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Medical radiation dosimetry higher doctoral degree thesis

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MEDICAL RADIATION DOSIMETRY

HIGHER DOCTORAL DEGREE THESIS

Doctor of Science

from

THE UNIVERSITY OF WOLLONGONG

by

Martin Jonathan Butson

Engineering Physics

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PARTS 1 -3 and APPENDICES

PART 1 CONFORMANCE WITH HIGHER DOCTORAL DEGREE REQUIREMENTS

1.1 Basis of the Application

I am a graduate of the University of Wollongong for both my undergraduate and postgraduate degrees, BSc(Hons) (1992) and PhD (1998). Also since 1996 until present I have held the position of honorary fellow, honorary senior fellow and honorary principal fellow through the Department of Engineering Physics (Previously Dept of Physics). As my first degree of BSc (Hons) was finalised in 1992, I satisfy the requirements of rule 12:39 a i) and ii) (General Course Rules Handbook – "Admission requirements for Higher Doctoral Degrees) for application to the degree of Doctor of Science as a university graduate who is "with standing of not less than eight years admission to a first degree at the University of Wollongong"

1.2 Required Information

In relation to the requirement set out in 12:40, the academic unit associated most closely with my academic and research activities is the Department of Engineering Physics and more pointedly, the Centre for Medical Radiation Physics. The Centre for Medical Physics was inaugurated in 2005 under the direction of Prof Anatoly Rosenfeld. Medical radiation physics has been a subspecialty of the University of Wollongong's Physics Department since the mid 1980's when Dr Jagdish Mathur, introduced collaborative links with ANSTO (Australian Nuclear Science and Technology Organisation) and in 1990 with the newly formed ICCC (Illawarra Cancer Care Centre).

The list of publications required of 12:40 is given in part 2 together with the estimated percentage contribution of the authors. In relation to 12:40 d) v), 12 of my early publications which are marked with an asterixis (*) were submitted and referenced as part of my original PhD in Medical Physics, completed at the University of Wollongong. Copies of publications submitted for consideration are presented in part 4 as required by 12:40. An overview that demonstrated that the collective works provide an original and significant contribution to

knowledge: 12:40 is given in part 3. These publications have been divided into 3 broad streams of research and endeavour. Similarly, "evidence that the publications have standing as significant and sustained contributions to knowledge" 12:40 is presented throughout sections 3.2, 3.3 and 3.4 and in the form of summaries in subsections 3.2.1, 3.3.1 and 3.4.1. This is given together with a final summary (section 3.5) of the publications impact, journal citation indexes, citations and h-index.

PART 2 LIST OF PUBLICATIONS FORMING THE BASIS OF THE APPLICATION

2.1 Clinical Radiotherapy Physics

1.* Butson M., Wong T., Kron T., Mathur J., Clubb B., Metcalfe P. (1994) Surface doses from combined electron/photon fields in radiotherapy. Aust. Phys. Eng. Sci. Med. 17(1): 14 - 22.

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9. Kron T, Butson M, Hunt F, Denham J, (1996). "TLD Extrapolation for skin dose determination in vivo" , Radiotherapy and Oncology 41(1996) pg 119-123

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16. Butson M, Elferink R, Cheung T, Yu PK, Stokes M, Quach KY, Metcalfe P. (2000) Verification of lung dose in an anthropomorphic phantom calculated by the collapsed cone convolution Phys Med Biol 45(11):N143-9 method.
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17. Quach KY, Morales J, Butson M, Rosenfeld AB, Metcalfe PE (2000) Measurement of radiotherapy x-ray skin dose on a chest wall phantom. Med Phys 27(7):1676-80
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PART 3 CASE FOR AWARD OF DSc DEGREE BY PUBLICATION

3.1 Introductory Statement

Throughout my career as a clinical medical physicist my research has been mainly aimed at the improvement of cancer treatment using x-ray and electron beams by radiotherapy applications. My full time clinical workload entails the treatment of approximately 1000 new cancer patients every year with radiotherapy and the accuracy delivery of their radiation doses. Through out this time I have also been involved in an honorary capacity as a university academic with the University of Wollongong and an honorary research fellow with the City University of Hong Kong. Through these collaborations, my research has often included core physics research with a small but effective student supervision workload. As I continue my clinical research and treatment career , opportunities for research continually arise as we strive for improved cancer treatment, more accurate radiation dose verification and improvements to radiation delivery. This is where my application and evidence may differ considerably from a full time academic in that our clinical needs drive our research path. Attraction of grant funding for core research does not play a role in my world as all research is required 'immediately' with existing resources available within the Dept of Health's budget. Thus the creative aspect of my research strives to find new improvements based on hospital funding and currently available equipment. As a full time clinician, my student supervision levels will also be significantly less than a full time academic. However, through continual research and publication in medical radiation physics, I feel that I am a worthy candidate for consideration of the DSc degree.

The selected publications listed in section 2.1, 2.2, 2.3 form the basis of this DSc thesis and reflect the three main focuses of my research over the last 20 years. They provide the backbone of the sustained and significant contributions I have made to the scientific and medical community. They are clinical, translations and fundamental in their nature with the overriding emphasis on improvements to clinical radiotherapy cancer treatment. The publication areas are divided into three streams, Clinical Radiotherapy Physics (Section 2.1), Radiochromic film dosimetry for medical applications (Section 2.2) and Radiation Dosimetry of x-rays, electron and ultraviolet beams (Section 2.3). The first section provides

examples of what health professional's call clinical "coal face" research whereby fundamentally new procedures or techniques are researched and developed based on the needs of our current patient workloads and associated clinical problems. These techniques are often published and used worldwide by other health professionals who encounter similar problems in their own clinics. The second stream involves a relatively new area of radiation dosimetry tools which have now become a mainstream clinical dosimeter for measurement of radiation doses in therapy and diagnostic areas. These new detectors are called radiochromic films and are analogous of the older "x-ray" radiographic films used for imaging broken bones and the like. They have significantly improved qualities compared with radiographic film and have revolutionised the film dosimetry world in radiotherapy radiation measurement. I have been one of the leading authors and researchers in these areas and have provided significant and sustained research into the clinical improvements of radiation dosimetry with these films. I will show later that I am the worlds leading author in this new and exciting advancement for medical radiation dosimetry. In terms of sustained and significant impact, I will also show that at present, 14% (of the near 6000 citations to "radiochromic film" research) of all publication citations in this area of research are given to my work and publications. The final stream for my applications includes the medical physics research used for analysis of fundamental physics problems and areas requiring core theoretical and technological analysis. This includes areas like Monte Carlo theoretical analysis of the interaction of high energy x-rays with matter to improve our knowledge of the causes of skin dose delivered during radiotherapy. A complete list of my publications in international journals and conference proceedings is given in appendix 2 and includes an even wider scope of research across many aspects of medical physics including other areas such as nuclear medicine / radiation safety, brachy therapy and ultraviolet radiation detection.

Each paper presented involved significant personal input through experimental and theoretical calculation work. It also included manuscript preparation and editing. Of the 105 papers submitted as evidence for the application for the degree of DSc, I am the first author on 61 of these and have provided a significant percentage contribution of most others. I take pride in my work and do not accept offers of token authorship which I feel is evident through the high level of first author papers. Of the other, 44 papers I have been the corresponding author on 26, showing my high level of input and contribution to the vast majority of this work. i.e. First author on 58% of papers and first or corresponding author on 82% of all

published papers. The clinical medical physics environment utilises a small team based approach to problem solving and as such all papers have multiple authors, normally 3 to 5 members. I take pride in the fact that I am normally the lead investigator in such problems and actively direct the research involved for cancer treatment. This is highlighted by my major first author and corresponding author contributions to published work. Sections 3.2, 3.3 and 3.4 below will expand on the significance and sustained output from my research as evidence for the award of Doctor of Science degree.

3.2 Clinical Radiotherapy Physics

Beginning my career in clinical medical radiation physics at the Illawarra Cancer Care Centre (ICCC) allowed me to work with state of the art, radiotherapy equipment and techniques used at the fore front of treatment procedures. The centre had just been established at Wollongong Hospital through the kind donation of funds from the citizens of the Illawarra. The centre was equipment with a new Varian linear accelerator and associated planning computer software and control equipment to treat cancer patients with high energy x-ray and electron beams. As such we were in the enviable position of providing cutting edge clinical cancer treatment. The centre was established under the leadership of Chief Medical Physicists, Prof Peter Metcalfe, who now holds the position of the Cancer Institute Chair of Medical Physics at the University of Wollongong. As such I was pressed to excel in all areas of clinical medical physics and due to the high level of local media attention, often required to show the public our new techniques and treatment procedures. These facts inevitably gave me the skills to continually strive for the best possible outcomes and provide leading edge research in clinical radiotherapy. My first 12 papers were published from 1992 to 1998 whilst studying part-time for my PhD degree in Medical Physics at the University of Wollongong. These publications are highlighted in section 2 with an asterixis (*) and include publications 1,2,3,4,5,6,7,10,11,12 (Sections 3.1) and publications 1,2 (Section 3.2). My first research work (Publication 1) in clinical radiotherapy physics centred around a new type of treatment technique involving the use of dual or mixed photon/electrons in radiotherapy. Conventionally, it would normally be one or the other type of radiation beam used for cancer treatment however, the research was aimed at minimising the clinical impact on the patients skin during radiotherapy treatment. Electron beam produce a high radiation dose to the skin which in some instances can cause skin burning to occur from the radiotherapy treatment leaving the patient with pain and sometimes irreparable cosmetic damage. This work investigated the use of dual modality treatments whereby the tumour dose at depth inside the patient could be maintained whilst lowering the skin dose to an acceptable level to not cause permanent skin damage. This new technique was published and well used during the mid 1990's as an effective method for control of skin reactions where electron beam treatment was required.

In 1995 the ICCC purchased a new low energy x-ray machine for treatment of skin cancer and I was given the job of "commissioning" the Therpax Orthovoltage machine. This required investigating all radiation delivery properties of this machine and providing methods for patient treatment matched with beam energies and dosimetric qualities. Through this work, publication 2 was produced and it highlighted some interesting facts including the presence of a large degree of very low energy x-rays in the beam which if not accounted for and removed could lead to unwanted extra skin reactions during radiotherapy treatment.

Through both these initial research works, I developed an interest in skin dose delivery and measurement during radiotherapy and this became the topic of choice for my PhD. The accurate measurement of skin dose for high energy x-ray beams at this stage was quite a difficult process and current planning computer systems used for predicting radiation doses for radiation therapy were very inaccurate at the skin region. As such I investigated new ways of measuring skin dose. At this stage, Prof Anatoly Rosenfeld of the Centre for Medical Radiation Physics had just joined the Physics Department at the University of Wollongong. He was an expert in nuclear physics and had developed radiation detector systems called the MOSFET. Upon collaboration with Prof Rosenfeld, I discovered that by changing the design characteristics of his detectors, I could utilize the thin silicon active layers within the encapsulated device to accurately measure skin doses in radiotherapy. From this work, publication 3 was performed and it has become one of the leading publications on skin dose measurements with MOSFET detectors. The Centre for Medical Radiation Physics have to date further improved the design of such detectors and now produce a clinical MOSFET dosimetry system called the MOSKIN detector system which is used worldwide. My original investigations and work provided the backbone for this current work. Whilst the MOSFET device provided accurate radiation dosimetry for skin dose at a point, there was a need to measure radiation doses over a 2 dimensional area as the skin dose could vary with the patient treatment parameters, such as the curved surfaces of the breasts and tangential radiation treatment. Current film detectors such as radiographic x-ray film were not able to be used due to their packaging requirements and their high energy dependence which meant that accurate dosimetry in this region could not be performed. As such I researched for a new type of detector which could hopefully accurately measure over a 2 dimensional region at a very shallow depth like the skin layer. My investigations brought me to a type of high energy nuclear device normally used in nuclear reactors called radiochromic films. These detectors possessed the characteristics of being thin films, 2 dimensional as well as characteristics of being relatively human tissue equivalent which was another ideal characteristic for

measurement of radiation in a clinical situation. Publication 4 shows the initial and very promising work of the use of a prototype radiochromic film called Gafchromic MD-55 for measuring surface and skin doses in high energy radiotherapy. Not only did we measure accurate radiation doses but it was performed over a 2 dimensional area, never achieved previously in radiotherapy. This provided the starting benchmark for radiochromic film use in radiotherapy. Today, Gafchromic film is probably the most widely used film detector in clinical medical physics. I will expand more on this topic in the section devoted to my research into radiochromic films for medical dosimetry applications. The analysis of skin dose in radiotherapy resulted in the evidence that their was a large and unwanted contribution from lepton contamination or the production of electrons and positrons from outside the patient which was then incident upon the skin during treatment and causes skin damage. Through investigative research and theoretical calculations a method was developed using static magnetic fields to remove this contamination before it struck the patient. Publication 5 was produced though the invention of a prototype Neodymium iron boron magnetic deflector for use in clinical radiotherapy for the reduction of skin dose. Further work has been performed by University of Wollongong PhD students to improve the design of these devices and to date commercial applications are still being investigated.

Being able to accurately measure skin and surface dose meant that we could now provide accurate data for clinical treatment and planning. As such the next step in the research process was to theoretically calculate and construction planning algorithms for the accurate pre calculation of skin dose that would be delivered to patients during radiotherapy. This was performed through publications 6, 7, 10 and 11. These works provided empirical models which accounted for changing patient parameters like field size, use of beam modifying devices, SSD, angle of incidence and beam energy. This was incorporated into the Illawarra Cancer Care Centre planning system. Further to this, current planning systems (Phillips Pinnacle 3-4 Convolution panning systems) used world wide now incorporate an empirical model for skin dose assessment into their systems loosely based on the original empirical models produced by myself. This work completed my PhD and provided the basis for further work on this topic by allowing measurement and calculation of skin doses for many other treatment sites and techniques in radiotherapy physics. Over the next 15 years, these techniques have been utilized and honed to provide a myriad of more useful clinical information about skin doses. Publications 8, 9, 12, 13, 17, 19, 21, 23, 24, 25, 31, 32 and 33 investigate and provide important information regarding skin doses to many sites and

treatment types using high energy and low energy x-ray radiotherapy and has provided a backbone of information on skin dose and accurate dosimetry in clinical radiotherapy. Using database analysis of the WEB of SCIENCE a search was performed on "surface dose" in radiology, nuclear medicine and medical imaging and it was found that I was amongst the top 10 researchers published in this area world wide.

Expanding on clinical radiotherapy research performed, my attentions were also turned to many other topics which became important at various stages due to the clinical imperatives on the department at that time. These include topics such as effective and accurate irradiation of blood products to reduce the risk of Graft versus Host disease (GVHD) (Publications 14, 20), prostate and abdominal treatments, (Publications 27, 28) as well as thoracic cancer treatment (Publications 16, 17). More over, facial treatment and skin cancers have also been researched and investigated for accurate dosimetry techniques including developments of technique for measurement and calculations of doses around the eyes and bony structures (publications 18, 34, 35, 37). Establishment of clinically important machine characteristics has also been performed to further enhance the accuracy of clinical radiotherapy treatment. This has included but not limited to improving electron beam modelling characteristics (publication 15), improving the accuracy of the conversion of X-ray CT data to physical density data for accurate radiotherapy planning (publication 22) and improving the knowledge of new treatment devices such as multileaf collimators (publications 26, 29, 30) , new linear accelerator treatment couches (Publication 23, 25) and phantom materials used for the study of radiation properties (Publication 36, 37, 38). Together, this work has provided the medical physics community with a significant and sustained level of research and data which has been utilized effectively both in Australia and World Wide.

3.2.1 Standing and Significance of research

The standing and significance of my published works in clinical radiotherapy physics can be seen by involvement with refereeing clinical medical physics articles, my associate editor status for 2 journals, my published works and by my conference presentations and published proceedings. The clinical world differs from the

academic world in that it is quite difficult to attend conferences and accept invited speakership roles as well as advisory roles on groups and organisations. As my clinical role always comes first I cannot commit to many invited speaker roles nor invitations to sit of organisations chairs or committees. However, by investigation of the published works and conference presentations (normally present a larger quantity at a conference as not many are attended), it is evident that a substantial and sustained research output and a high standing has been achieved. I current serve as an associate editor of the Australia Asian journal of cancer and of the ACPSEM. I have also been a quest associate editor for medical physics, the leading clinical medical physics journal of the US. I have also refereed articles for 6 other international journals over the last 15 years as will be given in my CV (appendix 2).

3.3 Radiochromic film dosimetry for medical applications

Radiochromic film, is a relatively new and exciting dosimetric tool which can be used in radiotherapy applications such as cancer treatment and diagnostic evaluation of doses. Some of its main advantages over other existing film type detectors have included its automatic colouration process and thus eliminating the need for a film processor, its physical robustness, the ability to keep it in normal room lighting, its low energy dependence and thus highly level of mixed energy beam dose evaluations and the ability to reuse the film if required. These characteristics have been developed over the last 20 years of use and I have been one of the leading authors and investigators who have advanced these films for dosimetry in radiotherapy and medical applications. The films had their beginnings in high energy nuclear power radiation industry where extremely large mega Rad doses were measured. It was discovered that various chemical monomers and polymers would produce a colour change upon irradiation and the change could be proportional to the dose delivered. In the early 1990's whilst performing my PhD I investigated this film type and if it was possible to use it for radiotherapy applications and especially at the time, the measurement of skin and surface dose. The initial results are given in section 2.3.1 under clinical radiation physics and showed that there was potential for measurement of radiotherapy radiation doses with these types of detectors. However, there were still many characteristics which needed improvement and research to fully understand the radiation characteristics of these detectors. This started a series of investigations to provide the medical physics community with in-depth knowledge concerning radiochromic film dosimeters and methods to improve the accuracy of radiation dosimetry in the clinical setting. Publication 1 was amongst the first works which endeavoured to outline the possible inaccuracies caused by ambient room lights and readout sources on radiochromic films. Results showed how inaccuracies could be found if the films were not treated correctly during irradiation and readout. Publication 2 showed how the film could be used to measure skin dose outside the main radiation beam in a 2 dimensional map which had not been achievable before and allowed clinicians to see the skin doses outside the treatment field which were often neglected before. Further investigation of the films physical characteristics in

measuring skin dose produced publication 3 whereby an extrapolation technique could be applied to multiple layered films to accurately measure the true surface dose, which were not achievable before with any detectors over an area. During this period, as a clinical investigator I kept contact with the films manufacturers in the USA and especially Prof David Lewis, head of ISP's Gafchromic film production centre as I would feed back to him the clinical needs for radiochromic film. In turn Prof Lewis and his team would continually improve the quality and characteristics of the radiochromic film products they were developing. At this time I was offered a position to become a managing director and executive salesperson for Gafchromic film in the Asia Pacific region however, I decided to turn down the offer as I felt that it could compromise my research into improving the product as an independent researcher. ISP were happy with this and continued to heed my advice and published works to better their product. A series of publications covering the fundamental radiation and physical characteristics of the films followed over a period of a few years and the films developed into products which were developed specifically for niche areas of use from higher dose radiotherapy to low dose diagnostic procedures. These publications are 4 to 37 inclusive. Of most importance of these publications was a report series book entitled "Medical Radiation dosimetry using radiochromic film" which was commissioned by the Materials Science reports series and published in 2003. It provided the medical physics community with the current knowledge of radiochromic film and dosimetry techniques for radiation dosimetry. I was asked to write this report series as I was the leading author on radiochromic film in medical radiation dosimetry.

Some of the topics covered by the published works include the following areas of research i) using radiochromic film in ambient lighting, effects of dosimetric accuracy and methods of improving dosimetry (Publications 5, 10, 22)

ii) Fundamental physical phenomena associated with measurement of absorption spectra and optical properties of radiochromic films (13, 14, 15, 17, 18, 19, 20, 23, 26, 28, 30, 33, 34, 35, 36, 37).

iii) Effects of phantom and patient in-vivo measurements on radiochromic film dosimetry – methods of improvement (Publications 4, 6, 7, 8, 9, 11, 12, 24, 29, 32,).

Finally the last major source of research has been in the energy dependence of radiochromic films to x-ray radiation. Without accurate knowledge of energy

dependence, a film detector will not provide accurate knowledge of delivered dose. Radiochromic films have provided the medical physics world with a new low energy dependence film which has significantly improved the ability to accurately measure radiation doses for therapy applications over a 2 dimensional map. My contributions to this work are well documented and given in publications (16,21, 25, 27 and 31).

3.3.1 Standing and Significance of research

Radiochromic film dosimetry has now become one of the main tools for measurement of radiation doses in radiotherapy for 2 dimensional mapping. It is used extensively in Intensity Modulated Radiation Therapy (IMRT) dose verification, conventional Radiotherapy as well as measurement of doses in superficial and orthovoltage x-ray treatment and diagnostic procedures. My contributions to the field of radiochromic film dosimetry have provided the medical physics community with a significant and sustained output of quality information to allow others to accurately use these tools in their settings. I am currently known as the foremost expert in radiochromic film dosimetry in Australia and assumedly in the world and I am the worlds leading author on the subject by some distance (based on ISI publications sited by the search "radiochromic film". Investigation of the WEB OF SCIENCE data base journals reveals that I have published 52 publications and am the worlds leading author on the subject (39 as first author) referenced by keywords "radiochromic film". This far exceeds all other researchers besides my colleagues Prof Yu and Prof Cheung from the City University of Hong Kong, whom I collaborate with on this subject. The next highest level of Authorship comes from Prof Soares (20) and Prof McLaughin (19) both from the USA. As such my findings and research in radiochromic film are utilized throughout the world and extensively in medical physics department worldwide. Using SCOPUS analysis, out of my top 20 papers for citations by other, which have been cited more than 1000 times, 15 have been on the use of radiochromic film. Utilizing the WEB OF SCIENCE database shows that papers published under the keyword topic of "radiochromic film" have been cited in total 5,932 times from 1990 till 2010 (Accessed 5-3-10). Of these cites, 830 are citations to my published providing 14% of the worlds citations to radiochromic film in medical radiation dosimetry. This indeed shows the significance

and sustained impact of my published works in medical physics and radiochromic film dosimetry.

3.4 Radiation Dosimetry of x-ray, electron and ultraviolet beams

My third area of excellence deals with the more fundamental aspects of radiation dosimetry and draws together aspects from Monte Carlo computer modelling of radiation detectors and radiation transport through to other forms or radiation dosimetry including ultraviolet radiation and electron beams. Monte Carlo is a computerised technique of simulation the interactions of x-rays with matter in order to predict how dose will be delivered or measured in the patient or phantom dosimetry system required. In early 1993, I began working with Monet Carlo (the code name) for transport of x-rays within matter to evaluate skin dose and build up dose characteristics in megavoltage x-rays beams. The initial work was for my PhD and incorporated design of surface dose phantoms and methods to provide high accuracy results with very thin scoring voxels which were required for this type of analysis. This work extended into modelling effects from air generated contamination (Publication 6) and further to these models to incorporate magnetic fields into the simulated design with the interest in removal of electron contamination (publication 30). The ability to quantify, measure and remove the electron contamination component of a therapy x-ray beam became the core research topic in this area and publications 3,5,7,11,12,14,17,25,26,27 provided an overview of the work in this area. Topics covered included the effects of the air column above the patient on skin dose, the effects of bolus material used, the treatment couch, head cast material and other sources of contaminations were investigated. These results provided significant and sustained knowledge of skin dose and the contributions to it from various radiotherapy treatment parameter sources. In measuring sources of electron contamination also came extensive research and clinical evaluation of other types of radiation detectors which could be used in phantoms and more importantly, in-vivo or on patients during clinical treatment. In efforts to perform such tasks whilst not effecting patient treatment, different detectors have been analysed and researched for use in various beam types and patient treatment configurations. Publication 2 showed the ability to convert existing radiographic film densitometers into radiochromic densitometers so as to improve the accuracy of in-vivo dosimetry. Publication 4 was an extensive study into the energy dependence properties of multiple detectors ranging from TLD , diodes, MOSFET and films such as radiographic and

radiochromic film. This work highlighted how different these detectors could be and that many correction factors were needed to accurately measure radiation with some types. Some of these others types of detectors were investigated in more detail in publications 7, 9,10, 13, 15, 16, 18, 19, 20, 21, 22, 23, 24, 28 and 29.) The majority were aimed at the use of either MOSFET's or radiographic films for in-vivo or phantom based radiation dosimetry. Results over the years have provided an increased knowledge base for these types of detectors and has been performed over a sustained period of time.

3.4.1 Standing and Significance of research

Over the last 10 years, MOSFET devices have also become a leading dosimetric tool for radiotherapy dose analysis especially for in-vivo applications. My work in this area has been performed mostly in collaboration with Prof Anatoly Rosenfeld who is the lead researcher for the centre of Medical Radiation Physics at the University of Wollongong. Initially my advances were to reconstruct the MOSFET devices to remove encapsulation, thus eliminating the higher density materials around the active layers providing a more accurate dosimetry for skin and surface dose detection. This has then provided the basis for Prof Rosenfeld's MOSKIN devices which are now used world wide in radiotherapy applications. The original paper on MOSFET's surface dose has been referenced more than 60 times and provided the base knowledge for skin dose detections with this style of detector. Further work incorporated design characteristics and use in-vivo on effects such as temperature dependence and use in clinical situations. Within this section I have also noted, papers on Monte Carlo modelling and the creation and design of magnetic deflector devices. My work n these areas has help to develop new code techniques whereby our ultimate aim is to produce new planning computer processes whereby improved dosimetric accuracy can be achieved. The magnetic deflector is still undergoing improvements by current PhD students to eventually provide a clinical useable device for the reduction of skin dose in radiotherapy treatment. Further work will enhance this process in the near future.

3.5 Final Summary

Combining my research into radiation detectors with the clinical experiences and use at the patient coal face has allowed me to provide a significant and sustained contribution to the knowledge of radiation dosimetry and clinical radiotherapy physics. Comparison of detectors, development of new radiation techniques, production and evolution of radiochromic film dosimetry into a major tool for radiotherapy clinics today has shown that my contributions have made their mark on the world and provided a sustained and significant contributions to the field of medical physics.

An easy and successful way to acknowledge the contributions of a researcher to their area of expertise is through the analysis of their citations and publication record. This can be performed with various database tools. I have performed such a search using SCOPUS. The search included all papers submitted as published works for this degree of Doctor of Science. By entering my name into the database search, the following results are produced.

Author	**Martin J Butson**
Publications listed	**102 publications**
Total Citations	**1058 citations**
H-index	**18**

Using the citation tracker, a summary of published citations are available.
As at 5-3-10 my record shows from my 102 published articles (3 articles not found in SCOPUS databases) I have received 1058 citations from other works and my h-Index is 18. I.e. at least 18 of my publications have been referenced at least 18 times by other works.

By comparison, the works of Prof Druce Dunne, eminent scientist, engineer and recipient of a DSc from the University of Wollongong in 2003 has 105 publications, 563 citations to his work and a h-index of 14 (as at 5-3-10). Prof Alan Johnson,

another eminent scientist and DSc award recipient from the University of Wollongong in 1995 currently has 99 publications, 1205 citations (as at 5-3-10) and a h-index of 20. Of these 20 papers, 8 were published after the award of the DSc. (Both DSc award recipients were searched using their names with SCOPUS. It is acknowledged that all publications may not be included in the results however; they are used as a base guide for comparison.

A h-index level of 18 was considered by Hirsch, the inventor of the h-index, to be that of at least professorial level and of international standing in your field of excellence. Of these 18 h-index papers, I am first author on 11 of them showing the high level of quality research performed by myself with the majority of the work being performed by me. It should also be noted that of my 105 publications that 61 are as first author and another 26 as corresponding author. As such it is easy to see that my contributions to all works were major one and very few papers submitted for the award of the DSc have I been a minor contributor.

In 2004, I was inducted as a fellow into the Australasian College of Physical Scientists and Engineers in Medicine (ACPSEM) for my contributions to medical radiation physics. At that time, I was the youngest every recipient of the award. Currently there are only 26 fellows of the ACPSEM in the Australasian region highlighting the significant status of this honour.

With this supplied evidence of sustained and significant contributions to the field of medical physics, I feel that I am worthy of consideration for the Degree of Doctor of Science from the University of Wollongong.

Appendix 1 Curriculum Vitae - Summary

Employment History

Feb 2007 till present : Senior Medical Physics Specialist and Principal Medical Physics Dosimetric Researcher : Southeastern Sydney and Illawarra Area Health Service

2006–2007 Principal Medical Physicist and Principal Med Phys dosimetry researcher : Southeastern Sydney and Illawarra Area Health Service

2003 – 2006 Principal Medical Physicist and deputy Director of Medical Physics (Southern Sector), Southeastern Sydney and Illawarra Area Health Service

2000 – 2001 Acting Director of Medical Physics and Acting Chief Radiotherapy Physicist , Illawarra Area Health Service

1998-present Contract research fellow, City University of Hong Kong (concurrent appointment).

1995 – 2003 Senior Radiotherapy Medical Physicist and Deputy Chief Physicist, Illawarra Area Health Service

1992 – 1995 Radiotherapy Medical Physicist, Illawarra Cancer Care Centre, Wollongong Hospital

1991 – 1992 Honorary Postgraduate Researcher – University of Wollongong and Illawarra Cancer Care Centre

Education

University of Wollongong 1989-1998

Doctor of Philosophy (PhD) (1994-1998)
Thesis entitled "Skin dose from Radiotherapy x-rays"

Honours in Bachelor of Science BSc(Hons) (1992)
Thesis entitled " Build up characteristics of megavoltage x-ray beams"

Bachelor of Science (BSc) 1989-1991

Professional Qualifications

2004 Fellowship of the Australasian College of Physical Scientists and Engineers in Medicine

2003	ACPSEM : Professional accreditation in Radiotherapy Equipment Commissioning and Quality Assurance.
2003	Department of Environment and Conservation, Radiation Control, IA29 & S29 Radiation Expert License
1992	NSW Environmental Protection Agency, IA8, IA29s and S29s radiation license for use of radiation apparatus for scientific research use and clinical use under general supervision.

Academic University Involvement

University of Wollongong, Department of Engineering Physics

2001 – present	Associate Professor /Principle Honorary Fellow
1999-2001	Honorary fellow

City University of Hong Kong, Department of Physics and Materials Science

2004- present	Contract research fellow consultant
1998- 2004	Contract senior research consultant

Lectureship and practical demonstration of University Degree Courses

University of Wollongong

1995 - present	Physics 353 (3rd year) Radiotherapy Physics
1995 – present	Physics 353 (3rd year) Laboratories
2001– present	Physics 952 (MSc) Radiation Therapy Physics
2001 – present	Physics 952 (MSc) Laboratories

Post Graduate research supervision

Kan M, (1998 – 2000) Spectral analysis of meavoltage photon beams produced by linear accelerators PhD City University of Hong Kong

Quach Kim (2000-2005) Monte Carlo and Convolution models of radiotherapy dose beyond air cavities. PhD University of Wollongong.

Mohamed Al Naghy (2002-2003) Dosimetric properties of GAFchromic XR type R radiochromic film for medical dosimetry MSc , UOW

Nice Pungadned (2002- 2005) Magnetic repulsion of electron contamination in high energy x-ray radiotherapy PhD , UOW

Sian Price (2003 - 2004) Multileaf interleaf leakage measurement with various radiation detectors. MSc , UOW

Brad Oborn (2004- 2005) Magnetic deflection of linear accelerator contaminates. MSc, UOW

Michael Currie (2004-2005) Assessment of skin absorption spectra using reflectance spectroscopy MSc, UOW

Brad Oborn – (2006-2009) Optimizing radiotherapy dose delivery with magneto/radiotherapy. PhD, UOW

Hani Alnawaf : Niche applications of radiochromic film products to diagnostic and therapeutic medical x-rays. (in progress 2008 present) , UOW

Undergraduate research supervision

More than 20 honours students thesis supervisions performed.
First :- Lee, Kerry. (1996) Properties of a new variable collimator at orthovoltage energies. BSc Med. Phys. (hons), University of Wollongong.
Latest :- Melissa Sirocky – (2006) Gafchromic film, evaluation of scanner properties Wollongong BSc(Hons).

Text Books and Book Acknowledgements

Radiochromic film for Medical Radiation Dosimetry, 2003, Materials Science & Engineering R: Reports, 41, Elsevier Science, Butson, M.J., Yu, K.N., Cheung, T., Metcalfe, P.E., 2003.

Acknowledgements for contributions to :- Metcalfe P., Kron T., Hoban P. (1997) The Physics of Radiotherapy X-rays from linear accelerators, Medical Physics Publishers, Madison Wisconsin, USA pp 1 - 477. ISBN: 0-944838-75-8 (hardcover), ISBN: 0-944838-76-6 (softcover).

Editorial Status for International Scientific/ Medical Journals.

2001 – present: Assistant Editor for Austral-Asian Journal of Cancer
International journal published by the International Cancer Research and Promotion Council, India.

2008 – present Associate Editor of Australasian Physical and Engineering Sciences in Medicine.
International journal published by Australasian College of Physical Scientists and Engineers in Medicine and the College of Biomedical Engineers, Australia.

Referee Status for International Scientific / Medical Journals.

2003 – present Referee for Applied Radiation and Isotopes Journal
International journal published by Elsevier Science, United Kingdom.
1999 – present : Referee for Medical Physics Journal
International journal published by American Institute of Physics, USA.
1999 – present : Referee for Radiation Measurements Journal
International journal published by Elsevier Science, United Kingdom.
1998 – present : Referee for Physics in Medicine and Biology
International journal published by Institute of Physics Publishing, United Kingdom.
1997 – present : Referee for Australasian Physical and Engineering Sciences in Medicine.

International journal published by Australasian College of Physical Scientists and Engineers in Medicine and the College of Biomedical Engineers, Australia.

2005 – present Guest Associate Editor for Medical Physics
International journal published by American Institute of Physics, USA.

2006 – present Referee for Iranian Journal of Science and Technology : Transactions A ; Sciences. School of Sciences :Shiraz , Islamic Republic of Iran.

Appendix 2 COMPLETE LIST OF PUBLICATIONS

PUBLISHED JOURNALS AND CONFERENCE PROCEEDINGS ARTICLES

1992

1. Metcalfe P., Kron T., Clubb B., Butson M., Mathur J. (1992) Radiotherapy X-ray surface dose; what happens in the first millimetre? Aust. Phys. Eng. Sci. Med. Conference, Gold Coast, Queensland, Australia.

1993

2. Kron T., Butson M., Wong T., Metcalfe P. (1993) Readout of TLD dosimetry chips using a contact panchet heater. Aust. Phys. Eng. Sci. Med. 16(3): 137-142.

1994

3. Butson M., Perez M., Mathur J., Metcalfe P. (1994) Prediction of near surface dose from X-rays used for radiotherapy patient treatment: the incident angle effect. Aust. Phys. Eng. Sci. Med. Conference, Perth, Australia.

4. Butson M., Wong T., Kron T., Mathur J., Clubb B., Metcalfe P. (1994) Surface doses from combined electron/photon fields in radiotherapy. Aust. Phys. Eng. Sci. Med. 17(1): 14 - 22.

1995

5. Rosenfeld A., Carolan M., Kaplan G., Butson M., Metcalfe P., Allen B. (1995) The effect of encapsulation on MOSFET response in Neutron-Gamma and X-ray fields. Invited Poster at Experimental Radiation Oncology Workshop, sponsored by the Clinical Oncology Society of Australia, (Abstract in Proceedings) Sydney, Australia.

6. Rosenfeld A., Carolan M., Butson M., Metcalfe P., Allen B., Khivrich V.(1995) MOSFET dosimeters in mixed gamma-neutron and megavoltage X-ray fields: the role of encapsulation Aust Phys. Eng. Sci. Med. Conference, Queenstown, New Zealand.

7. Butson M., Mathur J., Metcalfe P. (1995) Skin dosimetry and skin effects in radiotherapy. Invited Poster at Experimental Radiation Oncology Workshop sponsored by the Clinical Oncology Society of Australia. (Abstract in Proceedings) Sydney, Australia.

8. Rosenfeld A., Carolan M., Kaplan G., Butson M., Metcalfe P., Allen B. (1995) The effect of encapsulation on MOSFET response in Neutron-Gamma and X-ray fields. Invited Poster at Experimental Radiation Oncology Workshop, sponsored by the Clinical Oncology Society of Australia (Abstract in Proceedings) Sydney, Australia.

9. Butson M., Mathur J., Metcalfe P. (1995) Dose characteristics of a therapax 300kVp orthovoltage machine. Aust. Phys. Eng. Sci. Med. 18(4): 133-138.

1996

10. Butson M., Rosenfeld A., Mathur J., Carolan M., Wong T., Metcalfe P. (1996) A new radiotherapy surface dose detector : the MOSFET. Med. Phys. 23(5): 655-658.

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Scanner Uniformity Improvements for Radiochromic Film Analysis with Matt Reflectance Backing.

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Abstract

A simple and reproducible method for increasing desktop scanner uniformity for the analysis of radiochromic films is presented. Scanner uniformity, especially in the non-scan direction (i.e. in portrait mode) for transmission scanning is well known to be problematic for radiochromic film analysis and normally corrections need to be applied. These corrections are dependant on scanner coordinates and dose level applied which complicates dosimetry procedures. This work has highlighted that using reflectance scanning in combination with a matt, white backing material instead of the conventional gloss scanner finish, significantly increases the scanner uniformity can be achieved within 90% of the scanning area. Uniformity within ± 1% over the scanning area for our epsonV700 scanner tested was found. This is compared to within ± 3% for reflection scanning with the gloss backing material and within ± 4% for transmission scanning in the portrait direction. The Matt backing material used was simply 5 layers of standard quality white printing paper (reflex 80gm/cm^2). It was found that 5 layers was the optimal result for backing material however most of the improvements were seen with a minimum of 3 layers. Above 5 layers, no extra benefit was seen. The results showed that the uniformity could be increased with this scanning procedure and that results for 2 dimensional dosimetry could be achieved to within ± 1% (for scanner uniformity) using this technique. This may eliminate the need to perform scanner corrections for position on the desktop scanners when using transmission mode for radiochromic film dosimetry.

Keywords,

Radiochromic film, Gafchromic, dosimetry, scanner uniformity, x-ray

Introduction

Radiochromic film has provided the medical physics community with a new, two dimensional dosimeter which can be used for many applications for dosimetry in radiotherapy, and medical imaging. One of its main advantageous characteristics is its low energy dependence to x-rays for EBT and EBT2 Gafchromic film (Butson et al 2006, Cheung et al 2006). Clinical applications for radiochromic film include kilovoltage x-ray applications (Gotanda et al 2007, 2008, 2009, Butson et al 2007, Currie 2007) and high energy x-ray applications (He et al 2008, Butson et al 1998, 1999). The films have undergone various changes over the years which have seen many variations on films types such as ISP's Gafchromic MD-55 , HS and EBT (Klassen et al 997, Meigooni et al 1996, Butson et al 2002, 2003, 2005, Cheung et al 2002) for radiotherapy applications and XR-R XR-T and XRQA (Delle Canne et al 2006, Chu et al 2007, Butson et al 2005, 2009, Cheung et al 2005) for diagnostic procedures to name a few. Other companies also have radiochromic film products which are more suited for high radiation dose applications such as B3 Windose (GEX Corporation, Centennial, Colorado, USA), Radiachromic film [2,3] (FWT technologies, Goleta CA, USA) or Radiation Imaging Film / SIRAD's [4,5] (JPLabs, Middlesex, NJ, USA) radiachromic Butson et al 2004,2005,2006, Cheung et al 2007, Miller 2003). The most commonly used films would be the original Gafchromic EBT film and now the new EBT2 radiochromic film. As these films are initially clear and turn a blue colour upon irradiation, they are suited for analysis on a common computer desktop scanner (Bouchard et al 2009, Ferreira et al 2009) as well as other more specific densitometry and spectroscopy equipment. It is well known though that desktop scanners have an intrinsic scanner non uniformity when scanning is performed in transmission mode especially in the portrait (or non-scanning) direction(Paelinck et al 2006, Menegotti et al 2008, Saur et al 2008). Menegotti et al 2008 measured a variation in normalised pixel value of up to 19% whereas Saur et al 2008 found differences of the order of 800 pixel value units. Whilst the variations seen appear to be scanner specific, all scanners exhibit some effect which if not

corrected for, can affect dosimetric accuracy for 2 dimensional dose assessment for procedures like IMRT dose verification. Due to the nature of the EBT film, both reflectance and transmission scanning can be performed. Kalef-erza et al (2008) compared these two scanning techniques and assessed reflection mode to be superior for accuracy especially at lower doses. However , both transmission scanning and reflectance scanning still produce a non-uniformity in scanner response which appears to be due to the scattering nature of light within the scanner itself especially at the scanning edges. This work has investigated the effects on scanner uniformity response for an Epson V700 desktop scanner and devised a simple method using Matt white backing paper to improve the scanner uniformity in reflection mode analysis compared to traditional transmission mode analysis.

Materials and Methods

Gafchromic EBT, radiochromic film (Lot no. 47277-06I) has been utilized for the measurement of scanner uniformity response in two dimensional radiation dosimetry. The films were exposed to solar ultraviolet radiation to produce a uniform coloration over the entire sheet of the film. This was opposed to a large x-ray field where a variation in delivered dose may exist due to flattening filter design. Films were exposed to solar Ultraviolet to produce a "x-ray radiation dose equivalent" darkness of approximately 2Gy (6 MV X-rays) and 5 Gy (6 MV X-rays). These values for reflected optical density were 0.42 OD and 0.69 OD respectively. During analysis no corrections were made for intra film non uniformity however, the films were scanned in the same position each time so that any variations would be at a constant position. Previous work by Saur et al 2008 has shown that film uniformity has been found to be within 2% for EBT film.

All films were analysed using a PC desktop scanner and Image J software on a PC workstation at least 24 hours after irradiation to minimize effects from post irradiation colouration (Cheung et al 2005). The films were kept in a light proof container when not being analysed to reduce coloration from ambient light and UV sources (Butson et al 1998). The scanner used for quantitative analysis of uniformity was an Epson Perfection V700 photo, dual lens system desktop scanner using a scanning resolution of 50 pixels per inch. The images produced were 48 bit RGB colour images and analysis was performed using the red component of the data. The films were examined in both transmission and reflectance modes. When scanning in reflectance mode, scans were performed in various configurations. These included the use of the normal gloss white scanning background as well as the use of various layers of pure white 80 gm/cm^2 matt paper (Reflex). These sheets are the common paper used for printing. The white sheets were placed behind the EBT film during the scan process in layers ranging from 1 up to 10 layers. In reflectance mode, Reflective optical density (ROD's) for all films were calculated to evaluate uniformity response in landscape and portrait directions. ROD is defined as equation 1 : -

$$ROD = \log (65536/P_t) \qquad 1$$

Where P_t is the pixel value of the reflected intensity through the EBT film. All scanner properties were kept the same for transmission scanning except that the light source used was the scanners transmission light source and the gloss white backing was removed. The films when scanned were always positioned in the same manner to eliminate differences in results caused by film polarisation effects (Butson et al 2006, 2009). For analysis of the data, the outer 1cm edge of the scanned film results were removed from the data. We have performed this as it is not an area we would normally include in the scan results due to cutting damage or marked due to handling. Results given are the average for 5 scans of each film piece performed in series using a 2cm average profile through either the landscape or portrait direction of the film. Results are quoted as

normalised OD. The average OD value over the scan length was given the value of 1 and the other results normalised to this value.

Results and Discussion

Figure 1 a shows the normalized optical density results for an EBT radiochromic film which has not been irradiated. The scan was performed in landscape mode along the scan direction of the film / scanner. The outer 1cm of film OD has been removed from the results as mentioned in the material and methods due to any uncertainties in analysis due to film cutting or handling marks as is our normal process in film dosimetry. As can be seen for a 0cGy film, in landscape mode, there is minimal scanner non uniformity for transmission mode and reflection mode with 5 layers of matt white sheet backing (approximately within ± 1%) for the entire length. In reflection mode without the white backing, there is a larger (up to 5%) increase in OD near the beginning of the film scan. Figure 1b shows similar results for landscape mode for the film scanning scenarios with an exposed film (approximately 2 Gy equivalent). These results also show low level variations along the scan plan with the transmission and matt backing reflection methods producing less than ± 1% variation and normal reflection mode with an approximate 1.5% variation at the beginning of the scan and less than 1% elsewhere. These results are similar to other researchers (Menegotti et al 2008, Saur et al 2008) whereby a relatively uniform response is seen in landscape mode or along the scan plan direction.

Figure 2 however shows the profile results for a scan performed in the portrait direction or across the scan plane for a non irradiated EBT Gafchromic film when analysis is performed in reflection and transmission mode. If transmission mode is used, a significant variation across the profile is seen with a variation of up to 7% seen on this film. The largest OD values (or darkest scan results) were seen at the edges. A similar but not as large effect is seen for reflection mode with the normal

gloss white backing material whereby an approximate 4% variation is seen. The variation follows a similar pattern as transmission mode with the outer edges being measured as darker than the centre. When the film is scanned with a Matt white backing material, the variation is significantly reduced as shown by the figure where 5 layers of white backing material are used. The variation has been reduced to less than 2 % across the film piece. Figure 3 shows the same profile measurement in portrait mode when the scans were performed with varying layers of white paper behind the EBT film. Results shown are for 0 sheets (normal) 1 , 3 and 5 sheets backing. Up to 10 sheets in multiples of 1 were tested. As can be seen, there is a significant improvement in uniformity by using 1 sheet of backings paper over the normal gloss background. Further improvements are seen for 3 sheets. It was found that 5 sheets provided the most uniform response across the film profile and that by adding more sheets of white backing paper, no further increase in uniformity was achieved. For this experiment, the standard deviation of results across the portrait profile for the normal gloss background, 1 sheet, 3 sheets and 5 sheets were found to be 0.0113, 0.0047, 0.0041 and 0.0040 respectively. This shows that 3 to 5 sheets of matt white backing paper placed behind the EBT film and scanning in reflection mode increases the uniformity of scanner response. Similar effects were seen for irradiated films.

Figure 4a shows the results for a film irradiated with solar UV to reach a darkness of approximately equivalent to 2 Gy X-rays at 6MV energy. Figure 4b for a darkness equivalent of 5Gy. Results show that the scanner uniformity for the matt backing reflection mode scan is far superior to the normal reflection scan and to transmission scan mode as well. In each case, the uniformity across the film in portrait mode was found to be within ± 1% as compared to variations of up to 7% for transmission mode. The improvement in uniformity is expected to be achieved by the minimization of both reflections within the scanner and other sources of scattered light which can form a significant part of the signal for transmission mode and for reflectance mode scanning with the high gloss white backing normally provided with the scanner. By utilizing a matt white

backing, we reduce the reflected or scatter light to a level which obviously provides a much more uniform response in both the landscape and portrait scanning direction. To perform high accuracy film dosimetry using radiochromic film and desktop scanners in transmission mode, normally a scanner uniformity correction needs to be applied to the results as shown by Menegotti et al 2008. These are shown to be both dose and position dependant. The use of the matt backing material has appeared to minimize the scanner non uniformity to a level which could be acceptable for dosimetry purposed thus eliminating the need to perform such corrections. As reflection mode scanning is normally much quicker to perform, the use of reflection mode and the matt backing material would certainly increase the speed of analysis whilst retaining a high level of accuracy for film dosimetry. Results have of course only been performed on our Epson V700 scanner and others would need to assess their own desktop scanner for this level of uniformity before adopting this procedure into clinical practice.

Conclusion

The work has shown that by using a matt white backing material for reflection scanning of radiochromic film, the non uniformity of scanner results in the portrait direction can be minimized to a level within ± 1% using an Epson V700 desktop scanner. This provides an improvement on normal reflection scanning with the gloss white background and transmission scanning where up to 7% variations were seen over the same scan area. Matt backing, reflection scanning may be used to eliminate the need for scanner non uniformity corrections which need to be applied for transmission mode scanning when high accuracy dosimetry is required.

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Captions to Figures

Figure 1. Variation in normalised OD in landscape (along scan direction) axis for non irradiated (a) and an exposed (2Gy equivalent darkening) (b) EBT Gafchromic film pieces in transmission, normal reflection and Matt Backing reflection mode.

Figure 2 : Variation in normalised OD in portrait mode (across scan direction) for non irradiated EBT Gafchromic film pieces in transmission, normal reflection and Matt Backing reflection mode. Significant differences in uniformity of results are seen.

Figure 3: Effects of the layers of Matt backing material on the uniformity of reflection mode scanning in portrait mode.

Figure 4 : Variation in normalised OD in portrait mode (across scan direction) for EBT films irradiated to 2 Gy (a) and 5 Gy (b) (equivalent darkening) in transmission, normal reflection and Matt Backing reflection mode. Significant differences in uniformity of results are seen.

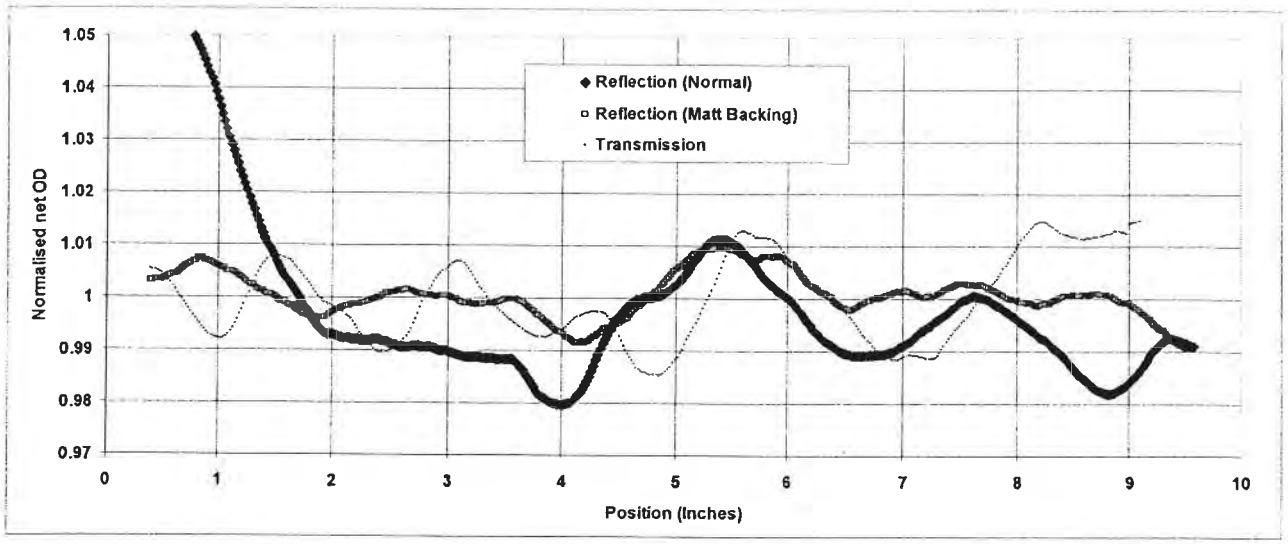

Figure 1a

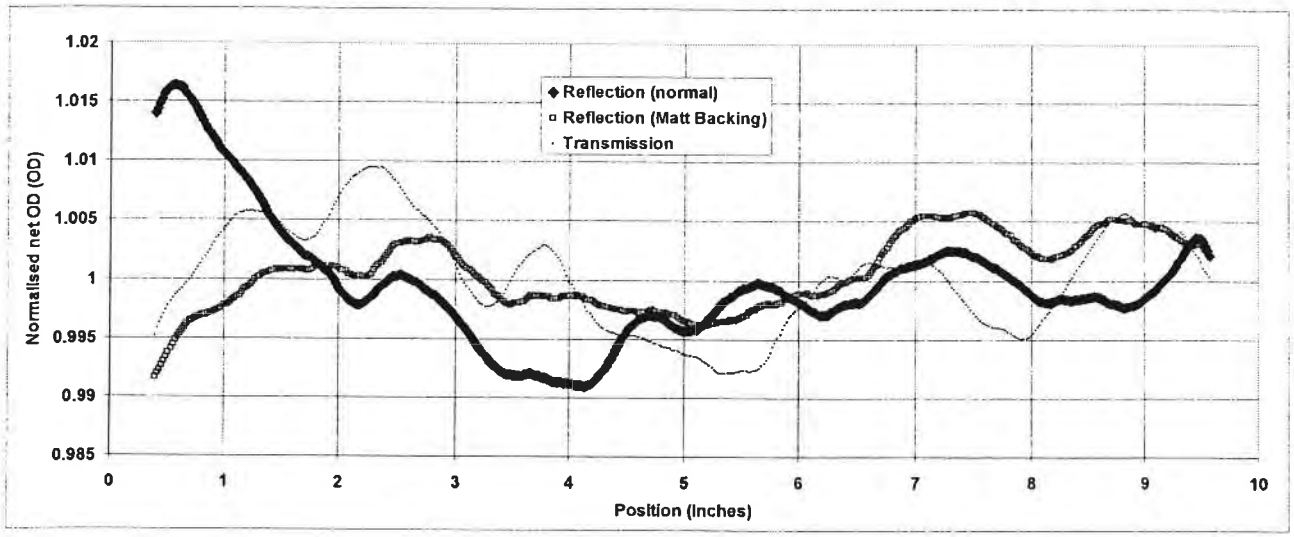

Figure 1b

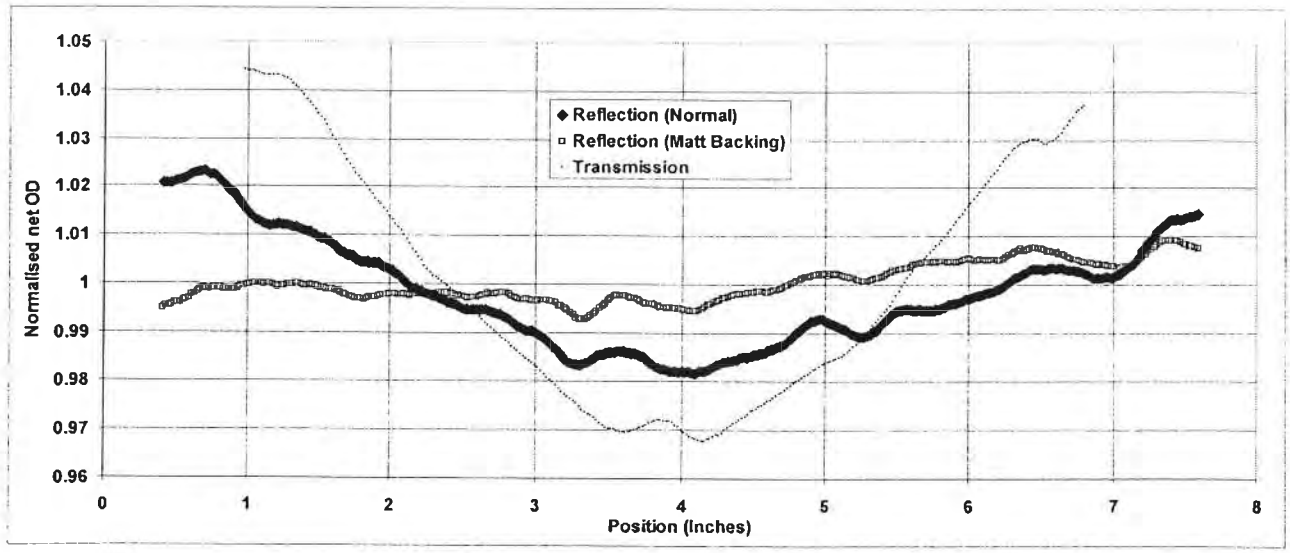

Figure 2

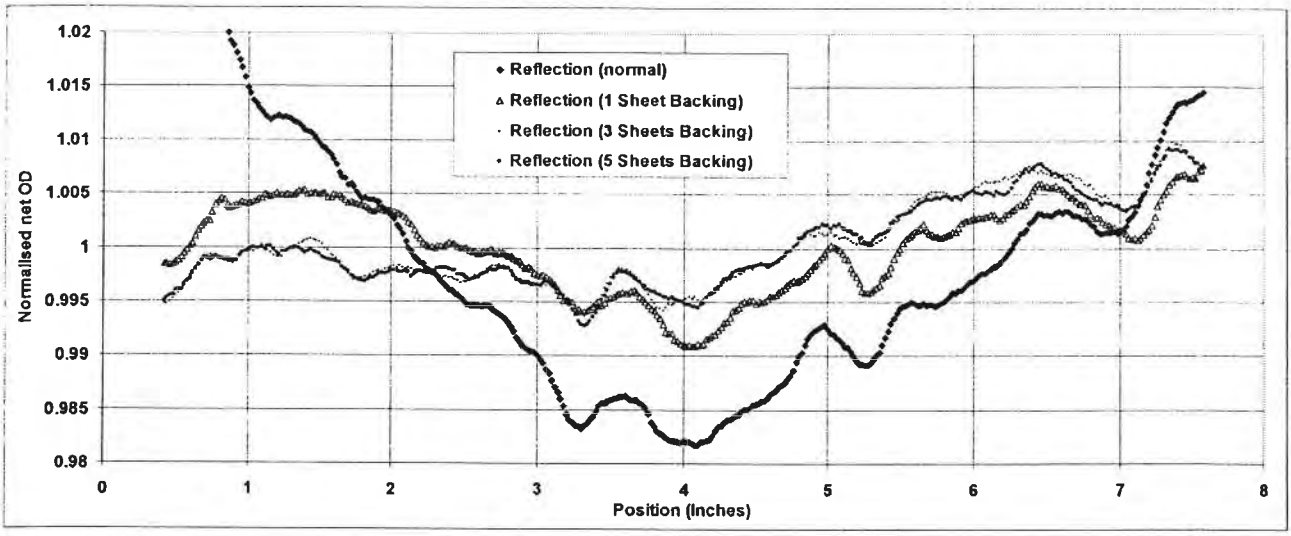

Figure3

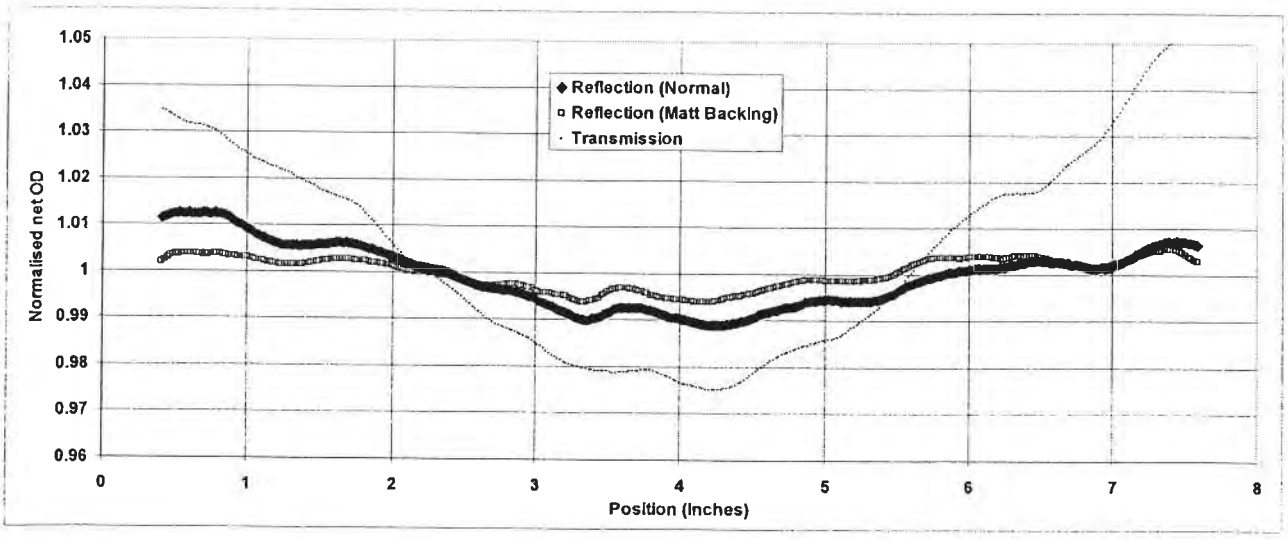

Figure 4a

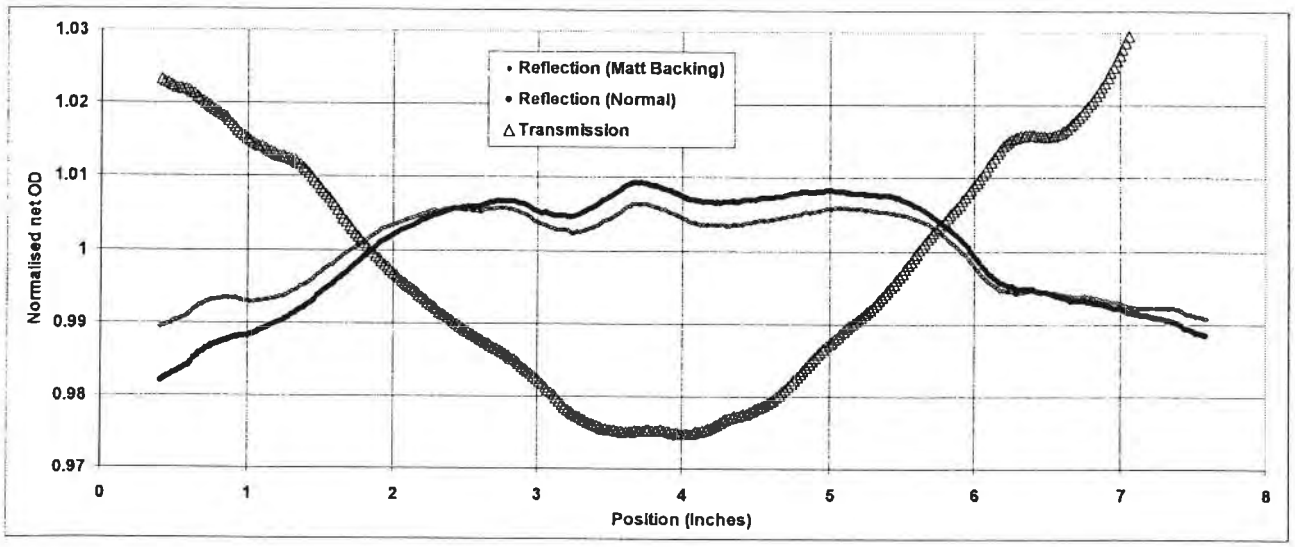

Figure 4b

4.3 Radiation Dosimetry of x-ray, electron and ultraviolet beams

(Volume 4)

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