FABRICATION AND CHARACTERIZATION OF NORMOXIC POLYMER GEL DOSIMETER BY USING RAMAN SPECTROSCOPY AT LOW X-RAY ENERGIES

by

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LIST OF SYMBOL

°C	Degree Celcius
cm	Centimeter
E	Energy
eV	electroVolt
Gy	Gray
h	Planck constant
Hz	Hertz
kV	kiloVolt
m	Meter
mA	miliAmpere
MeV	MegaelectroVolt
mg	milligram
min	Minute
mL	milliliter
mM	miliMolar
n	Number if atoms per cm^3 in a material
nm	nanometer
sec	second
x	Thickness of material
Δ	Delta
μ	Linear attenuation coefficient
ν	Frequency
σ	Absorption cross section in cm^2

LIST AF ABBREVIATION

3D	Three dimensional
AA	Ascorbic acid
BIS	N, N' – methylene-bis-acrylamide
CT	Computed tomography
HEA	2-hydroxyethyl acrylate
HEMA	2-hydroxyethyl methacrylate
MAGAS	Polymer gel dosimeter composed of Methacrylic acid, Ascorbic acid and Gelatine
MAGIC	Polymer gel dosimeter composed of Methacrylic acid, Ascorbic acid, Copper sulphate and Gelatine
MRI	Magnetic resonance imaging
NIPAM	N-isopropyl-acrylamide
PAG	Polyacrylamide gel
PAGAT	Polyacrylamide gel with THPC as anti-oxidant
PHEAG	Polyhydroxyethyl acrylate gel dosimeter
PHEMAG	Polyhydroxyethyl methacrylate gel dosimeter
PMAA	Polymethacrylic acid
PVA	Polyvinyl alcohol
THPC	Tetrakis (hydroxyl-methyl) phosphonium chloride
TLD	Thermoluminescent dosimeter
USM	Universiti Sains Malaysia

FABRIKASI DOSIMETER POLIMER GEL NORMOKSIK DAN PERINCIAN STRUKTURNYA MENGGUNAKAN SPEKTROSKOPI RAMAN PADA SINAR-X BERTENAGA RENDAH

ABSTRAK

Dosimeter polimer gel adalah dosimeter yang difabrikasi dengan menggunakan bahan kimia yang sensitive terhadap radiasi, dimana pempolimeran akan berlaku selepas proses radiasi. Dua jenis dosimeter gel polimer normosik telah difabrikasi, iaitu PHEAG (polihydroksiyetil akrilat) dan PHEMAG (polihydroksetil metakrilat). Kedua-dua polimer ini telah difabrikasi dengan menggunakan bahan-bahan seperti gelatin, N' N-methylene-bis-acrylamide (BIS), asid askorbik (AA), air dinyah ion dan monomer 2-hydroxyethyl acrylate (HEA) dan 2-hydroxyethyl methacrylate (HEMA) masing-masing untuk PHEAG dan PHEMAG. Kebolehan AA untuk mengikat oksigen di dalam larutan gel diuji dengan menggunakan alat pengukur oksigen terlarut. Konsentrasi AA yang digunakan ialah 5, 10, 15 dan 35 mM, dan diaplikasikan kepada setiap kumpulan PHEAG dan PHEMAG yang difabrikasi. Kepekaan PHEAG dan PHEMAG terhadap sinar-X bertenaga rendah dikaji dengan memerhatikan perubahan struktur di dalam PHEAG dan PHEMAG selepas diradiasi dengan menggunakan spektroskopi Raman. Selaras dengan perubahan di dalam mod regangan C=C (1430 cm^{-1} untuk HEA; 1425 cm^{-1} untuk HEMA; 1642 cm^{-1} untuk BIS) dan mod bengkokan vinil CH_2 (1270 cm^{-1} untuk HEA; 1265 cm^{-1} untuk HEMA; 2955 cm^{-1} untuk BIS), parameter kesensitifan (D_o) untuk setiap mod telah dikira. Hasil kajian menunjukkan kadar pengikatan oksigen meningkat dengan kenaikan konsentrasi AA. Konsentrasi monomer tidak mempengaruhi kadar pengikatan oksigen kerana monomer tidak terlibat di dalam reaksi oksidasi spontan asid askorbik. Sebanyak 35 mM telah dipilih sebagai konsentrasi AA yang digunakan di dalam proses fabrikasi PHEAG dan PHEMAG untuk kajian perincian Raman. Kajian menunjukkan bahawa konsentrasi optimum bagi PHEAG ialah 3% BIS dan 5% HEA, manakala bagi PHEMAG ialah 3% BIS dan 5% HEMA. Hasil kajian menunjukkan kadar penggunaan monomer (HEA dan HEMA) dan pengikat silang (BIS) meningkat dengan kenaikan tenaga sinar-X. Penggunaan BIS lebih besar berbanding HEA dan HEMA menandakan bahawa kadar pempolimeran PHEAG dan PHEMAG sangat bergantung kepada konsentrasi pengikat silang. Kajian juga menunjukkan PHEMAG adalah lebih radiosensitif berbanding PHEAG. Kajian ini juga menunjukkan PHEAG dan PHEMAG memberi reaksi positif terhadap sinar-X bertenaga rendah.

FABRICATION AND CHARACTERIZATION OF NORMOXIC POLYMER GEL DOSIMETER BY USING RAMAN SPECTROSCOPY AT LOW X-RAY ENERGIES

ABSTRACT

Polymer gel dosimeters are fabricated from radiation sensitive chemicals which, upon irradiation, polymerize as a function of the absorbed radiation dose. Two types of normoxic polymer gel dosimeters were fabricated, which is PHEAG (polyhydroxyethyl acrylate) and PHEMAG (polyhydroxyethyl methacrylate) gel dosimeters. These polymer were fabricated by using gelatin, N' N-methylene-bis-acrylamide (BIS), ascorbic acid (AA), deionized water and 2-hydroxyethyl acrylate (HEA) for PHEAG and 2-hydroxyethyl methacrylate for PHEMAG. The ability of AA to bind oxygen in the gel solution was investigated by using an oxygen dissolve meter. The concentrations of AA used are 5, 10, 15 and 35 mM and each concentration was applied to each batch of PHEAG and PHEMAG. The sensitivity of PHEAG and PHEMAG towards low X-ray energy was investigated. The structural changes of the monomeric components in PHEAG and PHEMAG after irradiation were analyzed using Raman spectroscopy. In accordance with the changes in C=C stretching (1430 cm^{-1} for HEA; 1425 cm^{-1} for HEMA; 1642 cm^{-1} for BIS) and vinyl CH2 bending (1270 cm^{-1} for HEA; 1265 cm^{-1} for HEMA; 2955 cm^{-1} for BIS), sensitivity parameter (D_o) for each mode was calculated. Results show that the oxygen scavenging rate increased with increasing AA concentration. Monomer concentration does not affect the oxygen scavenging rate because monomer does not involve in the spontaneous oxidation of AA. A 35 mM was chosen as the AA concentration for PHEAG and PHEMAG used in Raman characterization. For

PHEAG, the most sensitive gel composition is 3% BIS and 5% HEA where else for PHEMAG is 3% BIS and 5% HEMA. Results indicate that the rate of monomer (HEA and HEMA) and cross linker (BIS) consumption increased with increasing X-ray energy. The consumption of BIS is always greater than HEA and HEMA implying that the rate of polymerization is highly dependent on the concentration of cross linker rather than the concentration of monomers. Finally, PHEMAG was found to be more radiosensitive than PHEAG. It is shown that PHEAG and PHEMAG gives a positive response towards low energy X-ray.

CHAPTER 1

INTRODUCTION

1.1 Background

A radiation dosimeter is a device that measures, either direct or indirect, the quantities exposure, kerma, absorbed dose or equivalent dose, or their time rates, or related quantities of ionizing radiation. When a dosimeter is irradiated with ionizing radiation, it exhibits a quantifiable and reproducible change in physical or chemical property, which can be related to the absorbed dose using appropriate analytical techniques. Dosimeter is an important device in diagnostic and radiation therapy as this device was used in radiation measurement for machines quality control and radiotherapy treatment planning.

The search of a dosimetry technique that allows three dimensional imaging of a radiation dose has led to the development of radiation-sensitive gels. The first gel was introduced by Day and Stein in 1950, which contains Folin's phenol and changes colour upon irradiation. Subsequent to this study, Fricke gel was introduced (Baldock *et al.* 2010). In Fricke gel dosimeters, radiation-induced free radicals produced by radiolysis of water oxidize ferrous Fe^{2+} ions into ferric Fe^{3+} ions. Current interest in gel dosimetry technique follows on from a new type of gel dosimeter that based on radiation-induced polymerization in solutions of monomers and polymers. This new type of gel dosimeter is known as polymer gel dosimeter. Here, acrylic molecules embedded within the gel matrix polymerize upon radiation, with the degree of polymerization are dependent to the absorbed dose received by the gels (Maryanski *et al.* 1993).

Polymer gels dosimeter fabrication procedure depends on the composition, type of gel and equipment used. The bases of polymer gel dosimeters are monomers, gelling agent and water. The gels are then poured into vials which have low oxygen permeability usually Pyrex glass, and left to set in the refrigerator. Once irradiated, the radiation-induced chemical and physical changed of the gel is read out using numbers of imaging modalities such as X-ray computed tomography (CT), magnetic resonance imaging (MRI), ultrasound and vibrational spectroscopy techniques.

1.2 Problem statement

The gel dosimeters content is normally 90% of water. Therefore, polymerization of polymer gels are initiated by some entities produced from water. After irradiation, water molecules are dissociated into several ions and reactive radicals during a process termed radiolysis.

These free radicals play an important role in the initiation and termination of the polymerization reaction. However, these free radicals are very sensitive to oxygen as oxygen will quickly quench these radicals. This will disrupt the polymerization process. To overcome this problem, the fabrication and storing of polymer gel dosimeters have to be done under an oxygen-free environment. As a result, manufacturing of polymer gels is often laborious and difficult to attain stability.

A new type of polymer gel have been introduced and known as normoxic polymer gel. An anti-oxidant was introduced into the gel formulation to quench the free oxygen in the gel solutions. With the introduction of normoxic polymer gel, the fabrication process can be done under normal atmospheric condition. AA is one of the most common anti-oxidant used in polymer gel dosimeter. Usually, copper sulphate is added together with AA to enhance the capability of AA to bind oxygen in gel solution. However, the presence of the catalyst in the gel solution can inhibit the polymerization process as the catalyst will react with the free radicals in the gel solutions.

Polymer gel dosimeters can be categorized as chemical dosimeters that rely on a radiation-induced chemical radiation (Baldock *et al.* 2010). Several types of radiation have been used to study the polymer gel reaction and the most popular types are high energy X-rays from clinical linear accelerator and gamma rays from cobalt source. However, studies for low energy X-rays especially fewer than 2 Gy has not been comprehensively investigated.

Magnetic resonance imaging (MRI), optical tomography and x-ray computed tomography are the most widely used imaging techniques for polymer gel dosimetry. The use of ultrasound to image polymer gel dosimeter was introduced by Mather *et al.* (2002). However, the chemical structure changes of the gel according to radiation changes were not fully understood using aforementioned imaging techniques. Technique that can assist better understanding of polymer gel dosimeter chemical structure changes could therefore enable polymer gel dosimetry to become a more practical option in radiotherapy dosimetry.

In conclusion, a more clear comprehension of polymer gel dosimetry will make fulfilling the needs of dosimetric system for 3D treatment planning a likely prospect, as records has so far shown.

1.3 Objectives of research

The objectives of this study are:

i. To fabricate normoxic polymer gel dosimeters based on two acrylic acid monomers, namely 2-hydroxyethyl acrylate (HEA) and 2-hydroxyethyl methacrylate (HEMA).
ii. To measure the oxygen concentration in HEA and HEMA polymer gel using the dissolve oxygen meter.
iii. To characterize the structural changes of HEA and HEMA polymer gel dosimeters at different x-ray energy using Raman spectroscopy.

1.4 Scope of research

This study only involved two types of polymer gel that is polyhydroxyethyl acrylate gel (PHEAG) dosimeter and polyhydroxyethyl methacrylate gel (PHEMAG) dosimeters. The chemicals used for fabrication are BIS, gelatine, AA and HEA for PHEAG fabrication and HEMA for PHEMAG fabrication. The capability of AA to quench oxygen was investigated in both PHEAG and PHEMAG dosimeters by measuring the oxygen concentration with dissolve oxygen meter. The inclusion criteria's in this research are structural changes of PHEAG and PHEMAG with different monomer concentration and the peak intensities for Raman spectra of each irradiated gel of PHEAG and PHEMAG. The exclusion criteria's in this research are variation of cross linker and anti-oxidant concentration in polymer gel and area under the peak of Raman spectra.

1.5 Outline of thesis

In Chapter One, the introduction, problem statement, research objectives and scope of research were discussed. Chapter Two provides the reader general background and literature review of polymer gel dosimeters methodology, including the polymer gel fabrication, irradiation process of polymer gels and characterization of irradiated polymer gels. Theoretical background, including basic interaction of radiation with matter, polymerization process and Raman scattering phenomena is also included in this chapter. Chapter Three gives a brief description on materials used in this research and describes the experimental methods involved in this study comprising the fabrication steps of HEA and HEMA polymer gels, the oxygen measurements process, the irradiation process and the polymer gels characterization process. Chapter Four covers the results and discussions of corresponding measurements done in Chapter Three. Finally, Chapter Five is the conclusions of the study and suggestions for future work.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Introduction

This chapter describes the theory pertinent to this research and is briefly discussed to provide the basis of radiation interaction with polymer gel dosimeters and the basic principle of the equipment used in this research. This chapter also indicates the ideas relevant to the present research relating to the other studies and is briefly discussed to provide the foundation of the proposed research in order to develop the method and procedures, careful review of literature and studies must be done for the development of the research.

2.2 Theory

2.2.1 Interaction of X-ray with matter

X-rays is a form of electromagnetic radiation or emission of light which originate principally from rapid deceleration of the electrons when they interact with the nucleus of the target atom. X-rays has a much shorter wavelength than visible light, so x-rays photons have much higher energy than photons of light. X-ray radiation has a wavelength in the range of 0.01 to 10^{-9} m, corresponding to frequency in the range of 3×10^{16} Hz to 3×10^{-9} Hz and energy between 120 eV to 120 keV. X-ray can be generated using an X-ray tube, a vacuum tube that uses high voltage to produce a high velocity electron released by a hot cathode. X-ray is created when the high velocity electron hit the metal target known as the anode. Five types of interactions with matter by X-ray photons; Rayleigh scattering, Compton effect, photoelectric effect, pair production and photonuclear interaction. In this study, the first three is the most important as the x-ray energy used in this study are in the range below 1.02 MeV.

When an x-ray photon passes through matter, this individual photon will be scattered or absorbed from the incident beam. The probability of photon absorption is proportional to the thickness of the matter. This leads to an exponential decrease of intensity with thickness. The intensity decreased ΔI (photons/cm^2.sec) is proportional to the thickness travelled through Δx and the initial intensity I, i.e.

$$\Delta I = -\mu I \Delta x \tag{2.1}$$

where, $\mu = n\sigma$ is the absorption coefficient or linear attenuation coefficient, measured in cm^{-1}, n is the number of atoms per cm^3 in the material and σ is the absorption cross section in cm^2. In this case, upon integrating, we have

$$I = I_o e^{-\mu x} \tag{2.2}$$

where, x is the thickness of material in cm.

2.2.2 Radiation effects

2.2.2(a) Ions, excited molecules and free radicals

Materials that are exposed to ionizing radiation such as X-rays undergo chemical effect known as radiation-chemical change. Radiation-chemical change or radiolysis is typically produced by a mixture of reactive intermediates that includes short-lived ions, electronically excited molecules and, at a later stage in the process, free radicals.

When a photon moves in matter and experience energy loss, it will slow down and give rise to a trail of excited and ionized atoms and molecules in its path. Ions are produced through ionization process where the bound electrons in atoms and molecules gain sufficient energy and the transient excited state such that, electrons are expelled. Ionization is the distinctive consequence of the absorption of ionizing radiation by matter and a key reaction in all radiolysis mechanisma:

$$AB \rightleftharpoons AB^{+} + e^{-} \qquad (2.3)$$

Eq. 2.3 shows the ionization process of and organic molecules where AB denotes the organic molecule, $\rightleftharpoons$ represents a radiation-induced event, AB^{+} is the positive ion and e^{-} is an electron.

Ionizing radiation can produce excited molecules in matter directly (Eq. 2.4) and also indirectly by ion recombination (Eqs. 2.5 and 2.6)

$$AB \rightleftharpoons AB^* \tag{2.4}$$

$$AB \rightleftharpoons AB^+ + e^- \tag{2.5}$$

$$AB^+ + e^- \longrightarrow AB^{**} \longrightarrow A + B \tag{2.6}$$

An asterisk is used to designate a molecule or ion in an excited state. Excited molecules are produced directly by ionizing radiation when the incident photon does not have enough energy to eject an electron from the molecule and instead moves the electron from one orbital to another of higher energy.

During ionization, an electron is ejected (Eq. 2.5). This electron may have considerable high energy, and experiences energy loss when it interacts with other molecules and later recombine with a positive ion and neutralizes the ion. This process is a normal event during irradiation or as an after-effect at the end of irradiation. The immediate product of this recombination process is a neutral but highly excited molecule (AB^{**}). This highly excited molecule posses energy larger than any bond strength. As a result, this highly excited molecules will break down into free radicals (A, B) (Eq. 2.6) (Spinks and Woods, 1990). Free radicals are atoms or molecules that possess one or more unpaired electrons which can take part in chemical bonding. Most reactions in polymer are attributed to conventional free radical process, but some can be credited to ions.

2.2.2(b) Free radical chain polymerization

Free radical polymerization is a method of polymerization by which a polymer forms by the continuous addition of free radical building blocks. This type of polymerization is a chain reaction that involved four steps process that are free radical generation, initiation, propagation and termination (Spinks *et al.* 1990).

The first step is free radical generation. This process involves the production of active molecule intermediates. These intermediates molecules are known as free radicals. It can be produced through several ways, which are thermal decomposition, photolysis, ionizing radiation such as electrons, gamma rays and x-rays and redox reactions (Spinks *et al.* 1990).

The second process is initiation. When free radicals are generated together in the presences of vinyl monomers, these radicals will react with the covalent bonds, changing the monomer molecule into a radical. This radical initiation is an important step for chain reaction (Spinks *et al.* 1990).

The third process is propagation. It is a process where polymer increases its chain length. It is a chain reaction, which can continue until we run out of monomer, or until termination occurs (Spinks *et al.* 1990).

The final process is termination. Chain termination will occur when all the monomer have been used. Termination can also occur by several different mechanisms:

i. Combination of two active chain ends:
   a) Combination: two chains end of two free radicals will pair up their unpaired electrons and forming one long chain. This mode of termination will lead to molecular weight increase (Spinks *et al.* 1990).
   b) Radical disproportionation: hydrogen atom abstraction from one chain end to another, producing two groups in a polymer, terminal unsaturated group and terminal saturated group (Spinks *et al.* 1990).

ii. Interaction with inhibitors: oxygen is the common inhibitor. Interaction between the growing chain and molecular oxygen will produce oxygen radical, which is less reactive. This will slows down the rate of propagation (Spinks *et al.* 1990).

2.2.3 Raman spectroscopy

Raman scattering was discovered by Sir C. V. Raman in year 1928. Since then, Raman spectroscopy has become one of the most popular analytical techniques. This technique provides comprehensive information about the vibrational modes of molecules by monitoring macroscopic light scattering. The arrangements for Raman spectroscopy are shown in Figure 2.1.

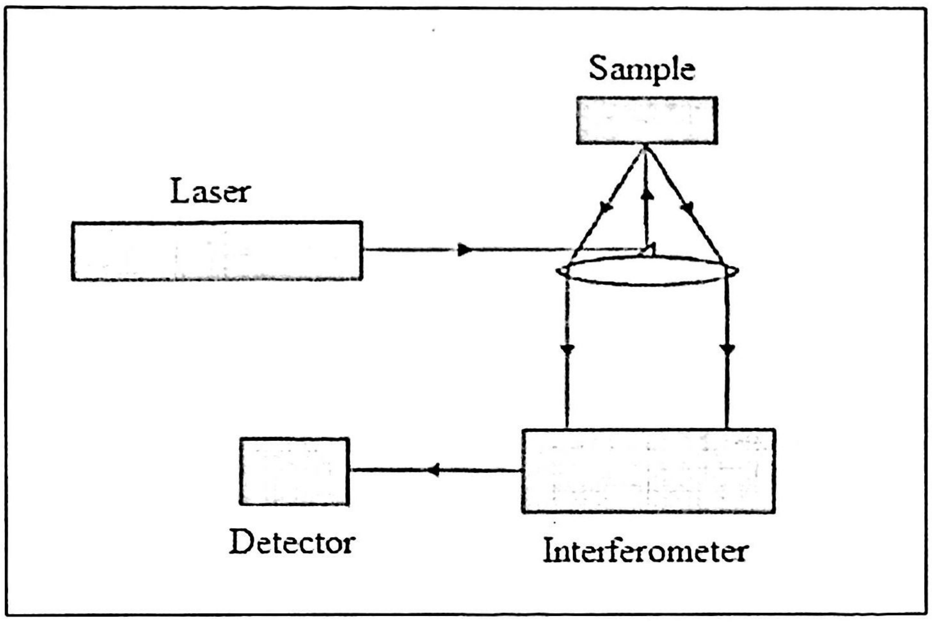

Figure 2.1: Arrangement for Raman spectroscopy. Scattered radiation is monitored perpendicular to the incident radiation (Baldock *et al.* 1998).

2.2.3(a) The Raman scattering process

When photons are scattered from an atom or a molecule, most photons are elastically scattered, such that the scattered photons have the same kinetic energy (frequency) and wavelength as the incident photons. No energy from the incident radiation is absorbed by the atom or molecule. This process is called Rayleigh scattering. Raman spectroscopy is based on inelastic scattering. Only a small fraction of molecules, undergo inelastic scattering. Figure 2.2 shows the energy level diagram for Rayleigh and Raman scattering. Figure 2.2(a) depicts the Rayleigh scattering and Figure 2.2(b) and 2.2(c) depicts for Raman Stokes and anti-Stokes scattering respectively. During Raman scattering, the excited molecule relaxes to different vibrational state, not to the original state. The energy carried by the inelastically scattered photon is different from the incident photon. This energy difference between the incident and scattered photon appears as the frequency shift between the scattered light v' and the excitation frequency. These two frequencies can be related to the vibrational energy by the following equation,

$$h\nu = h\nu' + \Delta E_{vibration} \tag{2.7}$$

There are two types of Raman bands which is anti-Stokes lines and Stokes lines. An anti-Stokes line happens when the final vibrational state of the excited molecule is lower in energy than the original state; hence the scattered photon will show a higher frequency than the incident photon. A blue shift from the excitation frequency will be observed. Stokes line happens when the final vibrational state of the excited molecule is higher in energy than the original state; hence the scattered photon will show a lower frequency than the incident photon. A red shift from the excitation frequency will be observed.

At room temperature, most molecules are in ground state, hence the Stokes lines exhibit higher Raman intensity than anti-Stokes lines. Therefore, the Stokes lines are more commonly used for molecular characterization.

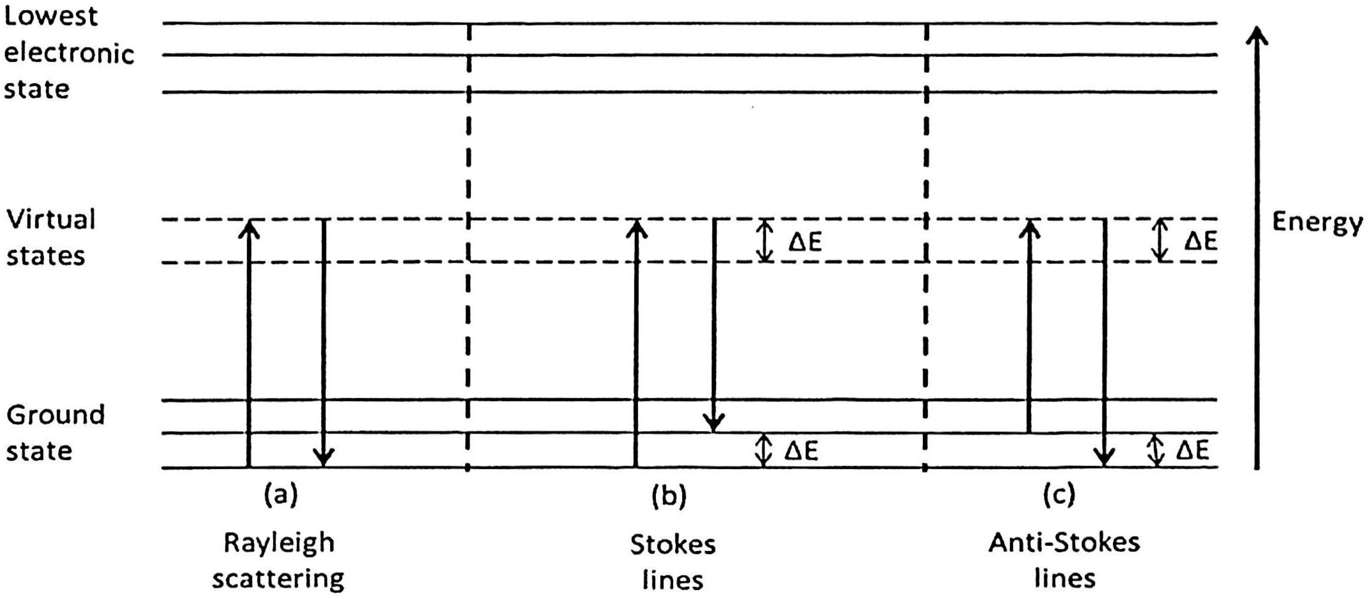

Figure 2.2: Diagram of the energy level changes due to Rayleigh scattering (a), Stokes Raman scattering (b) and Anti-Stokes Raman scattering (c). An incident photon raises the electron into a virtual energy level. If it returns to the same energy level, then it will emit a photon of the same wavelength as the incident, an example of Rayleigh scattering. If it falls to a final energy level that is different to the initial energy level, then it emits a photon with a different wavelength to the incident photon. This difference in energy will depend on the particular molecular structure of the chemical, and therefore can be used to identify it.

2.2.4 Spontaneous oxidation of ascorbic acid in polymer gel dosimeter

The suggested chemical reaction pathway of spontaneous oxidation of AA is shown in Figure 2.3. For normoxic polymer gel dosimetry, the ascorbate ion (a) is likely produced by proton exchanged with water. Oxygen will then attack the ascorbate ion and produced ascorbate anion radical and hydroxyperoxide radical (b). These radicals formed in step (b) are believed to be responsible for initiation of a polymerization reaction. According to reaction steps (c) and (d), the ascorbate anion radical will react with both hydroxyperoxide radical and oxygen. Step (d) is the most important step as oxygen is scavenged by the ascorbate anion radical. Both reactions will further oxidize the ascorbate anion radical to dehydroascorbic acid. According to step (d), oxygen radicals might also be created. The hydrogen ion produces from step

(a) will react with hydroxyperoxide ion from step (c) to produce a hydrogen peroxide molecule.

When oxygen is present in the gel, the oxygen will quickly react with the free radical produce from radiolysis, monomer and co-monomer. This reaction leads to the formation of peroxide radicals.

$$R^* + O_2 \longrightarrow ROO^* \qquad (2.8)$$

$$Mn^* + O_2 \longrightarrow MnOO^* \qquad (2.9)$$

Equations (4.1) and (4.2) show the interaction between oxygen with radicals produce from radiolysis and monomer radicals. These peroxide radicals are very unstable and will quickly react with other radicals and triggering the termination process.

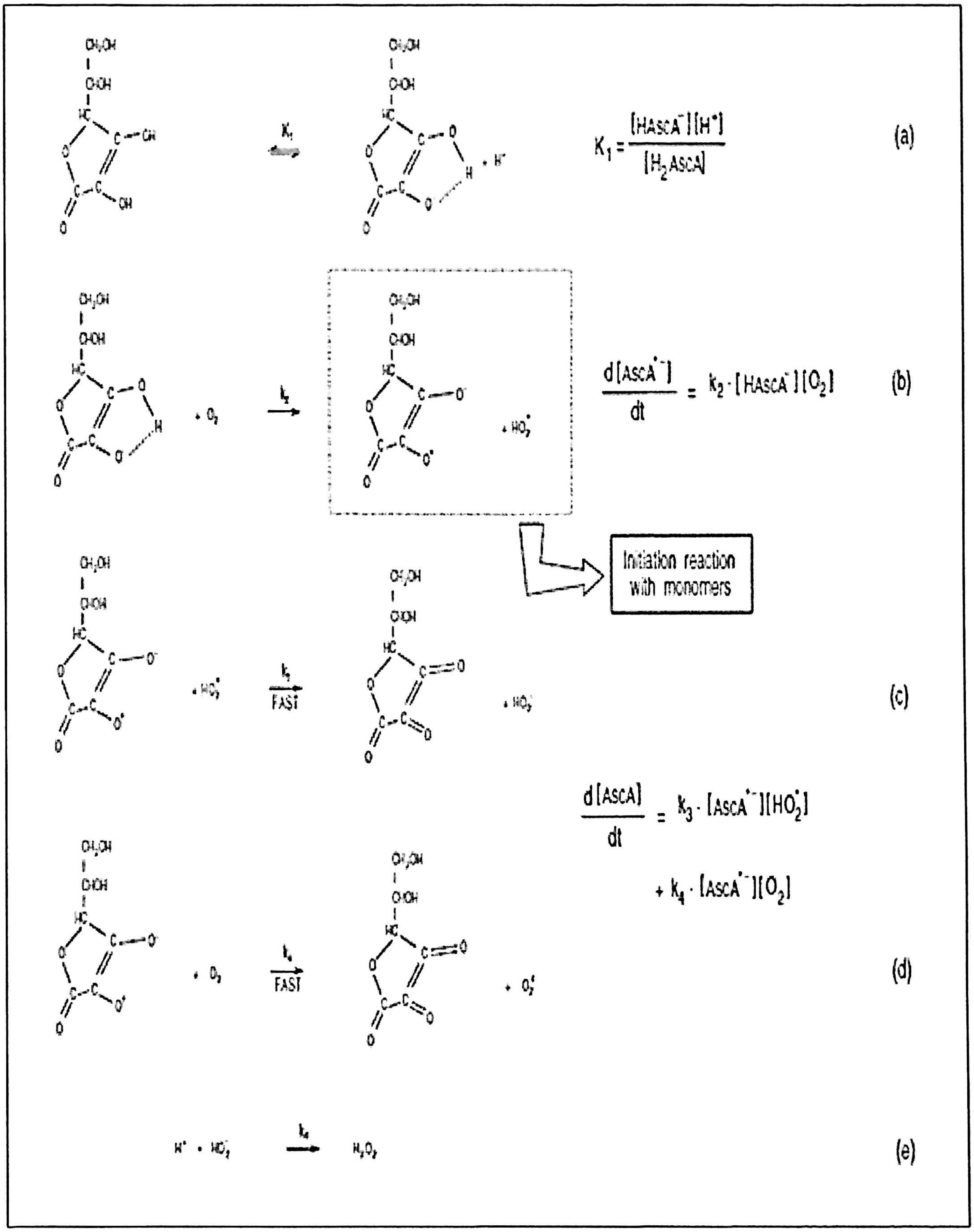

Figure 2.3: Reaction scheme for the spontaneous oxidation of ascorbic acid. The reactions listed are based upon a scheme suggested by Khan and Martell (1967).

2.3 Literature review

2.3.1 Polymer gel dosimetry

Polymer gel dosimeters consist of a gel infused with radiation sensitive materials. After irradiation a measurable change is induced in the active materials which are held in position by the gel matrix, thus preserving a spatial record of the irradiation. The gel usually consists of water mixed with a gelling agent such as agarose, gelatine or polyvinyl alcohol (PVA). The radiation sensitive materials to date have mainly been acrylamide and BIS, however many formulations have been investigated and no doubt several more will show radiation sensitivity in future studies.

Polymer gel dosimeters have several advantages over current techniques. Not only are they three-dimensional dosimeter, but the dosimeter itself are also radiological tissue equivalent resulting in more accurate modelling of radiation dose distribution. Finally, because gels are manufactured as a liquid, they can be poured into containers of varying shape and can thus easily become anthropomorphic phantoms.

2.3.2 Normoxic polymer gels

Polymer gels are formed by using one or two acrylic monomers in a solution with gelatine. Hypoxic condition is essentials in manufacturing, storage and usage of polymer gels as the polymerization of these acrylic gels is the result of respond to the free radicals formed after radiation. However, these free radicals are quickly quenched by oxygen. This most likely occurs because oxygen scavenges free radicals initiators such as $OH^{\cdot}$ and $H^{\cdot}$ that are produced during water radiolysis. These free radicals play an important role in the initiation and termination of the polymerization reaction (Hepworth *et al.* 1999). Usually, oxygen is removed from the gels by permeating the sol with inert gas such as nitrogen and argon for several hours during the gels fabrication (Maryanski *et al.* 1996; Fong *et al.* 2001). This is achieved by using a glove box facility to purge nitrogen and equal care must be taken when housing the gels since even minutes of oxygen contamination can alter the gels reaction, linearity and reproducibility (Fong *et al.* 2001). Therefore, the gels are usually housed in glass vessels which have low gas penetrability. As a result, manufacturing of polymer gels is often laborious and difficult to attain stability.

For above reasons, an acrylic gel dosimeter that can be used in normal atmospheres would likely be of great benefit. Significant development has been made in the field of gel dosimetry with the introduction of a new type of polymer gel dosimeter known as MAGIC (Fong *et al.* 2000). Oxygen inhibition problem are avoided by binding the atmospheric oxygen in a metallo-organic compound thus enabling polymer gels to be manufactured under normal atmospheric conditions. This new type of polymer gel dosimeters are known as normoxic gel dosimeters. The theory behind eliminating the setback of oxygen in MAGIC gel is in the use of an anti-oxidant. The anti-oxidant will binds the free oxygen contained within the aqueous gelatine matrix into metallo-organic complexes (De Deene *et al.* 2002a). With the introduction of the MAGIC normoxic polymer gels, a number of other polymer gel formulations have been studied for their potential use as normoxic polymer gels (De Deene *et al.* 2002; Brindha *et al.* 2004, 2004a; Karlsson *et al.* 2007; Venning *et al.* 2004, 2005, 2005a). De Deene *et al.* (2002) have suggested a gel formulation named MAGAS, which is consisted of methacrylate acid monomer, gelatine and AA. MAGAS does not use hydroquinone or copper sulphate as in MAGIC polymer gel dosimeter. De Deene stated that the presence of ascorbic acid as the anti-oxidant alone is sufficient to quench oxygen so as to prevent oxygen from inhibiting polymerization of polymer gels. A list of different normoxic gel formulation published can be found in Appendix A.

2.3.3 Polymer gel dosimetry methodology

Polymer gel dosimeters are manufactured in a chemistry laboratory using conventional chemistry apparatus. The manufacturing procedure will vary depending on the composition, type of gel and equipment used. The methods to fabricate normoxic polymer gels are explained in various literatures (Fong *et al.* 2001; De Deene *et al.* 2002, 2002a; De Deene *et al.* 2006; Sedaghat *et al.* 2010). The bases of normoxic polymer gels are monomers, gelling agent, anti-oxidant and water. Gelling agent is combined with purified water in a mixing vessel and is continuously stirred while heating to approximately 48 °C or until the gel is completely dissolved and the solution is clear. Monomers are then added to the solution and are continuously stirred until completely dissolved. The anti-oxidant is the last ingredient to be added to minimize exposure of the solution to atmospheric oxygen (De Deene *et al.* 2002).

Normoxic gels are manufactured under fume hood and then poured into an anthromorphic phantom or Pyrex glass, which have low oxygen transport properties. Once the gels have been sealed within the phantom, they are left to cool and set in the refrigerator. Apart from the ability to measure absorbed dose, the polymer gel dosimeter phantom and calibration samples should be radiologically tissue equivalent, stable in time and space, and dose rate and energy independent with the effect of temperature and pressure on the gel negligible (De Deene *et al.* 2004). Other important factors are the effect of temperature during polymer gel fabrication (De Deene *et al.* 2000) and storage (De Deene *et al.* 2007). The gels are irradiated using a linear accelerator or a gamma source. After a period of time post irradiation and after radiation induced chemical reactions have taken place the dose information contained within the gel is readout.

There are numbers of imaging modalities that can be used such as magnetic resonance imaging (MRI) (Maryanski *et al.* 1994; De Deene *et al.* 1998; Pappas *et al.* 1999; De Deene *et al.* 2004a), x-ray CT (Hilts *et al.* 2000; Trapp *et al.* 2001; Hill *et al.* 2005; Baxter and Jirasek 2007), ultrasound (Mather *et al.* 2002), optical CT (Maryanski *et al.* 1996; Oldham *et al.* 2001; Heard *et al.* 2009) and vibrational spectroscopy techniques (Baldock *et al.* 1998a; Jirasek *et al.* 2001a; Jirasek and Duzenli, 2002; Hilts *et al.* 2004).

2.3.4 Polymerization in polymer gels

Polymerization of polymer gels starts with the radiolysis of water. When a molecule of water, H_2O absorbs ionizing radiation, it will be ionized into two ions; a hydrogen ion (H^+) and a hydroxyl ion (OH^-). Both ions are chemically active and their reactions are up to about 10^{-16} sec. Nonetheless, high energy radiation can cause break-up of water molecule into two uncharged species called free radicals, and this case H and OH. These radicals are more active chemically than ions and can cause different chemical reactions when react with compounds or molecules in their vicinity.

In the process of radiation-induced polymerization, free radicals react with the monomers to form free radicals of one monomer unit and these monomers combine with one another, thereby producing a polymer of high molecular mass.

Radiolysis of water

$$H_2O \longrightarrow H^* + OH^* \tag{2.8}$$

$$RH + OH^* \longrightarrow R^* + H_2O \tag{2.9}$$

$$RH + H^* \longrightarrow R^* + H_2 \tag{2.10}$$

Initiation

$$R^* + M \longrightarrow RM^* \tag{2.11}$$

Propagation of active copolymer radicals

$$RM^* + M_{1\,(AAm)} \longrightarrow RM^* \tag{2.12}$$

$$RM^* + M_{2\,(BIS)} \longrightarrow RM^* \tag{2.13}$$

Termination of inactive polymer

$$RM^* + RM^* \longrightarrow \text{inactive polymer} \tag{2.14}$$

After the formation of free radical species (H*, OH* and R*) due to radiolysis, free radical interactions with co-monomers (Eq. (2.8), (2.9) and (2.10)), result in breaking the double C=C bonds of co-monomers (M). The initiation of the polymerization process occurs via addition of free-radical fragments to the co-monomers presence in the solution (Eq. (2.11)). Thus the propagation results in the formation of high molecular weight copolymers (Eq. (2.12) and (2.13)). The growing copolymer radicals will become less accessible and possibly undergo slow reaction with co-monomer species, and eventually terminated (Eq. (2.14)) (Lepage *et al.* 2001c; Karlsson *et al.* 2007). The polymerization processes including radiolysis of water, gained from literature can be concluded in these steps.

The reaction between radical fragments and acrylamide monomer eventually lead to the formation of an insoluble polyacrylamide network in the gelatine matrix. Figure 2.4 shows the chemical structure of the monomer acrylamide, cross-linker BIS and polyacrylamide taken from Baldock *et al.* (1998). BIS, which has two vinyl groups tends to be consumed relatively more quickly than monomer of acrylamide, which has only one vinyl group (Jirasek *et al.* 2001; Lepage *et al.* 2001b). Polymer chains grow by propagation reaction involving both monomer and cross-linker until one of the co-monomer is consumed, or the active sides on the end of polymer chains are terminated. The polymer structures are kept in place by the gel matrix.

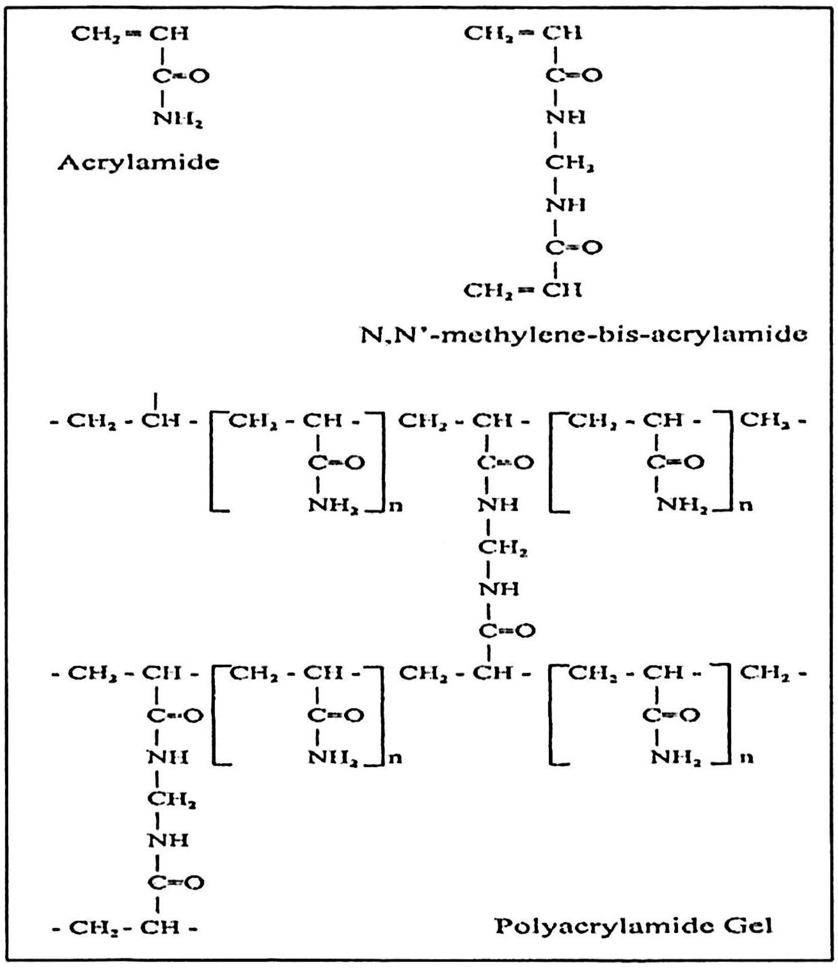

Figure 2.4: Chemical structure of acrylamide, *N,N'*-methylene-bisacrylamide and Polyacrylamide gel (PAG) (Baldock *et al.* 1998).

2.3.5 Oxygen concentration measurement of polymer gel dosimeters

Potentiometric oxygen measurements in solution provide an easy way to get the first impression on the rate of oxygen scavenging by the anti-oxidant used in the normoxic polymer gel dosimeters (De Deene *et al.* 2002).

De Deene *et al.* (2002) study the ability of ascorbic acid to bind oxygen in solutions containing AA, methacrylic acid and copper sulphate by using an oxygen probe. Tested chemicals were housed in an Erlenmeyer flask and the oxygen probe was inserted in the solution. It is found that the presence of methacrylic acid will slow down the rate of oxygen scavenging in the solution. Higher initial reading of oxygen concentration was due to the acidity of the solution caused by methacrylic acid. The higher degree of acidity is believed to have an influence on the redox couple of the oxygen probe. It is also found that the absence of copper will slow down the rate of oxygen scavenging. Several days is needed for the AA to fully scavenge all oxygen in the gel solutions.

Jirasek *et al.* (2006) illustrates the use of potentiometric oxygen meter to measure the differential rate of oxygen consumption when different amounts of THPC (2mM, 4.75 mM, 9.5 mM and 19 mM) are added to PAGAT. Pyrex beakers were used to house the gel solution. A purpose built acrylic lid was designed to seal the beakers while permitting the oxygen probe to be immersed in the PAGAT solutions. It is found that the higher the concentration of THPC added in the gel solutions, the greater the oxygen scavenging rates. Low amount of THPC (e.g 2 mM) cannot scavenge all the free oxygen present in the gel solutions. This will inhibit the polymerization as oxygen concentration below 0.02 mg/L is needed for polymerization to occur. Results also show that moderate amount of THPC (e.g 4.75 mM) was sufficient to scavenge all the free oxygen in the gel solutions.