ENHANCEMENT OF DOSE RESPONSE AND NUCLEAR MAGNETIC RESONANCE IMAGING OF PAGAT POLYMER GEL DOSIMETER BY SILVER AND PLATINUM NANOPARTICLES

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By

NAJMEH DEYHIMIHAGHIGHI

Thesis submitted to School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for Degree of Master of Science

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With great respect, I would like to dedicate my dissertation work to my family. A special feeling of gratitude to my loving parents, Mohammad Deyhimihaghighi and Marzieh Ameli, whose words of encouragement and push for tenacity ring in my ears, for all their love, sacrifices and faith. My sister, Maryam, has never left my side and is very special person for me.

I also dedicate this dissertation to the memory of my grandmothers for their blessfull prayers.

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Radiotherapy is a treatment technique used to inactivate cancerous cells using ionizing radiation, typically of high-energy photons or electrons beam, which are delivered to the tumor volume without destroying the healthy surrounding tissues. The absorbed dose distributions in tissue volume can be studied in three dimensions (3D) by using a soft tissue equivalent polymer gel dosimeter, which centers on polymerization of monomers induced by free radicals as a result of radiolysis of water by ionizing radiation. In the presence of metal nanoparticles, the dose sensitivity of a polymer gel may be improved, from which its 3D dose distribution of nuclear magnetic resonance imaging (MRI) can be used in radiotherapy treatment plans.

In the present study, the normoxic polyacrylamide gelatin and tetrakis hydroxy methyl phosphoniun chloride (PAGAT) (4.5% N, N′-methylen-bis-acrylamide (bis), 4.5% acrylamid (AA), 5% gelatine, 5 mM tetrakis (hydroxymethyl) phosphonium chloride (THPC), 0.01 mM hydroquinone (HQ) and 86% deionized water) polymer gel dosimeters were synthesized with and without the presence of silver (Ag) and platinum (Pt) nanoparticles. The Ag nanoparticles with average particle sizes of 20 nm and particle concentration of 3.14×10^{-2} mg/l and Pt nanoparticles with average particle sizes of 10 nm and particle concentration of 1×10^{-2} mg/l were synthesized by laser ablation method from their respective metals in distilled water. The concentration of metal nanoparticles were varied from 3.14×10^{-2} to 9.42×10^{-2} mg/l for Ag nanoparticles and 0.5×10^{-2} to 3×10^{-2} mg/l for Pt nanoparticles to form two types of PAGAT polymer gel dosimeters before irradiating with 6 to 25 Gy of 1.25-MeV ^{60}Co gamma rays. The predominant gamma rays interaction with matter is by Compton scattering effect as the photoelectric absorption effect is diminished.

MRI evaluated the polymerization of the dosimeters and the gray scale of the MRI film was determined using an optical densitometer. The results of optical densities demonstrate that the amount of polymerization increased with an increase in absorbed dose, while the increase of depth inside the dosimeters has a reverse effect. Moreover, it was found that there was a significant increase in the optical density-

dose responds by 27.10% for dosimeters adding with 1×10^{-2} mg/l Pt nanoparticles and by 11.82% for dosimeters with 6.28×10^{-2} mg/l Ag nanoparticles.

Abstrak tesis yang dikemukakan kepada senate Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENINGKATAN SAMBUTAN DOS DAN PENGIMEJAN RESONANS MAGNET NUKLEAR DOSIMETER GEL POLIMER PAGAT OLEH NANOPARTIKEL PERAK DAN PLATINUM

Oleh

NAJMEH DEYHIMIHAGHIGHI

Mei 2014

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Radioterapi adalah satu teknik rawatan yang digunakan untuk melumpuhkan aktiviti sel-sel kanser menggunakan sinaran mengion, biasanya daripada alur foton atau elektron bertenaga tinggi yang ditujukan kepada isipadu tumor tanpa memusnahkan tisu-tisu sekeliling yang sihat. Pengagihan dos diserap dalam isipadu tisu boleh dikaji dalam tiga dimensi (3D) dengan menggunakan dosimeter gel polimer bersifat setara dengan tisu lembut, yang tertumpu kepada pempolimeran monomer oleh radikal bebas akibat daripada radiolisis air oleh sinaran mengion. Kehadiran nanopartikel logam menyebabkan sensitiviti dos gel polimer boleh ditingkatkan, yang pengedaran dos 3D daripada resonans magnetik nuklear pengimejan (MRI) boleh digunakan dalam pelan rawatan radioterapi.

Dalam kajian ini, poliacrilamida gelatin normoxic dan tetrakis hidrolesil metil fosfonium klorida (PAGAT) (4.5% N, N□ bis-metilin-acrilamida (bis), 4.5% acrilamida (AA), 5% gelatin, 5 mM tetrakis (hidroksimetil) fosfonium klorida (THPC), hydroquinone (HQ) 0.01 mM dan 86% deionized air) polimer gel dosimeters telah disintesis dengan dan tanpa kehadiran nanopartikel argentum (Ag) dan platinum (Pt). Nanopartikel Ag dengan saiz zarah purata 20 nm dan ketumpatan zarah 3.14×10^{-2} mg/l dan nanopartikel Pt dengan saiz zarah purata 10 nm dan ketumpatan zarah 1×10^{-2} mg/l telah disintesis oleh kaedah laser ablasi daripada logam masing-masing di dalam air suling. Amaun nanopartikel digunakan adalah berbeza dari 3.14×10^{-2} hingga 9.42×10^{-2} mg/l bagi nanopartikel Ag dan dari 5 hingga 3×10^{-2} mg/l bagi nanopartikel Pt untuk membentuk dua jenis polimer gel dosimeter PAGAT sebelum penyinaran dengan dos dari 6 hingga 25 Gy oleh sinar gama ^{60}Co 1.25-MeV. Saling tindakan utama sinar gama dengan bahan ialah melalui saling tindakan serakan Compton dimana penyerapan fotoelektrik tidak memberi kesan.

Pempolimeran dosimeter diukur dengan MRI dan skala kelabu filem MRI ditentukan dengan menggunakan sebuah densitometer optik. Keputusan ketumpatan optik menunjukkan bahawa amaun pempolimeran meningkat dengan peningkatan dalam dos terserap, manakala pertambahan kedalaman di dalam dosimeter yang mempunyai kesan sebaliknya. Selain itu, didapati bahawa terdapat peningkatan ketara dalam tindakbalas ketumpatan optik-dos sebanyak 27.10% untuk dosimeter diisi dengan nanopartikel Pt 1×10^{-2} mg/l dan sebanyak 11.82% untuk dosimeter dengan nanopartikel Ag 6.28×10^{-2} mg/l.

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Najmeh Deyhimihaghighi

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirements for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AgNPs	Silver Nano Particles
AuNPs	Gold Nano Particles
a.u	Arbitrary unit
(AA)	Acrylamide
AAS	Atomic Absorption Spectroscopy
Bis	N, N′-methylene-bis-acrylamide
^{10}B	Boron-10
BNCT	Boron Neutron Capture Therapy
^{60}Co	Cobalt -60
^{137}CS	Cesium-137
CT	Computed Tomography
CTRx	Computerized Tomography scanner
^{12}C	Carbon-12
CPE	Charged Particle Equilibrium
DAA	Diacetone Acrylamide
DEF	Dose Effect Factor
FOV	Field Of View
FT raman	Fourier transform Raman spectroscopy
FID	Free-induction decay
Fe^{2+}	Ferrous ion
Fe^{3+}	Ferric ion
Gy	Gray
Hz	Hertz
HQ	Hydroquinone
^{131}I	Iodine-131
ICRU	International Commission on Radiological Units
^{192}Ir	Iridium-192
IMRT	Intensity Modulated Radiotherapy
LET	Linear Energy Transfer
LINAC	Linear Accelerator
MRI	Magnetic Resonance Imaging
^{60}Ni	Nicle-6-0
Nd: YAG	Neodymium-doped Yttrium Aluminum Garnet
NMR	Nuclear Magnetic Resonance
NPS	Nano Particles
NVF	N-vinyl formamide
PtNPs	Platinum Nano Particles
PVC	Polyvinyle Chloride
PVA	Polyvinyle Alcohol
OD	Optical Density
PDD	Percentage depth dose
PH	Power of Hydrogen
QA	Quality Assurance
RF	Radio Frequency
R_1	Relaxation Rate for T_1
R_2	Relaxation rate for T_2
SV	Sivert

SNR	**Signal to Noise Ratio**
SSD	**Source Sample Distance**
SRS/SR	**Stereotactic Radiosurgery**
SDS	**Sodium Dodecyl Sulfate**
SPR	**Surface Plasmon Resonance**
$AgNO_3$	**Silver nitrate**
SE	**Spin Echo**
THPC	**Tetrakis (Hydroxymethyl) Phosphonium Chloride**
T	**Tesla**
T1	**Longitudinal relaxation times**
T2	**Transverse relaxation times**
TEM	**Transmission Electron Microscope**
TR	**Repetition Time**
TE	**Echo Time**
TLD	**Thermoluminescence Dosimeter**
UV	**Ultra Violet**
UV-vis	**UV visible**
VP	**1-vinyle-2-pyrrolidinone**
XO	**Xylenol**
2D	**2 Dimension**
3D	**3 Dimension**

CHAPTER I

INTRODUCTION

1.1 Background of Study

1.1.1 Radiotherapy

Radiotherapy is a form of cancer treatment using high energy x-rays or gamma rays and electrons beam that are delivered to stop cancer cells from growing. The radiation beams affect the cells' ability to multiply. It can affect both cancer cells and normal tissues alike. The principal goal in radiotherapy is to deliver a determined dose to the tumor, although decrease the amount of dose that reaches normal tissues, which results in eliminating the diseased cells and improving the quality of life (Venning, 2005). There is an important stage of planning before irradiating cancerous cells. An x-ray machine and computerized tomography (CT) scanner are used to visualize the anatomical structure of the patient. These two methods give us a good overview of exact position of tumor in the body. In the radiotherapy treatment planning, parameters like tumor volume, distance of source to tumor volume, absorbed dose, and surrounding tissues are determined. With all this information, the planning computer program patterns the best position of treatment to deliver high doses to tumor and lowest amount to healthy tissue. For tumors that sit in deep, it is needed to manage several beams from different angles to obtain better result. Normally, one method to reduce the harmful effect of dose is to deliver the dose at several treatment times which is called 'fractional treatment', to give time for healthy tissues to recover and destroy cancerous cells. However, a rapid advancement in the field of dynamic treatment techniques such as stereotactic radiosurgery and intensity-modulated radiotherapy (IMRT) for treatment of cancer require 3D dose distribution (Maryanski, et al., 1992). Current dosimeters like thermoluminecent dosimeters (TLD) and radiographic film are able to achieve 1-D and 2-D doses, thus limiting the spatial resolution doses in 3D (Venning, 2005). In these limitations, polymer gel is a useful tool to measure dose in 3D and plays an important role. The amount of produced polymer inside the gel, allows a dose distribution in 3D form that can be visualized by MRI scan, and be used in radiotherapy treatment planning.

1.1.2 Polymer Gel Dosimeters

By knowing the energy of ionizing radiation and composition of materials, the absorbed dose may be calculated, which is basic information of dosimeters. A device

that indicates quantifiable and reproducible changes in physical or chemical properties is defined as dosimeter, which is related to dose delivered to material. The technique for measuring the radiation dose can be divided into the absolute method, which involves direct measurement of radiation dose such as calorimeters, ionizing chambers. And secondary method such as radio-chromatic dosimeter film, TLD, Fricke (ferrous sulfate) and polymer gel, which involves indirect measurements. Polymer gel along with MRI as mentioned before are the first 3D dose distribution dosimeter.

1.1.3 Nanoparticles in Treatment and Imaging

Applying high Z material as contrast agent in low energy x-ray is one of the raised concerns about risk in radiology procedure. As the bone is composed of high Z element, calcium, there is the same concern for it through radiologic process. High doses were reached to bone marrow when using kilo-voltage range x-rays. Increase in dose could be seen in situations where high Z materials like iodine are applied as contrast agent. Adams et al., (1977) showed the effect of ionization radiation combine with high Z element to chromosome aberration. It was observed that the presence of high Z material caused increase absorption of x-ray and thus increases the breakage of chromosome. The unpleasant effect in diagnosistic radiology can be used in radiotherapy desirably. It was proposed to load the tumor with high Z materials that cause an increase in the amount of dose delivered to the tumor, then this will allow maximum dose to be received by tumor and much less harm effect to healthy tissues.

Nanotechnology is a field involving chemistry, physics, biology and medicine, has predominant potential for early detection, diagnose accurately, and personalized treatment of cancer (Cai and Chen, 2007). Nanoparticle especially noble nanoparticles like silver (Ag), gold (Au), and platinum (Pt) nanoparticles are versatile agent with biomedical applications in the field of sensitive diagnostic experiment, radiotherapy enhancement, drug and gen delivery. They were proved to be non-toxic in gen and drug delivery applications. Characterization of nanoparticles and comparing them to their bulk material counterparts make them a significant choice to get a better result in different fields. In the field of radiotherapy, metal nanoparticles are studied because of their potential application in the enhancement of radiation dose regarding the treatment or improving the planning stage in determining the exact dose. Metal nanoparticles with high atomic number are noticed to be radiation dose enhancers. The metal, which is used, depends on the source. They can increase the photoelectric effect or Compton effect then increase the amount of dose that reaches the tumors. It uses in vivo in the tumors or utilize in dosimeter to make it more sensitive to dose. Radio-sensitization observed by several authors points out gold nanoparticles (AuNP) as the best candidates to be used as flagships of radionanotherapy (Hainfeld, et al., 2010; Herold M, et al., 2000; Jones, et al., 2010; Rahman, 2010; Zhang, et al., 2009). From dosimetric point of view, the use of Au nanoparticles in radiotherapy was motivated by the fact, that probability of photoelectric increases due to the presence of high Z (Au□79) material inside the

polymer gels and hence increases the absorbed dose (Marques, et al., 2010). Ag and Au nanoparticles have attracted immense attention because of their potential application in different fields such as chemical and biochemical sensing, biological imaging, medical diagnostic and therapeutic. These two nanoparticles have great optical properties due to excellent Surface Plasmon Resonance (SPR) (Lee and El-Sayed, 2006). Thus, in this current research, Ag nanoparticles were embedded in PAGAT polymer gel dosimeter and irradiated with gamma ray (γ-ray) to investigate the characteristic dosimerty of Ag nanoparticles as the particle, which have the same specifications as Au. Also, Porcel et al. (2010) studied Pt nanoparticles as radiation sensitizer in radiotherapy cancer treatment which Pt nanoparticles count as high Z element (78) and it shows great enhancement of biological efficiency of radiation and increase the lethal dose to kill DNA in cancerous cell. Therefore, Pt nanoparticles were also used as another enhancer in this research with PAGAT polymer gel for dosimetry application.

1.2 Problem Statement

Gel dosimeter is a method, which can measure absorbed dose in 3D with high spatial resolution. Moreover, the initial aim of studying polymer gel is to prepare more effective device to detect the absorbed dose in 3D with high dose resolution so that it will be possible to map two doses with slight differences accurately (Lepage, et al., 2001a). As the polymer gels are tissue equivalent, it can be utilized as phantom of body to investigate the effect of metal nanoparticles as dose enhancer and increase the contrast in MRI. Au nanoparticles as dose enhancer were studied by several authors and were found to be excellent particles for reaching this aim. But growing requirement in this field leads to the investigation of other metal nanoparticles to enhance the dose and measurement of 3D dose distribution more accurately with lower price, which can be used as contrast agent in radiology, dose enhancer in radiotherapy and dosimetry of the ionizing radiation.

1.3 Significant of Study

Gel dosimeter is always considered as the best dosimeter for measuring 3D dose distribution .The first step to synthesize this kind of dosimeters easily and then use it widely is to prepare them on normal atmosphere, which is called normoxic. After that it is studied to increase the sensitivity of the polymer gel by adding some kind of

metal nanoparticles like gold (Au). It can make them more accurate. As the polymer gels are tissue equivalent, they can be used as a phantom to assess the effect of dose in the presence of nanoparticles inside the body so as to increase the effect of dose in treatment in radiotherapy. The significant of this study is to establish two types of metal nanoparticles (silver and platinum) inside the polymer gel, which can increase the dose in body tissue and raise the contrast in MRI.

1.4 Objective of Study

The primary purpose of this study is to improve the sensitivity of polymer gel to enhance the contrast in MRI and measure the dose in 3D more accurately by adding silver and platinum nanoparticles. If these two particles can enhance the dose, it can be used in radiotherapy for treatment. More details of investigation are presented as below:

1. Synthesized PAGAT polymer gel using the Venning method and synthesized Pt and Ag nanoparticles by laser ablation method.

2. Investigation of 3D dose distribution of PAGAT polymer gel dosimeter using different concentrations of Ag and Pt nanoparticles as contrast agent for enhancing gray scales of MRI images of the radio-sensitive polymer gel for use in radiotherapy treatment planning.

3. Investigation of dose with depth in presence of Ag and Pt nanoparticles.

1.5 Outline of the Thesis

The structure of this thesis is divided into six chapters. Chapter I, deals with general introduction about research background, objectives of study, problem statement and significant of study. Chapter II, focuses on the history of polymer gel dosimetry and related literature in view of metal nanoparticles, which apply in radiotherapy treatment and dosimetric point of view. The general theory of interaction of ionizing radiation with matter, mechanism of polymerization of polymer gel dosimeter, properties of platinum and silver and general physics in Magnetic resonance imaging (MRI) are explained in chapter III. The methodology of study including materials, the experimental methods to prepare the samples are described in chapter IV. The major part of this thesis is in chapter V, which presented the result of experiment, analyzed and discussed. Chapter VI depicted the conclusion including a brief summary and suggested future work.

REFERENCES

Abou El-Nour, K.M., Eftaiha, A., Al-Warthan, A., Ammar, R.A. (2010). Synthesis and applications of silver nanoparticles. *Arabian journal of chemistry, 3, 135-140.*

Adams, F.H., Norman, A., Mello, R.S., Bass, D. (1977). Effect of Radiation and Contrast Media on Chromosomes Preliminary Report. *Radiology, 124, 823-826.*

Ahmadi, T.S., Wang, Z.L., Green, T.C., Henglein, A., El-Sayed, M.A. (1996). Shape-controlled synthesis of colloidal platinum nanoparticles. *Science-New York then Washington1924-1925.*

Akhlaghpoor, S., Zahmatkesh, M., Pourbeigi, H. (2003). 3D MRI gel dosimetry based on image intensity (A new approach). *Iranian Journal of Radiation Research, 1, 45-50.*

Alexander, P., Charlesby, A., Ross, M. (1954). The degradation of solid polymethylmethacrylate by ionizing radiation. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 223, 392-404.*

Aljamal, M.A.M. (2008). Magic polymer gel dosimetry using x-ray computed tomography : a feasibility study. *Universiti Sains Malaysia*.

Andrews, H.L., Murphy, R.E., LeBrun, E.J. (1957). Gel Dosimeter for Depth ‐ Dose Measurements. *Review of Scientific Instruments, 28, 329-332.*

Audet, C., Hilts, M., Jirasek, A., Duzenli, C. (2002). CT gel dosimetry technique: Comparison of a planned and measured 3D stereotactic dose volume. *Journal of Applied Clinical Medical Physics, 3, 110-118.*

Azadbakht, B., Adinehvand, K. (2011). Determination of Percentage Depth Dose (Pdd) of Pagat Gel Dosimeter By Electron Beams. *Australian Journal of Basic and Applied Sciences, 5, 2306-2310.*

Azadbakht, B., Adinehvand, K. (2012). Investigation of the Post Time Dependence of PAGAT Gel Dosimeter by Electron Beams using MRI Technique. *Research Journal of Applied Sciences, 4.*

Azadbakht, B., Hadad, K., Zahmatkesh, M. (2009). Response verification of dose rate and time dependence of PAGAT polymer gel dosimeters by photon beams using magnetic resonance imaging. Paper presented at the *Journal of Physics: Conference Series*.

Baldock, C. (2006). Historical overview of the development of gel dosimetry: a personal perspective. Paper presented at the *Journal of Physics: Conference Series*.

Baldock, C., Burford, R., Billingham, N., Wagner, G., Patval, S., Badawi, R., Keevil, S. (1998a). Experimental procedure for the manufacture and calibration of polyacrylamide gel (PAG) for magnetic resonance imaging (MRI) radiation dosimetry. *Physics in medicine and biology, 43, 695.*

Baldock, C., De Deene, Y., Doran, S., Ibbott, G., Jirasek, A., Lepage, M., McAuley, K., Oldham, M., Schreiner, L. (2010). Polymer gel dosimetry. *Physics in medicine and biology, 55, R1.*

Baldock, C., Harris, P., Piercy, A., Healy, B. (2001). Experimental determination of the diffusion coefficient in two-dimensions in ferrous sulphate gels using the finite element method. *Australasian Physics & Engineering Sciences in Medicine, 24, 19-30.*

Baldock, C., Rintoul, L., Keevil, S., Pope, J., George, G. (1998b). Fourier transform Raman spectroscopy of polyacrylamide gels (PAGs) for radiation dosimetry. *Physics in medicine and biology, 43, 3617.*

Becker, M., Brock, J., Cai, H., Henneke, D., Keto, J., Lee, J., Nichols, W., Glicksman, H. (1998). Metal nanoparticles generated by laser ablation. *Nanostructured materials, 10, 853-863.*

Berg, A. (2009). Magnetic-Resonance-Imaging Based Polymer Gel Dosimetry: Methodology, Spatial Resolution, Applications. Paper presented at the *World Congress on Medical Physics and Biomedical Engineering, September 7-12, 2009, Munich, Germany*.

Boni, A. (1961). A polyacrylamide gamma dosimeter. *Radiation Research, 14, 374-380.*

Bonnett, D. (2001). Applications of polymer gel dosimetry. *Dosgel, 2001, 40.*

Boudou, C., Troprès, I., Estève, F., Elleaume, H. (2006). Preliminary study of a normoxic polyacrylamide gel doped with iodine. Paper presented at the *Journal of Physics: Conference Series*.

Boudou, C., Troprès, I., Rousseau, J., Lamalle, L., Adam, J.-F., Estève, F., Elleaume, H. (2007). Polymer gel dosimetry for synchrotron stereotactic radiotherapy and iodine dose-enhancement measurements. *Physics in medicine and biology, 52, 4881.*

Brindha, S., Venning, A., Hill, B., Baldock, C. (2004). Experimental study of attenuation properties of normoxic polymer gel dosimeters. *Physics in medicine and biology, 49, N353.*

Bronskill, M.J., Sprawls, P. (1993). The physics of MRI. *The American Institute of Physics, Inc., Woodbury.*

Bushberg, J.T., Boone, J.M. (2011). The essential physics of medical imaging (*Third, North American Edition ed.*)*: Lippincott Williams & Wilkins.*

Cai, W., Chen, X. (2007). Nanoplatforms for targeted molecular imaging in living subjects. *Small, 3, 1840-1854.*

Callister, W. (2003). Materials Science and Engineering an Introduction (*6th ed.*)*: New York : John Wiley & Sons.*

Caro, C., Castillo, P.M., Klippstein, R., Pozo, D., Zaderenko, A.P. (2010). Silver nanoparticles: sensing and imaging applications. *Silver nanoparticles.*

Caseiras, G.D.B. (2008). The use of conventional and advanced magnetic resonance techniques in the assessment of primary brain tumours. *UCL (University College London)*.

Chen, Y.-H., Yeh, C.-S. (2002). Laser ablation method: use of surfactants to form the dispersed Ag nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 197, 133-139.*

Cho, S.H. (2005). Estimation of tumour dose enhancement due to gold nanoparticles during typical radiation treatments: a preliminary Monte Carlo study. *Physics in medicine and biology, 50, N163.*

Cho, S.H., Jones, B.L., Krishnan, S. (2009). The dosimetric feasibility of gold nanoparticle-aided radiation therapy (GNRT) via brachytherapy using low-energy gamma-/x-ray sources. *Physics in medicine and biology, 54, 4889.*

Cosgrove, V., Murphy, P., McJury, M., Adams, E., Warrington, A., Leach, M., Webb, S. (2000). The reproducibility of polyacrylamide gel dosimetry applied to

stereotactic conformal radiotherapy. *Physics in medicine and biology, 45, 1195.*
Courbon F, Caselles O, Ibarrola D, Francois P, Bonnet J , I, B. (1999). Internal dosimetry using magnetic resonance imaging of polymer gel irradiated with iodine-131. Preliminary results. *DOSGEL199.*
Crescenti, R.A., Bamber, J.C., Partridge, M., Bush, N.L., Webb, S. (2007). Characterization of the ultrasonic attenuation coefficient and its frequency dependence in a polymer gel dosimeter. *Physics in medicine and biology, 52, 6747.*
Cueto, M., Sanz, M., Oujja, M., Gámez, F., Martínez– Haya, B., Castillejo, M. (2011). Platinum Nanoparticles Prepared by Laser Ablation in Aqueous Solutions: Fabrication and Application to Laser Desorption Ionization. *The Journal of Physical Chemistry C, 115, 22217-22224.*
Das, I.J. (1997). Forward dose perturbation at high atomic number interfaces in kilovoltage x-ray beams. *Medical physics, 24, 1781.*
Das, I.J., Chopra, K.L. (1995). Backscatter dose perturbation in kilovoltage photon beams at high atomic number interfaces. *Medical physics, 22, 767.*
Day, M., Stein, G. (1950). Chemical effects of ionizing radiation in some gels. *Nature 166, 146-147.*
De Deene, Y. (2004). Essential characteristics of polymer gel dosimeters. Paper presented at the *Journal of Physics: Conference Series*.
De Deene, Y., Baldock, C. (2002). Optimization of multiple spin–echo sequences for 3D polymer gel dosimetry. *Physics in medicine and biology, 47, 3117.*
De Deene, Y., De Wagter, C. (2001). Artefacts in multi-echo T2 imaging for high-precision gel dosimetry: III. Effects of temperature drift during scanning. *Physics in medicine and biology, 46, 2697.*
De Deene, Y., De Wagter, C., Van Duyse, B., Derycke, S., De Neve, W., Achten, E. (1998). Three-dimensional dosimetry using polymer gel and magnetic resonance imaging applied to the verification of conformal radiation therapy in head-and-neck cancer. *Radiotherapy and Oncology, 48, 283-291.*
De Deene, Y., De Wagter, C., Van Duyse, B., Derycke, S., Mersseman, B., De Gersem, W., Voet, T., Achten, E., De Neve, W. (2000a). Validation of MR‐based polymer gel dosimetry as a preclinical three‐dimensional verification tool in conformal radiotherapy. *Magnetic resonance in medicine, 43, 116-125.*
De Deene, Y., Hanselaer, P., De Wagter, C., Achten, E., De Neve, W. (2000b). An investigation of the chemical stability of a monomer/polymer gel dosimeter. *Physics in medicine and biology, 45, 859.*
De Deene, Y., Hurley, C., Venning, A., Vergote, K., Mather, M., Healy, B., Baldock, C. (2002a). A basic study of some normoxic polymer gel dosimeters. *Physics in medicine and biology, 47, 3441.*
De Deene, Y., Pittomvils, G., Visalatchi, S. (2007). The influence of cooling rate on the accuracy of normoxic polymer gel dosimeters. *Physics in medicine and biology, 52, 2719.*
De Deene, Y., Venning, A., Hurley, C., Healy, B., Baldock, C. (2002b). Dose–response stability and integrity of the dose distribution of various polymer gel dosimeters. *Physics in medicine and biology, 47, 2459.*

De Deene, Y., Vergote, K., Claeys, C., De Wagter, C. (2006). The fundamental radiation properties of normoxic polymer gel dosimeters: a comparison between a methacrylic acid based gel and acrylamide based gels. *Physics in medicine and biology, 51, 653.*

De Wagter, C. (2004). The ideal dosimeter for intensity modulated radiation therapy (IMRT): What is required? Paper presented at the *Journal of Physics: Conference Series*.

Del Gado, E., de Arcangelis, L., Coniglio, A. (1998). A percolation dynamic approach to the sol-gel transition. *Journal of Physics A: Mathematical and General, 31, 1901.*

Dolgaev, S., Simakin, A., Voronov, V., Shafeev, G., Bozon-Verduraz, F. (2002). Nanoparticles produced by laser ablation of solids in liquid environment. *Applied surface science, 186, 546-551.*

Duthoy, W., De Gersem, W., Vergote, K., Boterberg, T., Derie, C., Smeets, P., De Wagter, C., De Neve, W. (2004). Clinical implementation of intensity-modulated arc therapy (IMAT) for rectal cancer. *International Journal of Radiation Oncology* Biology* Physics, 60, 794-806.*

Duthoy, W., De Gersem, W., Vergote, K., Coghe, M., Boterberg, T., De Deene, Y., De Wagter, C., Van Belle, S., De Neve, W. (2003). Whole abdominopelvic radiotherapy (WAPRT) using intensity-modulated arc therapy (IMAT): first clinical experience. *International Journal of Radiation Oncology* Biology* Physics, 57, 1019-1032.*

Eliassaf, J., Silberberg, A., Katchalsky, A. (1955). Negative thixotropy of aqueous solutions of polymethacrylic acid. *Nature, 176, 1119.*

Ertl, A., Berg, A., Zehetmayer, M., Frigo, P. (2000). High-resolution dose profile studies based on MR Imaging with polymer BANG< sup> TM</sup> gels in stereotactic radiation techniques. *Magnetic resonance imaging, 18, 343-349.*

Ertl, H.H., Feinendegen, L.E., Heiniger, H. (1970). Iodine-125, a tracer in cell biology: physical properties and biological aspects. *Physics in medicine and biology, 15, 447.*

Evans, R.D. (1972). Gamma rays. *Chap. 8e in "American Institute of Physics Handbook", 3rd Ed., McGraw–Hill.*

Farajollahi, A., Bonnett, D., Ratcliffe, A., Aukett, R., Mills, J. (1999). An investigation into the use of polymer gel dosimetry in low dose rate brachytherapy. *British Journal of Radiology, 72, 1085-1092.*

Farajollahi, A., Bonnett, D., Tattam, D., Green, S. (2000). The potential use of polymer gel dosimetry in boron neutron capture therapy. *Physics in medicine and biology, 45, N9.*

Fong, P.M., Keil, D.C., Does, M.D., Gore, J.C. (2001). Polymer gels for magnetic resonance imaging of radiation dose distributions at normal room atmosphere. *Physics in medicine and biology, 46, 3105.*

Fukushima, E. (1989). NMR in biomedicine: the physical basis*: Springer.*

Funaro, M., Di Bartolomeo, A., Pelosi, P., Saponetti, M.S., Proto, A. (2011). Dosimeter based on silver-nanoparticle precursors for medical applications with linear response over a wide dynamic range. *Micro & Nano Letters, IET, 6, 759-762.*

Garnica-Garza, H. (2009). Contrast-enhanced radiotherapy: feasibility and characteristics of the physical absorbed dose distribution for deep-seated tumors. *Physics in medicine and biology, 54, 5411.*

Gore, J., Kang, Y. (1984). Measurement of radiation dose distributions by nuclear magnetic resonance (NMR) imaging. *Physics in medicine and biology, 29, 1189.*

Gore, J., Ranade, M., Maryanski, M., Schulz, R. (1996). Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: I. Development of an optical scanner. *Physics in medicine and biology, 41, 2695.*

Grebe, G., Pfaender, M., Roll, M., Luedemann, L. (2001). Dynamic arc radiosurgery and radiotherapy: commissioning and verification of dose distributions. *International Journal of Radiation Oncology* Biology* Physics, 49, 1451-1460.*

Gustavsson, H., Bäck, S.Å.J., Lepage, M., Rintoul, L., Baldock, C. (2004a). Development and optimization of a 2-hydroxyethylacrylate MRI polymer gel dosimeter. *Physics in medicine and biology, 49, 227.*

Gustavsson, H., Bäck, S.Å.J., Medin, J., Grusell, E., Olsson, L.E. (2004b). Linear energy transfer dependence of a normoxic polymer gel dosimeter investigated using proton beam absorbed dose measurements. *Physics in medicine and biology, 49, 3847.*

Gustavsson, H., Karlsson, A., Bäck, S.Å., Olsson, L.E., Haraldsson, P., Engström, P., Nyström, H. (2003). MAGIC-type polymer gel for three-dimensional dosimetry: Intensity-modulated radiation therapy verification. *Medical physics, 30, 1264.*

Haas O C L, Mills J A , Burnham K J, Bonnett D E, Farajollahi A R , Fisher M H, Glendinning A G, J, A.R. (1997). Experimental verification of beam intensity modulated conformal radiotherapy using patient specific compensators. *British Journal of Radiology, 70.*

Hadnagy, W., Stephan, G., Kossel, F. (1982). Enhanced yield of chromosomal aberrations in human peripheral lymphocytes in vitro using contrast media in X-irradiation. *Mutation Research Letters, 104, 249-254.*

Hainfeld, J., Slatkin, D., Focella, T., Smilowitz, H. (2006). Gold nanoparticles: a new X-ray contrast agent. *British Journal of Radiology, 79, 248-253.*

Hainfeld, J.F., Dilmanian, F.A., Zhong, Z., Slatkin, D.N., Kalef-Ezra, J.A., Smilowitz, H.M. (2010). Gold nanoparticles enhance the radiation therapy of a murine squamous cell carcinoma. *Physics in medicine and biology, 55, 3045.*

Hainfeld, J.F., Slatkin, D.N., Smilowitz, H.M. (2004). The use of gold nanoparticles to enhance radiotherapy in mice. *Physics in medicine and biology, 49, N309.*

Haraldsson, P., Bäck, S., Magnusson, P., Olsson, L. (2000). Dose response characteristics and basic dose distribution data for a polymerization-based dosemeter gel evaluated using MR. *British Journal of Radiology, 73, 58-65.*

Haraldsson, P., Karlsson, A., Wieslander, E., Gustavsson, H., Bäck, S.Å.J. (2006). Dose response evaluation of a low-density normoxic polymer gel dosimeter using MRI. *Physics in medicine and biology, 51, 919.*

Hashemi, R.H., Bradley, W.G., Lisanti, C.J. (2004). MRI: the basics (*2nd ed.*)*: Wolters Kluwer Health.*

Herold M, Das IJ , Stobbe CC, Iyer RV, JD, C. (2000). Gold microspheres: a selective technique for producing biologically effective dose enhancement. *International journal of radiation biology, 76, 1357-1364.*

Hill, B., Venning, A.J., Baldock, C. (2005). A preliminary study of the novel application of normoxic polymer gel dosimeters for the measurement of CTDI on diagnostic x-ray CT scanners. *Medical physics, 32, 1589.*

Hilts, M., Audet, C., Duzenli, C., Jirasek, A. (2000). Polymer gel dosimetry using x-ray computed tomography: a feasibility study. *Physics in medicine and biology, 45, 2559.*

Hilts, M., Duzenli, C. (2004). Image filtering for improved dose resolution in CT polymer gel dosimetry. *Medical physics, 31, 39.*

Hilts, M., Jirasek, A., Duzenli, C. (2005). Technical considerations for implementation of x-ray CT polymer gel dosimetry. *Physics in medicine and biology, 50, 1727.*

Hoecker, F.E., Watkins, I. (1958). Radiation polymerization dosimetry. *The International journal of applied radiation and isotopes, 3, 31-35.*

Hornak, J.P. (1996). The basics of MRI: JP Hornak.

Hrbacek, J., Spevacek, V., Novotny Jr, J., Cechak, T. (2004). A comparative study of four polymer gel dosimeters. Paper presented at the *Journal of Physics Conference Series*.

Huang, H., Sorensen, C. (1996). Shear effects during the gelation of aqueous gelatin. *Physical Review E, 53, 5075.*

Hurley, C., Venning, A., Baldock, C. (2005). A study of a normoxic polymer gel dosimeter comprising methacrylic acid, gelatin and tetrakis (hydroxymethyl) phosphonium chloride (MAGAT). *Applied Radiation and Isotopes, 63, 443-456.*

Ibbott, G.S. (2004). Applications of gel dosimetry. Paper presented at the *Journal of Physics: conference series*.

Ibbott, G.S., Maryanski, M.J., Eastman, P., Holcomb, S.D., Zhang, Y., Avison, R.G., Sanders, M., Gore, J.C. (1997). Three-dimensional visualization and measurement of conformal dose distributions using magnetic resonance imaging of BANG polymer gel dosimeters. *International Journal of Radiation Oncology* Biology* Physics, 38, 1097-1103.*

Jirasek, A., Duzenli, C. (2001). Effects of crosslinker fraction in polymer gel dosimeters using FT Raman spectroscopy. *Physics in medicine and biology, 46, 1949.*

Jirasek, A., Duzenli, C. (2002). Relative effectiveness of polyacrylamide gel dosimeters applied to proton beams: Fourier transform Raman observations and track structure calculations. *Medical physics, 29, 569.*

Jirasek, A., Hilts, M., Berman, A., McAuley, K. (2009). Effects of glycerol co-solvent on the rate and form of polymer gel dose response. *Physics in medicine and biology, 54, 907.*

Jirasek, A., Hilts, M., Shaw, C., Baxter, P. (2006). Investigation of tetrakis hydroxymethyl phosphonium chloride as an antioxidant for use in x-ray computed tomography polyacrylamide gel dosimetry. *Physics in medicine and biology, 51, 1891.*

Jones, B.L., Krishnan, S., Cho, S.H. (2010). Estimation of microscopic dose enhancement factor around gold nanoparticles by Monte Carlo calculations. *Medical physics, 37, 3809.*

Kamat, P.V. (2002). Photophysical, photochemical and photocatalytic aspects of metal nanoparticles. *The Journal of Physical Chemistry B, 106, 7729-7744.*

Karaiskos, P., Petrokokkinos, L., Tatsis, E., Angelopoulos, A., Baras, P., Kozicki, M., Papagiannis, P., Rosiak, J., Sakelliou, L., et al. (2005). Dose verification of single shot gamma knife applications using VIPAR polymer gel and MRI. *Physics in medicine and biology, 50, 1235.*

Karlsson, A., Gustavsson, H., Månsson, S., McAuley, K.B., Bäck, S.Å.J. (2007). Dose integration characteristics in normoxic polymer gel dosimetry investigated using sequential beam irradiation. *Physics in medicine and biology, 52, 4697.*

Kaurin D G l, Maryanski M J, Duggan D M, Morton K C, W, C.C. (1999). Use of polymer gel dosimetry, pelvic phantom and virtual simulation to verify setup and calculated three-dimensional dose distribution for a prostate treatment. *DOSGEL184.*

Kawasaki, M., Nishimura, N. (2006). 1064-nm laser fragmentation of thin Au and Ag flakes in acetone for highly productive pathway to stable metal nanoparticles. *Applied surface science, 253, 2208-2216.*

Kazakevich, P., Simakin, A., Shafeev, G., Viau, G., Soumare, Y., Bozon-Verduraz, F. (2007). Laser-assisted shape selective fragmentation of nanoparticles. *Applied surface science, 253, 7831-7834.*

Kennan, R.P., Richardson, K.A., Zhong, J., Maryanski, M.J., Gore, J.C. (1996). The effects of cross-link density and chemical exchange on magnetization transfer in polyacrylamide gels. *Journal of Magnetic Resonance, Series B, 110, 267-277.*

Khan, F.M. (2003). The physics of radiation therapy (*Vol. 3*)*: Lippincott Williams & Wilkins Philadelphia.*

King, S., Spiers, F. (1985). Photoelectron enhancement of the absorbed dose from X rays to human bone marrow: experimental and theoretical studies. *British Journal of Radiology, 58, 345-356.*

Kraft, G. (2000). Tumortherapy with ion beams. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 454, 1-10.*

Krutyakov, Y.A., Kudrinskiy, A.A., Olenin, A.Y., Lisichkin, G.V. (2008). Synthesis and properties of silver nanoparticles: advances and prospects. *Russian Chemical Reviews, 77, 233-257.*

Lee, K.-S., El-Sayed, M.A. (2006). Gold and silver nanoparticles in sensing and imaging: sensitivity of plasmon response to size, shape, and metal composition. *The Journal of Physical Chemistry B, 110, 19220-19225.*

Lepage, M. (2006). Magnetic resonance in polymer gel dosimetry: techniques and optimization. Paper presented at the *Journal of Physics: Conference Series*.

Lepage, M., Jayasakera, P., Bäck, S.Å.J., Baldock, C. (2001a). Dose resolution optimization of polymer gel dosimeters using different monomers. *Physics in medicine and biology, 46, 2665.*

Lepage, M., Whittaker, A., Rintoul, L., Baldock, C. (2001b). 13C ‐ NMR, 1H ‐ NMR, and FT ‐ Raman study of radiation ‐ induced modifications in radiation dosimetry polymer gels. *Journal of applied polymer science, 79, 1572-1581.*

Lepage, M., Whittaker, A.K., Rintoul, L., Bäck, S.Å.J., Baldock, C. (2001c). The relationship between radiation-induced chemical processes and transverse relaxation times in polymer gel dosimeters. *Physics in medicine and biology, 46, 1061.*

Love, P., Evans, P., Leach, M., Webb, S. (2003). Polymer gel measurement of dose homogeneity in the breast: comparing MLC intensity modulation with standard wedged delivery. *Physics in medicine and biology, 48, 1065.*

Low, D.A., Dempsey, J.F., Venkatesan, R., Mutic, S., Markman, J., Haacke, E.M., Purdy, J.A. (1999). Evaluation of polymer gels and MRI as a 3-D dosimeter for intensity-modulated radiation therapy. *Medical physics, 26, 1542.*

Mackie, A., Gunning, A., Ridout, M., Morris, V. (1998). Gelation of gelatin observation in the bulk and at the air - water interface. *Biopolymers, 46, 245-252.*

Mackiewich, B. (1995). Intracranial boundary detection and radio frequency correction in magnetic resonance images. *Citeseer*.

Mafune, F., Kohno, J.-y., Takeda, Y., Kondow, T. (2003). Formation of stable platinum nanoparticles by laser ablation in water. *The Journal of Physical Chemistry B, 107, 4218-4223.*

Mafune, F., Kohno, J.-y., Takeda, Y., Kondow, T., Sawabe, H. (2000a). Formation and size control of silver nanoparticles by laser ablation in aqueous solution. *The Journal of Physical Chemistry B, 104, 9111-9117.*

Mafune, F., Kohno, J.-y., Takeda, Y., Kondow, T., Sawabe, H. (2000b). Structure and stability of silver nanoparticles in aqueous solution produced by laser ablation. *The Journal of Physical Chemistry B, 104, 8333-8337.*

Mafune, F., Kohno, J.-y., Takeda, Y., Kondow, T., Sawabe, H. (2001). Formation of gold nanoparticles by laser ablation in aqueous solution of surfactant. *The Journal of Physical Chemistry B, 105, 5114-5120.*

Mahfouz, R., Cadete Santos Aires, F., Brenier, A., Jacquier, B., Bertolini, J. (2008). Synthesis and physico-chemical characteristics of nanosized particles produced by laser ablation of a nickel target in water. *Applied surface science, 254, 5181-5190.*

Maquet, J., Theveneau, H., Djabourov, M., Leblond, J., Papon, P. (1986). State of water in gelatin solutions and gels: An< sup> 1</sup> H nmr investigation. *Polymer, 27, 1103-1110.*

Marques, T., Schwarcke, M., Garrido, C., Zucolot, V., Baffa, O., Nicolucci, P. (2010). Gel Dosimetry Analysis of Gold Nanoparticle Application in Kilovoltage Radiation Therapy. Paper presented at the *Journal of Physics: Conference Series*.

Maryanski, M., Audet, C., Gore, J. (1997). Effects of crosslinking and temperature on the dose response of a BANG polymer gel dosimeter. *Physics in medicine and biology, 42, 303.*

Maryanski, M., Gore, J., Schulz, R. (1992). 3-D radiation dosimetry by MRI: solvent proton relaxation enhancement by radiation-controlled polymerisation and cross-linking in gels. *Proc. Int. Soc. for Magnetic Resonance in Medicine (New York).*

Maryanski, M., Gore, J., Schulz, R. (1994a). Three-dimensional detection, dosimetry and imaging of an energy field by formation of a polymer in a gel: Google Patents.

Maryanski, M., Schulz, R., Gore, J., Koehler, A., Mayo, C. (1994b). Three dimensional dose distributions for 160 MeV protons using MRI of the tissue-equivalent BANG polymer-gel. *Particles (PTCOG) Newsletters 10.*

Maryanski, M., Schulz, R., Ibbott, G., Gatenby, J., Xie, J., Horton, D., Gore, J. (1994c). Magnetic resonance imaging of radiation dose distributions using a polymer-gel dosimeter. *Physics in medicine and biology, 39, 1437.*

Maryanski, M.J., Gore, J.C., Kennan, R.P., Schulz, R.J. (1993). NMR relaxation enhancement in gels polymerized and cross-linked by ionizing radiation: a new approach to 3D dosimetry by MRI. *Magnetic resonance imaging, 11, 253-258.*

Mather, M.L., Charles, P.H., Baldock, C. (2003). Measurement of ultrasonic attenuation coefficient in polymer gel dosimeters. *Physics in medicine and biology, 48, N269.*

Mather, M.L., De Deene, Y., Whittaker, A.K., Simon, G.P., Rutgers, R., Baldock, C. (2002a). Investigation of ultrasonic properties of PAG and MAGIC polymer gel dosimeters. *Physics in medicine and biology, 47, 4397.*

Mather, M.L., Whittaker, A.K., Baldock, C. (2002b). Ultrasound evaluation of polymer gel dosimeters. *Physics in medicine and biology, 47, 1449.*

Matsubara, S., Suzuki, S., Suzuki, H., Kuwabara, Y., Okano, T. (1982). Effects of contrast medium on radiation-induced chromosome aberrations. *Radiology, 144, 295-301.*

McJury, M., Oldham, M., Leach, M., Webb, S. (1999a). Dynamics of polymerization in polyacrylamide gel (PAG) dosimeters:(I) ageing and long-term stability. *Physics in medicine and biology, 44, 1863.*

McJury, M., Tapper, P., Cosgrove, V., Murphy, P., Griffin, S., Leach, M., Webb, S., Oldham, M. (1999b). Experimental 3D dosimetry around a high-dose-rate clinical 192Ir source using a polyacrylamide gel (PAG) dosimeter. *Physics in medicine and biology, 44, 2431.*

McMahon, S.J., Mendenhall, M.H., Jain, S., Currell, F. (2008). Radiotherapy in the presence of contrast agents: a general figure of merit and its application to gold nanoparticles. *Physics in medicine and biology, 53, 5635.*

McNaught, A.D., Wilkinson, A. (1997). Compendium of chemical terminology (*Vol. 1669*)*: Blackwell Science Oxford.*

McPherson, J. (2013). Pair-Production Retrieved 7 january 2014, 2013, from **http://www.showme.com/sh/□h□zIK27Zw**

Meesat, R., Jay-Gerin, J.-P., Khalil, A., Lepage, M. (2009). Evaluation of the dose enhancement of iodinated compounds by polyacrylamide gel dosimetry. *Physics in medicine and biology, 54, 5909.*

Mello, R.S., Callisen, H., Winter, J., Kagan, A.R., Norman, A. (1983). Radiation dose enhancement in tumors with iodine. *Medical physics, 10, 75.*

Mesbahi, A., Jafarzadeh, V., Gharehaghaji, N. (2012). Optical and NMR dose response of N-isopropylacrylamide normoxic polymer gel for radiation therapy dosimetry. *Reports of Practical Oncology & Radiotherapy, 17, 146-150.*

Morones, J.R., Elechiguerra, J.L., Camacho, A., Holt, K., Kouri, J.B., Ramírez, J.T., Yacaman, M.J. (2005). The bactericidal effect of silver nanoparticles. *Nanotechnology, 16, 2346.*

Morris, K.N., Weil, M.D., Malzbender, R. (2006). Radiochromic film dosimetry of contrast-enhanced radiotherapy (CERT). *Physics in medicine and biology, 51, 5915.*

Neddersen, J., Chumanov, G., Cotton, T.M. (1993). Laser ablation of metals: a new method for preparing SERS active colloids. *Applied spectroscopy, 47, 1959-1964.*

Nichols, W.T., Sasaki, T., Koshizaki, N. (2006). Laser ablation of a platinum target in water. II. Ablation rate and nanoparticle size distributions. *Journal of applied physics, 100, 114912-114912-114916.*

Norman, A., Adams, F.H., Riley, R.F. (1978). Cytogenetic effects of contrast media and triiodobenzoic acid derivatives in human lymphocytes. *Radiology, 129, 199-203.*

Novotný Jr, J., Dvořák, P., Spěváček, V., Tintěra, J., Novotný, J., Čechák, T., Liščák, R. (2002). Quality control of the stereotactic radiosurgery procedure with the polymer-gel dosimetry. *Radiotherapy and Oncology, 63, 223-230.*

Oldham, M., Baustert, I., Lord, C., Smith, T., McJury, M., Warrington, A., Leach, M., Webb, S. (1998a). An investigation into the dosimetry of a nine-field tomotherapy irradiation using BANG-gel dosimetry. *Physics in medicine and biology, 43, 1113.*

Oldham, M., McJury, M., Baustert, I., Webb, S., Leach, M. (1998b). Improving calibration accuracy in gel dosimetry. *Physics in medicine and biology, 43, 2709.*

Oldham, M., Siewerdsen, J.H., Shetty, A., Jaffray, D.A. (2001). High resolution gel-dosimetry by optical-CT and MR scanning. *Medical physics, 28, 1436.*

Olsson, L., Westrin, B.A., Fransson, A., Nordell, B. (1992). Diffusion of ferric ions in agarose dosimeter gels. *Physics in medicine and biology, 37, 2243.*

Panajkar, M., Guha, S., Gopinathan, C. (1995). Reactions of Hydrated Electron with N, N′ -Methylenebisacrylamide in Aqueous Solution: A Pulse Radiolysis Study. *Journal of Macromolecular Science, Part A: Pure and Applied Chemistry, 32, 143-156.*

Papagiannis, P., Karaiskos, P., Kozicki, M., Rosiak, J., Sakelliou, L., Sandilos, P., Seimenis, I., Torrens, M. (2005). Three-dimensional dose verification of the clinical application of gamma knife stereotactic radiosurgery using polymer gel and MRI. *Physics in medicine and biology, 50, 1979.*

Pappas, E., Maris, T., Angelopoulos, A., Paparigopoulou, M., Sakelliou, L., Sandilos, P., Voyiatzi, S., Vlachos, L. (1999). A new polymer gel for magnetic resonance imaging (MRI) radiation dosimetry. *Physics in medicine and biology, 44, 2677.*

Pappas, E., Seimenis, I., Angelopoulos, A., Georgolopoulou, P., Kamariotaki-Paparigopoulou, M., Maris, T., Sakelliou, L., Sandilos, P., Vlachos, L. (2001). Narrow stereotactic beam profile measurements using N-vinylpyrrolidone based polymer gels and magnetic resonance imaging. *Physics in medicine and biology, 46, 783.*

Pileni, M. (1997). Nanosized particles made in colloidal assemblies. *Langmuir, 13, 3266-3276.*

Podgorsak, E.B. (2003). Review of radiation oncology physics: a handbook for teachers and students.
Porcel, E., Kobayashi, K., Usami, N., Remita, H., Le Sech, C., Lacombe, S. (2011). Photosensitization of plasmid-DNA loaded with platinum nano-particles and irradiated by low energy X-rays. Paper presented at the *Journal of Physics: Conference Series*.
Porcel, E., Liehn, S., Remita, H., Usami, N., Kobayashi, K., Furusawa, Y., Le Sech, C., Lacombe, S. (2010). Platinum nanoparticles: a promising material for future cancer therapy? *Nanotechnology, 21, 085103.*
Procházka, M., Mojzeš, P., Štepánek, J., Vlčková, B., Turpin, P.-Y. (1997). Probing applications of laser-ablated Ag colloids in SERS spectroscopy: improvement of ablation procedure and SERS spectral testing. *Analytical Chemistry, 69, 5103-5108.*
Pyatenko, A. (2010). Synthesis of silver nanoparticles with laser assistance. In D. P. Perez (Ed.), (*pp. 121): InTech*.
Pyatenko, A., Shimokawa, K., Yamaguchi, M., Nishimura, O., Suzuki, M. (2004). Synthesis of silver nanoparticles by laser ablation in pure water. *Applied Physics A, 79, 803-806.*
Raba'eh, K.a.m. (2007). polymeration of polyhydroxyethylacrylate (PHEA) and polyhydroxylmethacrylate (PHEMA) polymer gel dpsimeter used is radiotherapy. *university putra malaysia(UPM)*.
Rabaeh, K., Saion, E., Omer, M., Shahrim, I., Alrahman, A.A., Hussain, M. (2008). Enhancements in 3D dosimetry measurement using polymer gel and MRI. *Radiation Measurements, 43, 1377-1382.*
Radaideh, K.M., Alzoubi, A.S. (2010). Factors impacting the dose at maximum depth dose (dmax) for 6 MV high-energy photon beams using different dosimetric detectors. *Biohealth Sc Bulletin, 2, 38-42.*
Rahman, W.N. (2010). Gold nanoparticles: novel radiobiological dose enhancement studies for radiation therapy, synchrotron based microbeam and stereotactic radiotherapy.
Rahman, W.N., Wong, C.J., Ackerly, T., Yagi, N., Geso, M. (2012). Polymer gels impregnated with gold nanoparticles implemented for measurements of radiation dose enhancement in synchrotron and conventional radiotherapy type beams. *Australasian Physical & Engineering Sciences in Medicine, 35, 301-309.*
Rahman, W.N., Wong, C.J., Yagi, N., Davidson, R., Geso, M. (2010). Dosimetry and its enhancement using gold nanoparticles in synchrotron based microbeam and stereotactic radiosurgery. Paper presented at the *AIP Conference Proceedings*.
Ramm, U., Weber, U., Bock, M., Krämer, M., Bankamp, A., Damrau, M., Thilmann, C., Böttcher, H., Schad, L., et al. (2000). Three-dimensional BANGTM gel dosimetry in conformal carbon ion radiotherapy. *Physics in medicine and biology, 45, N95.*
Ratajska-Gadomska, B. (1999). A percolation approach to dye fluorescence quenching during the gelation process. *Journal of Physics B: Atomic, Molecular and Optical Physics, 32, 3463.*
Regulla, D., Hieber, L., Seidenbusch, M. (1998). Physical and biological interface dose effects in tissue due to X-ray-induced release of secondary radiation from metallic gold surfaces. *Radiation Research, 150, 92-100.*

Rintoul, L., Lepage, M., Baldock, C. (2003). Radiation dose distribution in polymer gels by Raman spectroscopy. *Applied spectroscopy, 57, 51-57.*

Robar, J.L., Riccio, S.A., Martin, M. (2002). Tumour dose enhancement using modified megavoltage photon beams and contrast media. *Physics in medicine and biology, 47, 2433.*

Roeske, J.C., Nunez, L., Hoggarth, M., Labay, E., Weichselbaum, R.R. (2007). Characterization of the theorectical radiation dose enhancement from nanoparticles. *Technology in cancer research & treatment, 6, 395-401.*

Rogers, D.W.O. (2014). Notes on the structure of radiotherapy depth-dose distributions: Carleton University, Ottawa, Canada.

Rose, J.H., Norman, A., Ingram, M., Aoki, C., Solberg, T., Mesa, A. (1999). First radiotherapy of human metastatic brain tumors delivered by a computerized tomography scanner (CTRx). *International Journal of Radiation Oncology* Biology* Physics, 45, 1127-1132.*

Saion, E., Iskandar, S., Azhar, A., Kadni, T., Ab Rahman, M. (2008). Polymethacrylic Gel (Pmag) as a Point Dosimeter. *Solid State Science and Technology, 16, 222-231.*

Salomons, G.J., Park, Y.S., McAuley, K.B., Schreiner, L.J. (2002). Temperature increases associated with polymerization of irradiated PAG dosimeters. *Physics in medicine and biology, 47, 1435.*

Sandilos, P., Angelopoulos, A., Baras, P., Dardoufas, K., Karaiskos, P., Kipouros, P., Kozicki, M., Rosiak, J.M., Sakelliou, L., et al. (2004). Dose verification in clinical IMRT prostate incidents. *International Journal of Radiation Oncology* Biology* Physics, 59, 1540-1547.*

Scheib, S., Vogelsanger, W., Gianolini, S., Crescenti, R. (2004). Normoxic polymer gel–basic characterisation and clinical use. Paper presented at the *Journal of Physics: Conference Series*.

Scheib, S.G., Gianolini, S. (2002). Three-dimensional dose verification using BANG gel: a clinical example. *Special Supplements, 97, 582-587.*

Schreiner, L.J. (2006). Dosimetry in modern radiation therapy: limitations and needs. Paper presented at the *Journal of Physics: Conference Series*.

Schulz, R., Nguyen, D., Gore, J. (1990). Dose-response curves for Fricke-infused agarose gels as obtained by nuclear magnetic resonance. *Physics in medicine and biology, 35, 1611.*

Seibert, J.A., Boone, J.M. (2005). X-ray imaging physics for nuclear medicine technologists. Part 2: X-ray interactions and image formation. *Journal of nuclear medicine technology, 33, 3-18.*

Senden, R., De Jean, P., McAuley, K., Schreiner, L. (2006). Polymer gel dosimeters with reduced toxicity: a preliminary investigation of the NMR and optical dose–response using different monomers. *Physics in medicine and biology, 51, 3301.*

Siddiqi, A., Yang, Y., Dextraze, K., Hu, T., Krishnan, S., Cho, S. (2009). SU‐FF‐J‐150: Experimental Demonstration of Dose Enhancement Due to Gold Nanoparticles and Kilovoltage X‐Rays Using Radio‐Sensitive Polymer Gel Dosimeter. *Medical physics, 36, 2511.*

Simons, W.W. (1978). The Sadtler handbook of proton NMR spectra (*Vol. 1*)*: Sadtler Philadelphia, PA.*

Sondi, I., Salopek-Sondi, B. (2004). Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for Gram-negative bacteria. *Journal of colloid and interface science, 275, 177-182.*
Spiers, F. (1949). The influence of energy absorption and electron range on dosage in irradiated bone. *British Journal of Radiology, 22, 521-533.*
Spiers, F. (1966). A review of the theoretical and experimental methods of determining radiation dose in bone. *British Journal of Radiology, 39, 216-221.*
Spinks, J.W.T., Woods, R.J. (1990). An introduction to radiation chemistry. New York Wiley 1964.
Sprawls, P., Bronskill, M.J. (1993). The physics of MRI: 1992 AAPM summer school proceedings*: American Association of Physicists in Medicine.*
Sylvestre, J.-P., Poulin, S., Kabashin, A.V., Sacher, E., Meunier, M., Luong, J.H. (2004). Surface chemistry of gold nanoparticles produced by laser ablation in aqueous media. *The Journal of Physical Chemistry B, 108, 16864-16869.*
Trapp, J., Bäck, S.Å.J., Lepage, M., Michael, G., Baldock, C. (2001a). An experimental study of the dose response of polymer gel dosimeters imaged with x-ray computed tomography. *Physics in medicine and biology, 46, 2939.*
Trapp, J., Michael, G., Baldock, C. (2001b). Theoretical considerations of scan parameters appropriate for CT imaging of polymer gel dosimeters. *DOSGEL.*
Tsuji, T., Iryo, K., Watanabe, N., Tsuji, M. (2002). Preparation of silver nanoparticles by laser ablation in solution: influence of laser wavelength on particle size. *Applied surface science, 202, 80-85.*
Venning, A. (2005). Investigation of radiation sensitive normoxic polymer gels for radiotherapy dosimetry*. Queensland University of Technology*.
Venning, A., Hill, B., Brindha, S., Healy, B., Baldock, C. (2005). Investigation of the PAGAT polymer gel dosimeter using magnetic resonance imaging. *Physics in medicine and biology, 50, 3875.*
Vergote, K., De Deene, Y., Bussche, E.V., De Wagter, C. (2004). On the relation between the spatial dose integrity and the temporal instability of polymer gel dosimeters. *Physics in medicine and biology, 49, 4507.*
Vergote, K., De Deene, Y., Claus, F., De Gersem, W., Van Duyse, B., Paelinck, L., Achten, E., De Neve, W., De Wagter, C. (2003). Application of monomer/polymer gel dosimetry to study the effects of tissue inhomogeneities on intensity-modulated radiation therapy (IMRT) dose distributions. *Radiotherapy and Oncology, 67, 119-128.*
Ward, A.G., Courts, A. (1977). The science and technology of gelatin (*Vol. 241*)*: Academic Press New York.*
Watanabe, Y., Perera, G.M., Mooij, R.B. (2002). Image distortion in MRI-based polymer gel dosimetry of Gamma Knife stereotactic radiosurgery systems. *Medical physics, 29, 797.*
Woodard, H., Laughlin, J. (1957). The Effect of X-Rays of Different Qualities on The Alkaline Phosphatase of Living Mouse Bone: II. Effects of 22.5-Mevp X-Rays. *Radiation Research, 7, 236-252.*
Wuu, C.-S., Schiff, P., Maryanski, M.J., Liu, T., Borzillary, S., Weinberger, J. (2003). Dosimetry study of Re-188 liquid balloon for intravascular

brachytherapy using polymer gel dosimeters and laser-beam optical CT scanner. *Medical physics, 30, 132.*
Yang, C.-Y. (2010). Anti silver nanoparticle bacteria. In D. Vasileska (Ed.), *Cutting Edge Nanotechnology* (*pp. 444): In Tec*.
Zehtabian, M., Faghihi, R., Zahmatkesh, M., Meigooni, A., Mosleh-Shirazi, M., Mehdizadeh, S., Sina, S., Bagheri, S. (2012). Investigation of the dose rate dependency of the PAGAT gel dosimeter at low dose rates. *Radiation Measurements, 47, 139-144.*
Zellmer, D., Chapman, J., Stobbe, C., Xu, F., Das, I. (1998). Radiation fields backscattered from material interfaces: I. Biological effectiveness. *Radiation Research, 150, 406-415.*
Zhang, S.X., Gao, J., Buchholz, T.A., Wang, Z., Salehpour, M.R., Drezek, R.A., Yu, T.-K. (2009). Quantifying tumor-selective radiation dose enhancements using gold nanoparticles: a monte carlo simulation study. *Biomedical microdevices, 11, 925-933.*