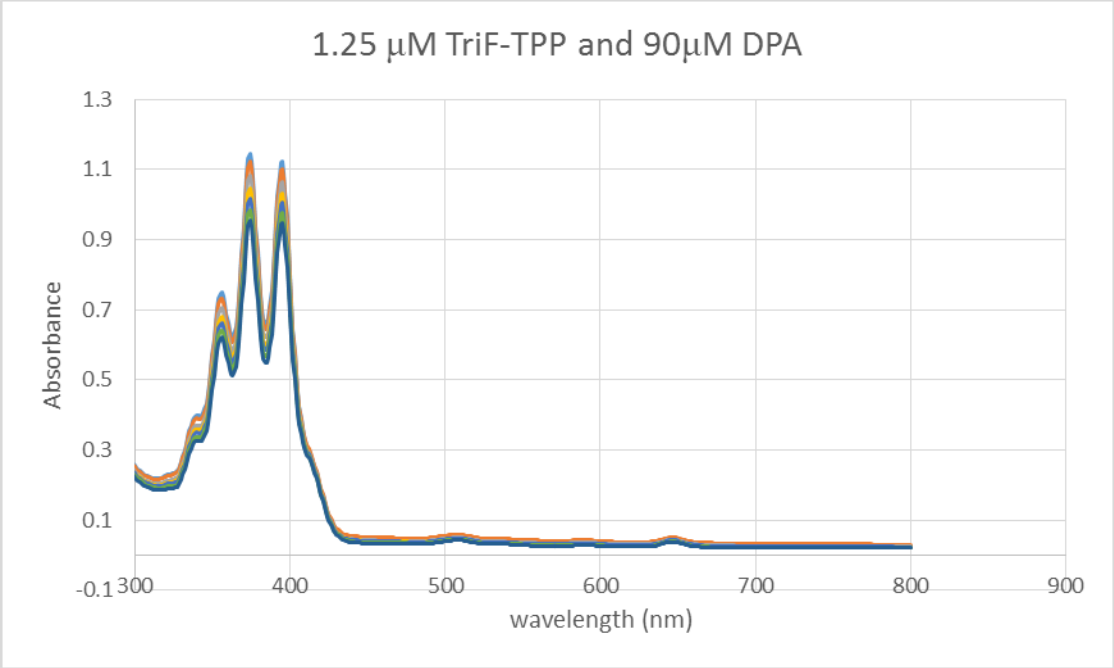

Figure 12: Spectra of 1.25 µM TriF-TPP and 90µM DPA in 1,4 Dioxane

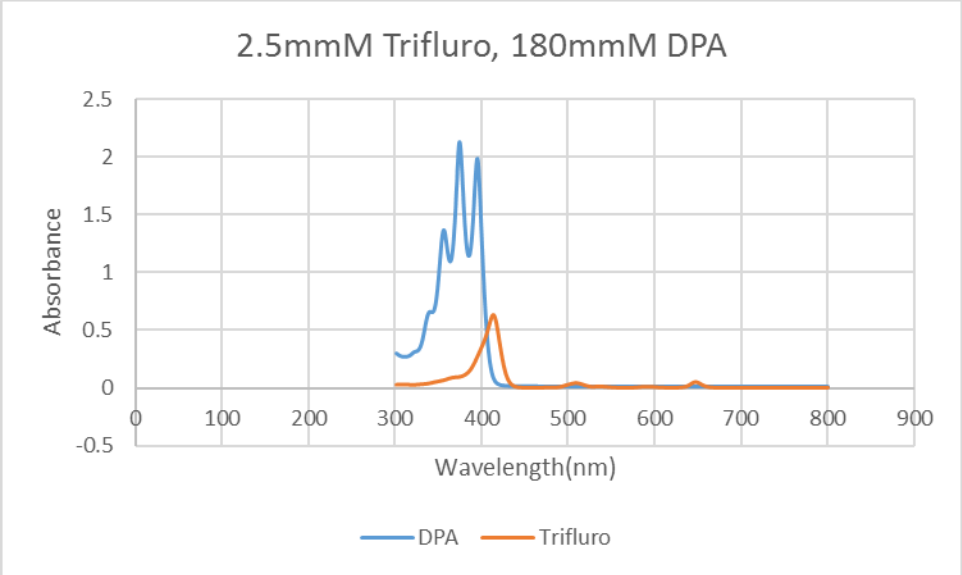

Figure 13: Spectra for 2.5 µM TriF-TPP and 180µM DPA in 1,4 Dioxane

The photolysis shown used the same methods as the previous photolysis except for a halved porphyrin concentration. The laser wattage, DPA concentration, instrumentation, path length, etc. were all kept constant. As demonstrated in Figure13, the molecules still absorbed at the same wavelength but were affected by the concentration of molecules in solution. By halving the concentration of the porphyrin, the absorbance value of the Soret band also fell to approximately half of its orginal absorbance value.

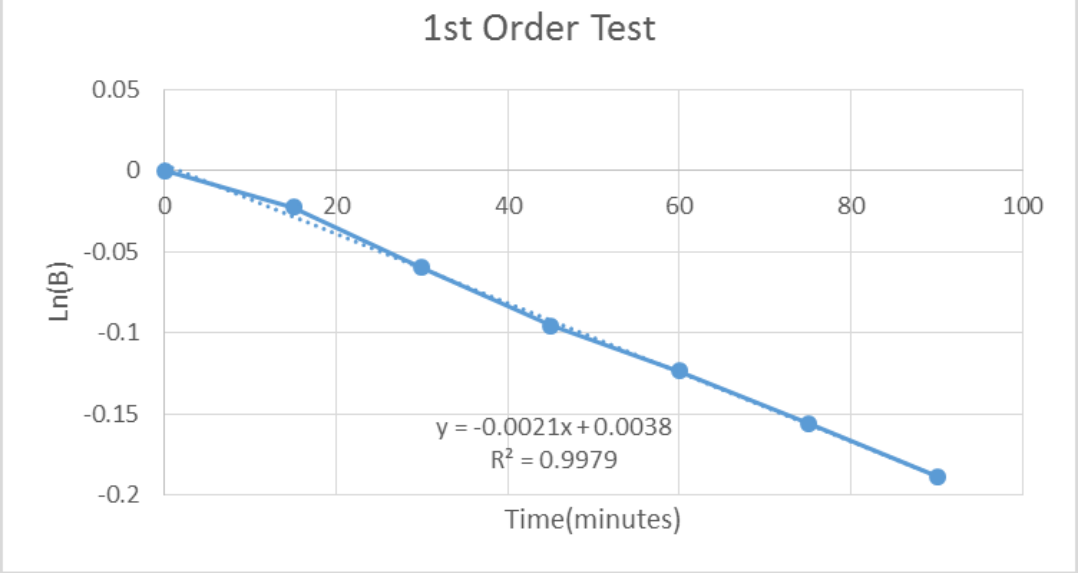

Figure 14: First Order Test, ln(b) v.s time of Experiment One 1.25 µM TriF-TPP and 90 µM DPA

The data analysis also used the same methods as the previous example. DPA demonstrated first-order dependence again. Integrated rate laws state that the slope of ln(b) v.s time is equal to the negative rate constant(-k). In order to be able to compare and contrast the effect of substituents on the rate and other chemical properties, the same methods described in the previous experiments were used on TetraF-TPP.

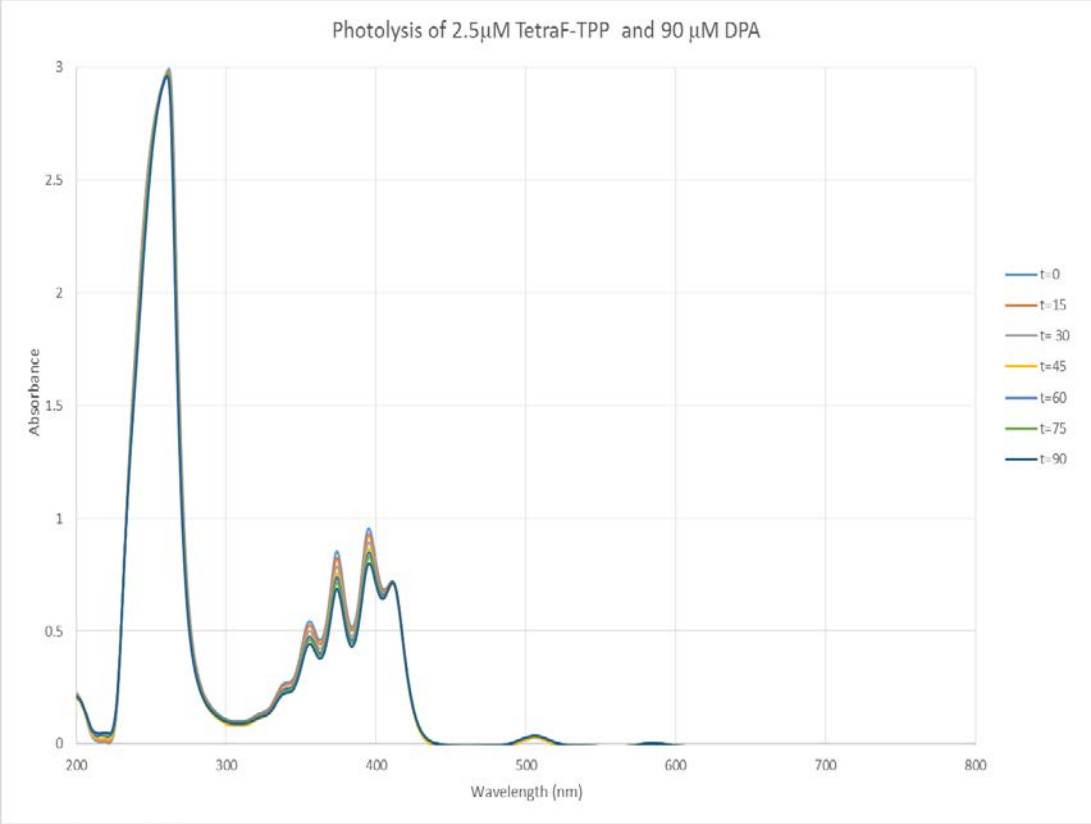

Figure 15: Spectra of 2.5 µM TetraF-TPP and 90µM DPA in 1,4 Dioxane during photolysis.

Figure 17 shows the first photolysis conducted on TetraF-TPP using the same methods as before. Figure 16 shows a second trial using the exact same methods and concentrations to ensure the same results could be achieved. The graph is comparable to that of TriF-TPP because the peaks associated with DPA continue to drop while the Soret and Q bands do not show photodecomposition. Figure 16 is analogous to Figure 13, but figure 16 Describes TetraF-TPP.

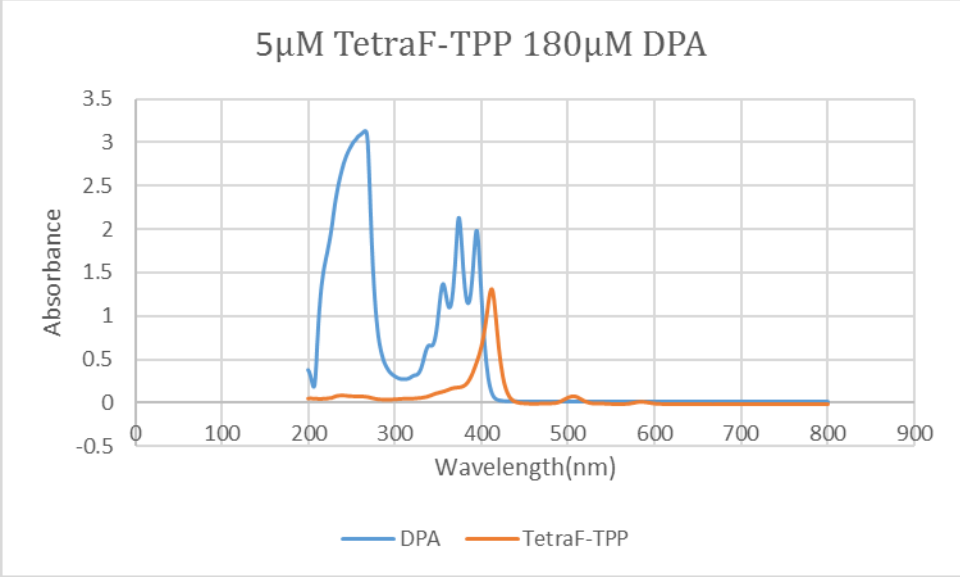

Figure 16: Spectra for 5 µM TetraF-TPP and 180µM DPA in 1,4 Dioxane prior to being mixed or photolyzed.

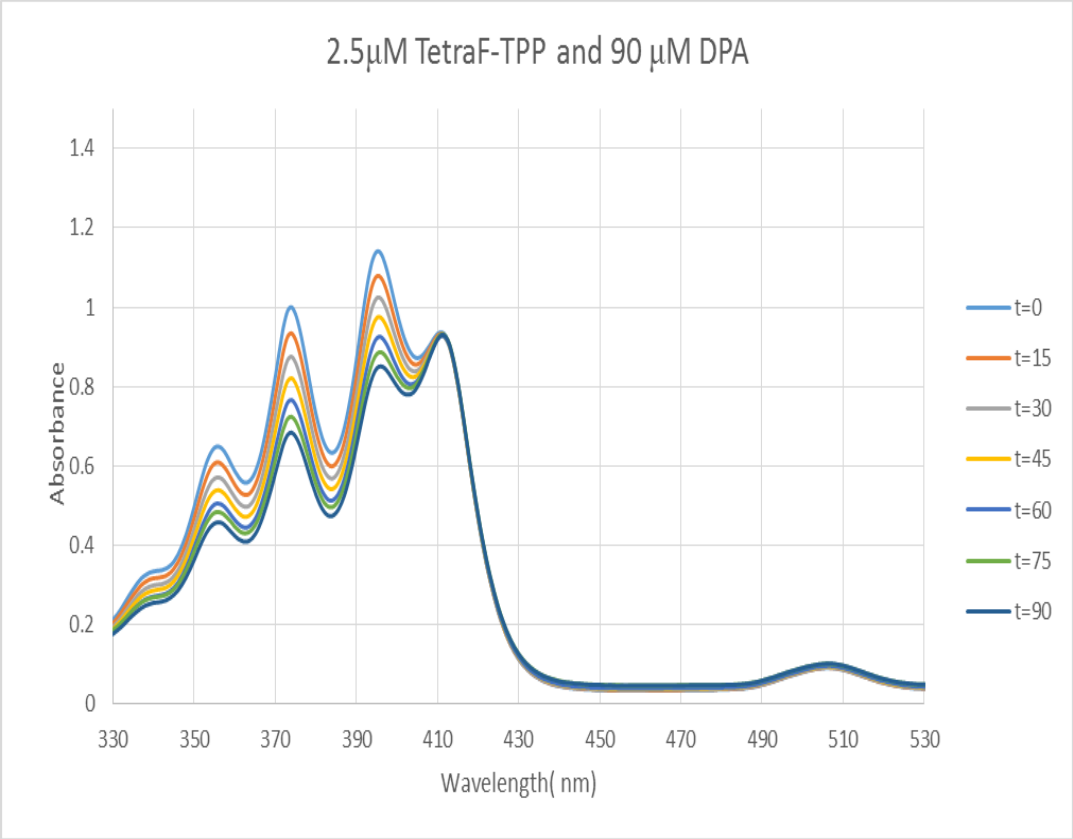

Figure 17: Spectra of repeat Experiment for 2.5 µM TetraF-TPP and 90µM DPA in 1,4 Dioxane during photolysis.

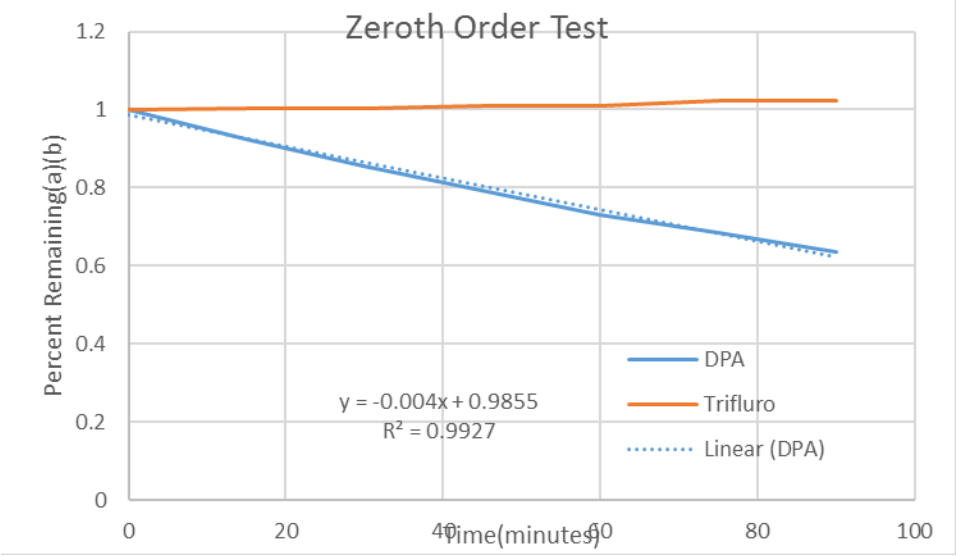

Figure 18: The percent remaining (b) v.s time. The percent (A) l is also shown for comparison. Experiment Two 2.5 µM TetraF-TPP and 90 µM DPA in 1,4 dioxane.

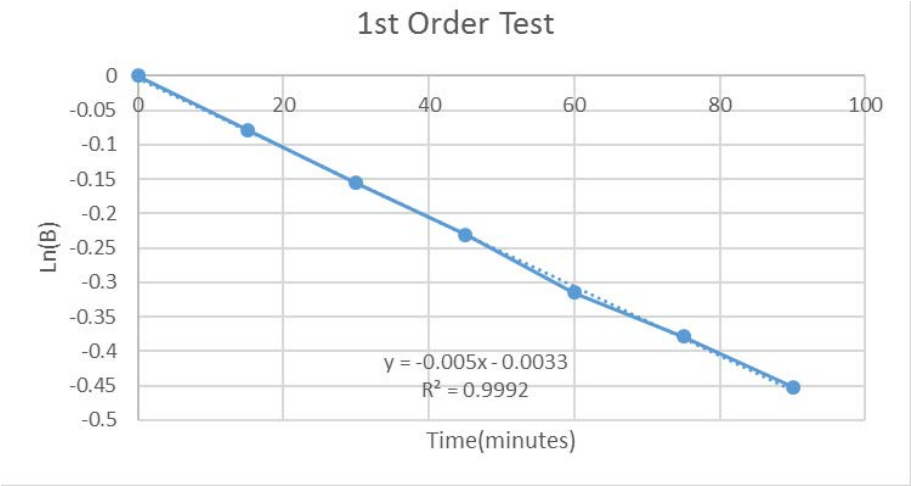

Figure 19: First Order Test, ln(b) v.s time of Experiment One 2.5 µM TetraF-TPP and 90 µM DPA

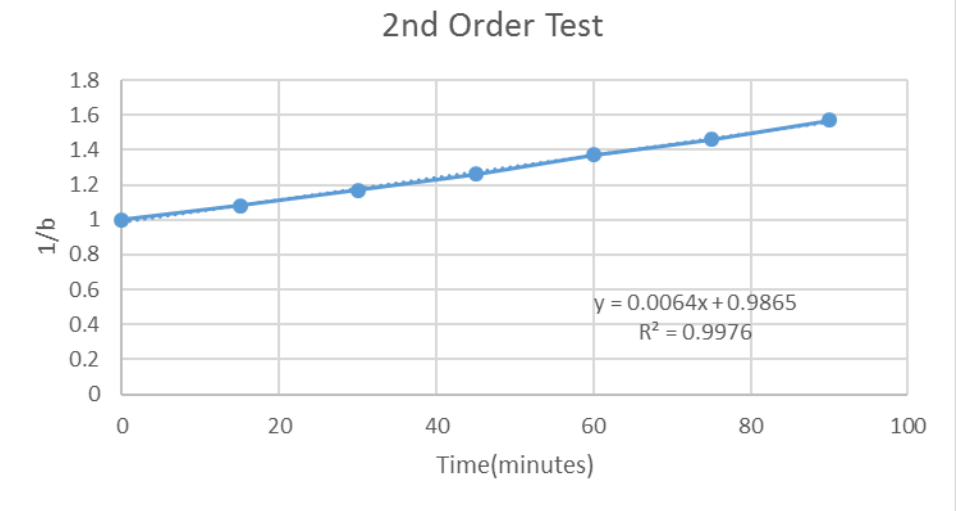

Figure 20: Second Order Test 1/b v.s time of experiment one 2.5 µM TetraF-TPP and 90 µM DPA in 1,4 Dioxane.

Figure 18-20 show the kinetic analysis performed on the second photolysis shown in Figure 17. The ln(b) v.s time was the most linear compared to the zeroth order plots in fugyre 18 and 20 respectively. Once again, DPA shows a first-order relationship despite which of the two porphyrins it is mixed with. The rate of TetraF-TPP porphyrin had to be determined experimentally by decreasing the porphyrin concentration by 50%.

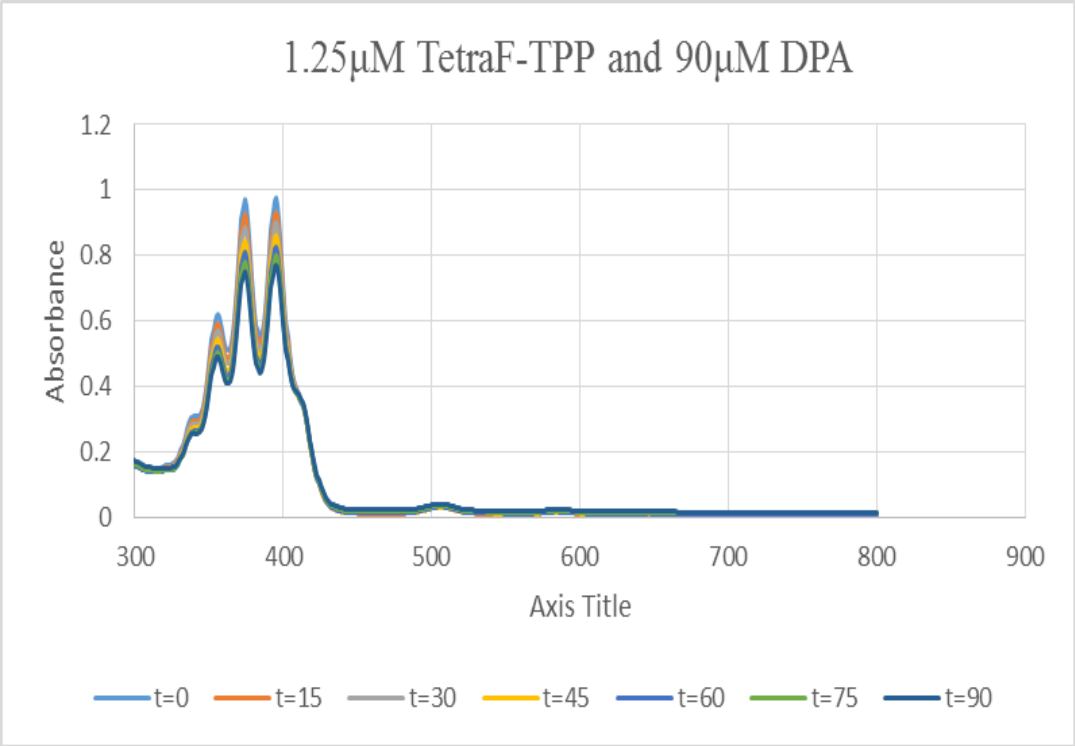

Figure 21: Spectra of 1.25 µM TetraF-TPP and 90µM DPA in 1,4 Dioxane during photolysis.

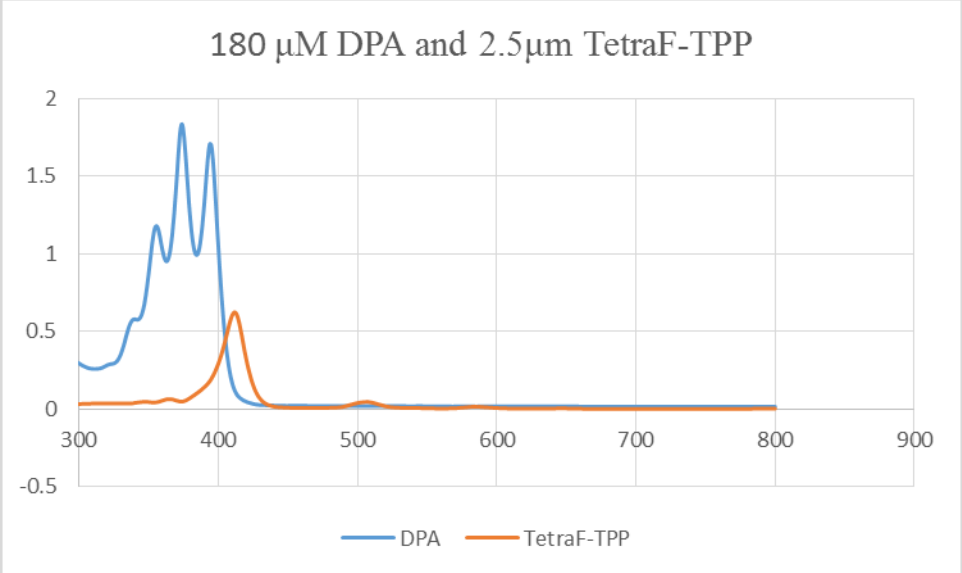

Figure 22: Spectra of 2.5 µM TetraF-TPP and 180µM DPA in 1,4 Dioxane prior to being mixed or photolyzed.

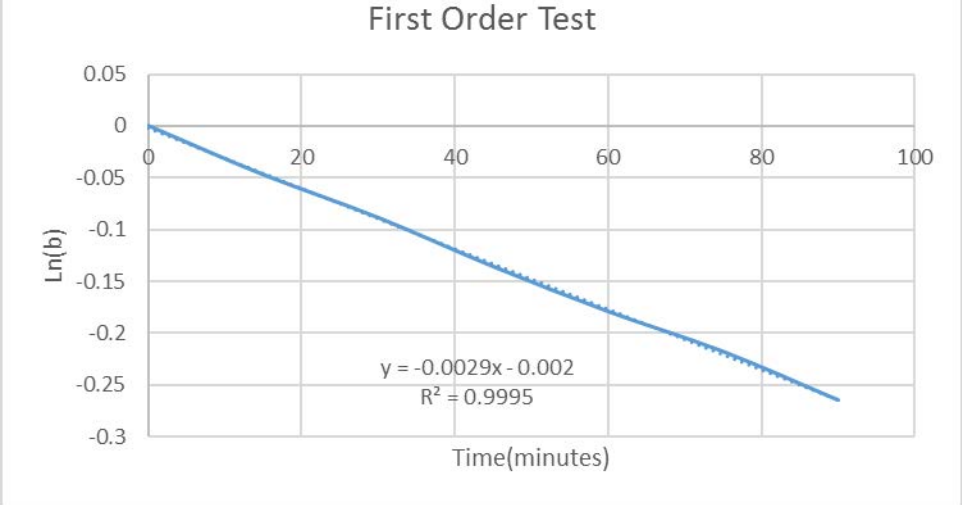

Figure 23: First Order Test, ln(b) v.s time of 1.25 μM TetraF-TPP and 90 μM DPAin Dioxane

Figure 21-23 display the steps in obtaining a rate constant shown in the slope of the first order test for 1.25μM TetraF-TPP; this data was collected using the same methods as the 1.25 TriF-TPP .

Table 3: Summary Table of (-k) values for each composition of solution.

Initial Porphyrin (μM)	Initial DPA (μM)	Initial Rate (M/sec)
2.5 Tri	90	-0.004891616
1.25 Tri	90	-0.00213896
2.5 Tetra	90	-0.005018358
1.25 Tetra	90	-0.00213896

Kinetic Analysis for porphyrin reaction order:

Initial Rate=$\frac{a_{15}-a_0}{15\,minutes-0minutes}$

$$R = k[DPA]^x[Porph]^y$$

x=1 because DPA was found to be first order

$$\frac{R_1}{R_2} = \frac{initial\ rate[DPA]_1{}^1[Porph]_1{}^y}{initial\ rate[DPA]_1{}^1[Porph]_2{}^y} = (\frac{[Porph]_1}{[Porph]_2})^y$$

$$y = \frac{Ln(\frac{R_1}{R_2})}{Ln(\frac{[Porph]_1}{[Porph]_2})}$$

By plugging in initial rates collected from the Zeroth order data(figure 18), the reaction order of TriF-TPP was found to be 0.954 and TetraF-TPP was found to be 1.29. These values indicate both porphyrins are first order. The variation from the value 1 are can be attributed to minor experimental error.

Carbon-13 NMR experiment required a solution that was much more concentrated than the solutions used in standard photolysis experiments because NMR is not as sensitive a method as UV-Vis spectroscopy. A 2.5mL sample of the solution was diluted by a factor of ten so that UV-Vis absorbance spectra could be collected. The diluted TriF-TPP/DPA solution spectra(Figure 24) was collected before and after photolyzing for 45 minutes. The spectra demonstrated that the characteristic DPA peaks in the 270-400nm region disappeared, which gave evidence that DPA reacted with the singlet oxygen to form

DPA-Endoperoxide. (Figure 27) After measuring the spectra, the solution was left in a lab cabinet for a week until the NMR instrument was available.

The purpose of the Carbon-13 NMR is to determine if the DPA is converted intro DPA-Endoperoxide. The spectra of the solution that did not get photolyzed still showed evidence that the solution was approximately 60% photolyzed. This raised questions about the contribution from ambient light from the lab could cause the porphyrin to absorb energy and led to the production of singlet oxygen. This led to an experiment in which a DPA/porphyrin solution was left on the lab counter for three weeks. The characteristic DPA peaks disappeared which indicated that the light from the laboratory caused photolysis (Figure 28). This is important because if porphyrin was used as a photosensitive drug, the patient would be forced to avoid all light sources.

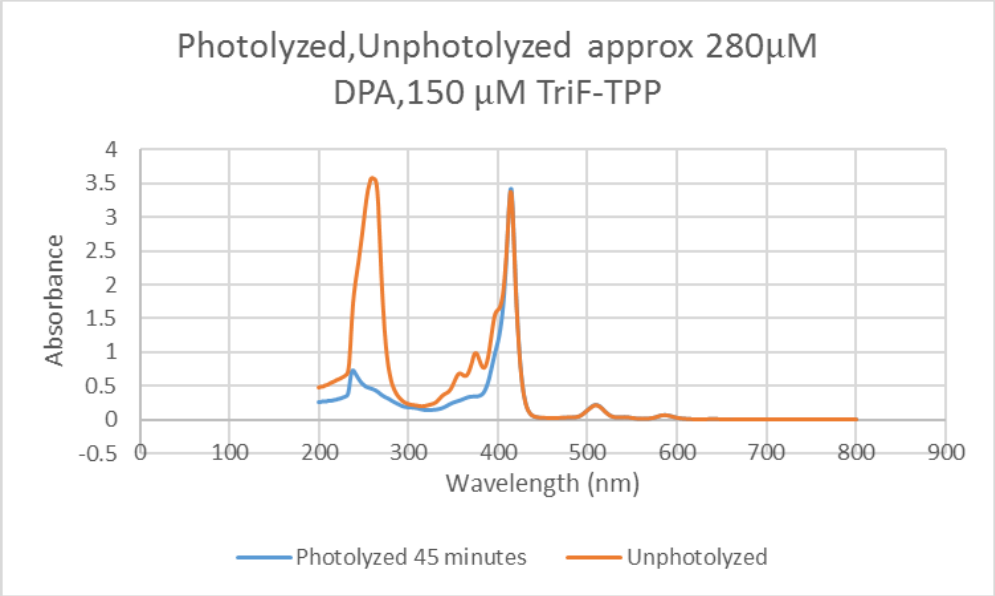

Figure 24: Spectra of concentrated DPA and TriF-TPP in chloroform before and after 45 minute photolysis.

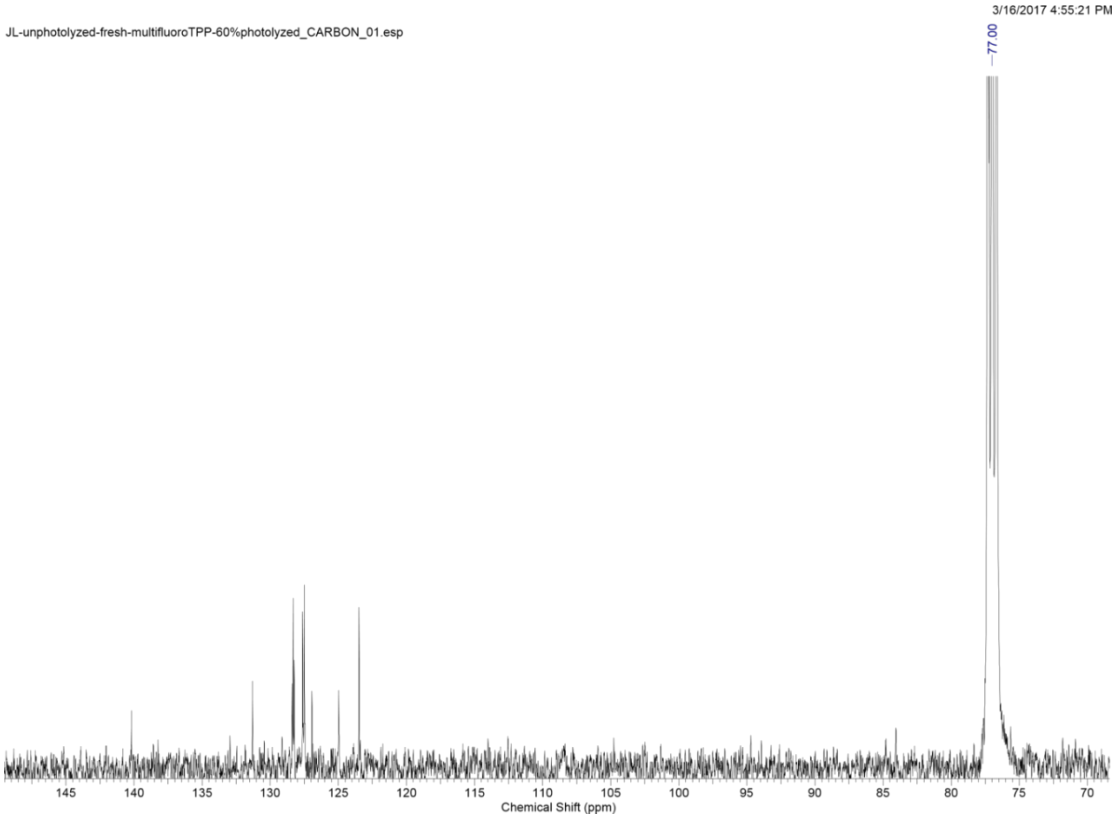

Figure 25. Unphotolyzed NMR spectra

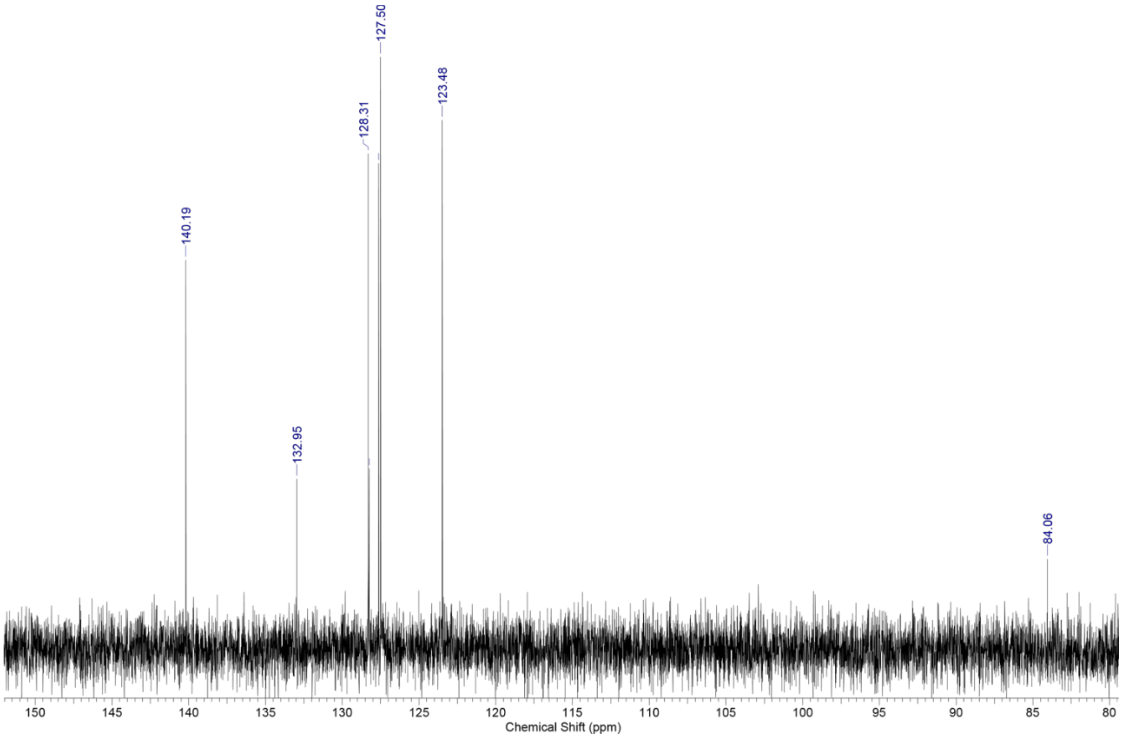

Figure 26: Photolyzed NMR spectra

Carbon-13 NMR shows the number of distinct carbons in a molecule.DPA has 8 distinct, Once DPA reacts with singlet oxygen to form DPA-EPO, there are still eight unique "types" of carbons. However, the peak at 84.06ppm is in the aliphate region as expected for DPA-EPO. However, the lack of peaks from DPA implies essentially 100% of the DPA was converted to DPA-Endoperoxide.

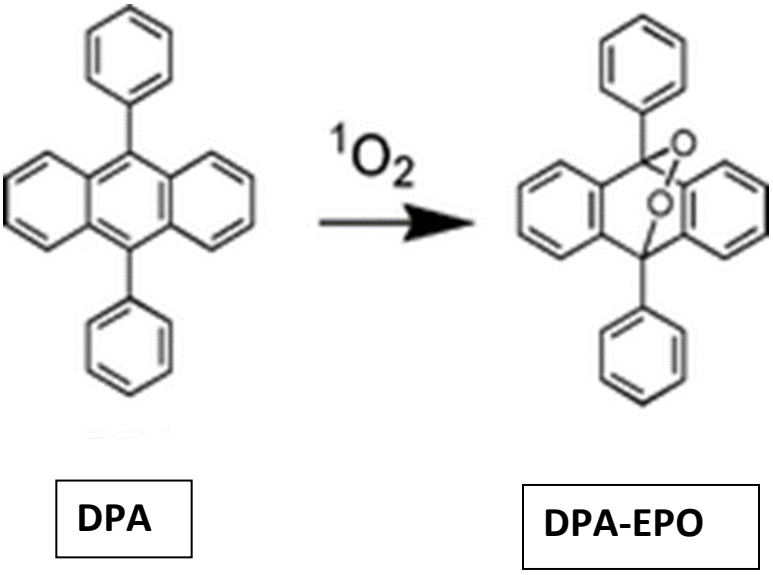

Figure 27: DPA reacts with singlet oxygen to form DPA EPO

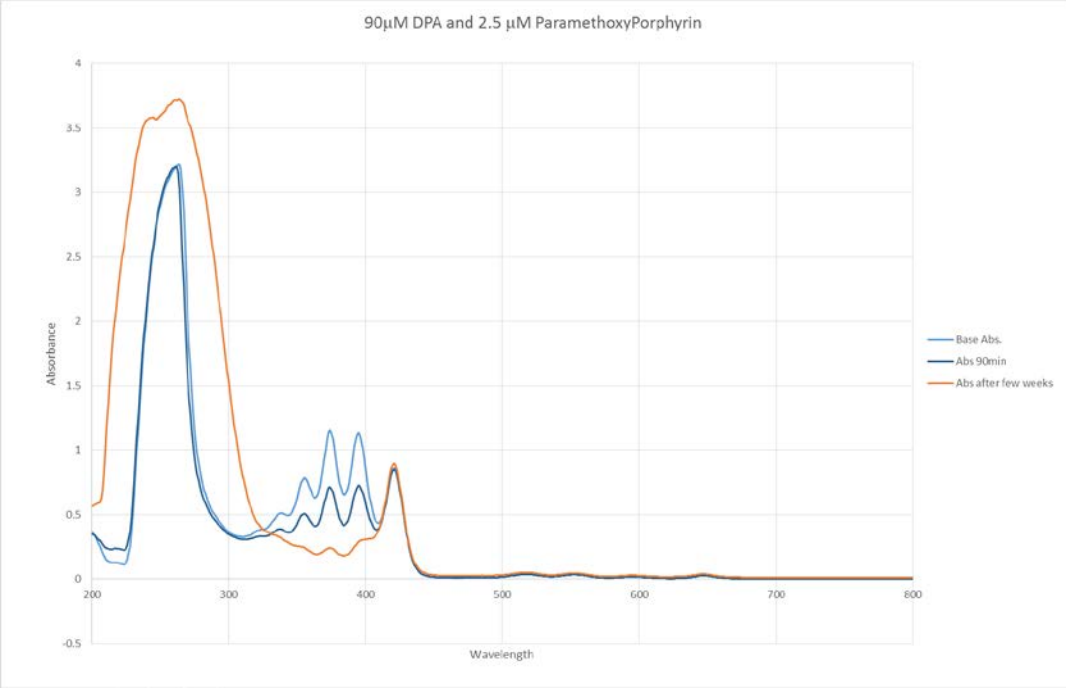

Figure 28: Spectra for porphyrin/DPA solution left on lab counter for multiple weeks. (Data obtained from fellow researcher, Chris Anderson)

Conclusion

The order of DPA and both porphyrins were both found to be one. This was predicted because it was shown that the concentration of porphyrin in solution affected the rate of DPA decomposition. For instance, once the porphyrin concentration was halved, the rate fell to approximately half of its original value. This demonstrates that there is a positive correlation between the amount of porphyrin in solution and the amount of singlet oxygen being produced. Kinetic information is important because it plays a critical role in determining dosage. Further experiments should be performed at shorter time intervals to get a more accurate values for the order.

The Carbon-13 NMR experiment provided critical evidence that DPA-EPO was formed. The presence of DPA-EPO indicates that singlet oxygen was formed because DPA-EPO is formed by the reaction of singlet oxygen and DPA. The NMR spectra also indicated that some of unphotolyzed product still formed singlet oxygen. This led to an experiment in which a porphyrin/DPA solution was left on the laboratory counter to determine the effect of ambient light on DPA-EPO production. UV-Vis spectra was collected after three weeks and showed that the characteristic DPA peaks disappeared. This is important because if porphyrin were administered to a patient to combat cancerous tumors, the patient would be forced to avoid light sources.

Porphyrins are not soluble in water. Therefore, porphyrins must be dissolved in nonaqueous solution. This is a problem because porphyrins need to be absorbed throughout the body and blood is an aqueous medium. For this research, 1,4 Dioxane was used as the solvent. Pharmacologist may be able to encapsulate the drug to find a better delivery method. Another factor that should be considered is the amount of tissue penetration at various wavelengths of light. For this study, the laser was set at 514nm. However, this would not be an efficient wavelength to pass through most tissue. Therefore, further research should be conducted in order to extend PDT to cancers that are beneath or in the bone such as brain tumors and bone neoplasm. This research should study the effect of different wavelengths of light on the production of $^1O_2$,as well as the wavelength necessary to penetrate deeper tissues. This information would allow

pharmacologist to be able to determine if porphyrins could be effective drugs for cancers that are beneath deep tissue.

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