GAMOS DICOM Simulation on Occupational EL Dose due to ^{99m}Tc and ^{131}I Exposures in Nuclear Medicine Departments

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Abstract. Radiation induced cataracts is a disease that is common amongst radiation exposed staff. About 30 percent of retired occupational radiation workers developed eye lens (EL) cataracts. Epidemiological studies on radiation therapy patients, occupational workers, and atomic bomb survivors show that 0.5 Gy of acute or fractioned radiation dose to EL causes one or both lens to cloud. The annual EL dose limit drawn by the International Commission for Radiation Protection (ICRP) was 150 mSv and was changed in 2012 to 20 mSv averaged over 5 years, with no single year exceeding 50 mSv. The limited number of researches done in Nuclear Medicine (NM) clinics with the Hp(3) dosimeters suggest that the annual EL dose from three procedures is measured to be between 4.5 and 9 mSv (i.e. dispensing, preparing and administering). These procedures are performed when the radioactive materials are in closed shielded containers or behind a barrier. Common radioactive material handled by occupational workers in NM clinics are ^{99m}Tc and ^{131}I . They pose less radiation hazard to workers EL in the three procedures when they are behind shielded containers. Moreover, once the radioactive material is administered into patients, they become open sources and pose more radiation hazard to workers. The Hp(3) dosimeter is a new uncommon dosimeter. Many radiation facilities use the Hp(0.07) and Hp(10) dosimeters coupled with many conditions and conversion factors to find approximate results. Therefore, simulations are performed to find the EL dose. However, some simulations are performed with little flexibility in simulation geometry, others utilize low-quality phantoms or present the simulation results in terms of fluxes or energy ranges. In the present study, the NM worker EL dose is simulated by utilizing a high-resolution Digital Imaging Communication in Medicine (DICOM) image in GEANT4 Architecture for Medical Oriented Simulation (GAMOS). A water cylinder homogeneously filled by radioactive material, representing the administered patient, was created in the simulation. The worker exposure scenario was simulated by placing the cylinder in three different directions and five different distances with respect to the DICOM image. The results of the simulation reveal that the highest occupational EL radiation dose is received from the anterior-posterior direction, followed by the lateral, and the posterior-anterior directions. The results of the conservative simulated scenario reveal that the worker EL dose is exposed to three tenths of the annual dose limit after 110 ^{131}I patients, or 300 ^{99m}Tc patients.

Keywords: EL Radiation Dose, GAMOS, GEANT4, Monte Carlo Simulation, EL Dose in Nuclear Medicine Reference, ^{131}I , ^{99m}Tc .

1. Introduction

Occupational EL radiation dose has been studied in many radiation facilities like nuclear energy, hospitals and in space trips as well as

in atomic bomb survivors ^[1-3]. Radiation-induced cataract is a common disease amongst occupational workers. It is shown that 0.5 Gy acute dose in the lens of the eye can cloud the lens in a matter of weeks or months ^[1]. For

low-level occupational workers exposures, there is 10-30% chance of radiation-induced cataracts to appear ^[1]. Radiation-induced cataracts dose limit model is a deterministic non-threshold model, which means that cataracts can even occur without a radiation dose ^[3]. Moreover, recent epidemiological studies suggest that radiation-induced cataract occurs if less than 0.5 Gy is deposited in the lens ^[1-4]. The EL dose limit drawn by the International Commission for Radiation Protection (ICRP) used to be 150 mSv/y, in 2012 and then it was reduced to 20 mSv/y, averaged over 5 years with no single year exceeding 50 mSv ^[2]. This reduction in lens dose has raised concern amongst occupational workers in all radiation fields.

Radioactive sources like ^{99m}Tc and ¹³¹I are commonly used in Nuclear Medicine NM departments. The gamma energy range of these two radionuclides is between 80 keV and 364 keV at different yields. The dose administered to patients for diagnosis and treatment are at a maximum of 25 mCi [935MBq] and 150 mCi [5.55GBq] for ^{99m}Tc and ¹³¹I, respectively^[5]. Radioactive materials are kept in closed shielded containers and are named open sources once they are transferred from the closed shielded containers to patients. Patients administered with a radioactive material become an open source from which radiation escapes; escaped radiation from patients comprises a radiation dose to NM workers' EL.

EL dose is clinically measured by $H_t(3)$ dosimeters, which are by far the most accurate for this purpose, because of their function to measure the dose at 3 mm depth ^[4]. $H_t(3)$ dosimeters can be Thermo Luminescent Dosimeter (TLD), Optically Stimulated Luminescence (OSL), and Ionization Chamber (IC). They specialize in measuring the dose at 3 mm depth ^[6]. This depth is of most concern because of the EL location with respect to the

point of placing the dosimeter ^[6]. The $H_t(3)$ dose-measuring depth can converge off of the lens sensitive volume ^[2,4,6]. $H_t(10)$ and $H_t(0.07)$ dosimeters are commonly used for deep depth dose and skin dose deterministic effect, respectively ^[6-7]. It should be noted that the whole body effective dose is not a good indication of the EL dose. As a matter of fact, the effective dose tables drawn by the ICRP exclude the EL, even in the remainder term. Also, the $H_t(0.07)$ dosimeters, require conversion factor to account for the lens depth, as well as that the $H_t(0.07)$ dosimeters are not a good measurement of dose due to beta particles ^[6,8,9].

Clinical research done in this topic shows little information with regard to the method with which procedures are performed in NM clinics (Table 1). Actually there is a variation in the results found in literature due to several reasons. For example, the number of occupational workers who are assigned to do one procedure, the duration of exposure in each procedure, the clinical procedure protocol, radiation uniformity, shielding parameters, and the location of the EL dosimeter with respect to the worker's lens. Some researchers have made a clear association between the lens dose and the clinical procedures. Other researchers have only presented the final value for the EL dose (Table1).

Table 1. Comparison between clinical lens dose in literature.

Isotope	Experimental (Clinical)		
	Dabin <i>et al.</i> , 2016 ^[10]	Summers <i>et al.</i> , 2012 ^[8]	Leide-Svegborn, 2012 ^[11]
¹³¹ I	50 µSv	30µSv	N/A
^{99m} Tc	N/A	22µSv	18µSv

The annual EL dose has been clinically measured between 4.5 to 9 mSv per year for ^{99m}Tc and ¹³¹I, respectively^[8]. Also, the EL is

estimated to receive $18\mu\text{Gy/procedure}$ for ^{99m}Tc [8]. The mentioned procedure is mainly, dispensing the radiopharmaceutical from the generator, preparing the vial, injecting and positioning the patient. On the other hand, for the ^{131}I procedure, it was measured to be $50\mu\text{Sv}$ per procedure and $30\mu\text{Sv}$ per procedure [10]. The variation of these values is due to the protocol used in each clinic and other factors stated earlier.

Monte Carlo (MC) simulations have been performed to find the dose to the lens of the eye [2, 12-14]. The existing simulations have been done by different simulation codes. Their [codes] EL dose results are in terms of fluxes for specified energy ranges and extracting the dose information is a tedious process, especially for isotopes like ^{131}I , that has more than one energy. The reference EL phantoms used for radiation protection simulations in International Commission for Radiation Protection (ICRP) 110, and 116 are stylized mathematical, and the computational phantoms. The phantoms were irradiated by three geometrical orientations Anterior-Posterior (AP), Lateral (LAT), and Posterior-Anterior (PA). The irradiation was directed from a parallel plane directly to the phantoms. The Digital Imaging Communication in Medicine (DICOM) phantom was selected because its results for EL dose is higher (more conservative) than the mathematical phantom for energies below 1 MeV [2]. Moreover, the current DICOM phantoms used for radiation protection by the ICRP are of low resolution [2,13]. Other simulation works in the literature utilized a cylindrical lens, and slab lens phantoms to find the EL dose with respect to photon energy [14]. However, using a cylinder or a slab is less of a representation of the EL and its surrounding anatomical structures [2, 13-15].

GEANT4 based Architecture for Medical Oriented Simulation 5.1.0 (GAMOS

5.1.0) is a simulation toolkit that works under Ubuntu 16.04 operating system [16]. The current GAMOS version enables users to model simulations using DICOM images and to tailor dose simulation for the EL. GAMOS is a free licensed and is capable of simulating all radiation involved scenarios whether for workers or patients, with utmost flexibility in simulation geometry.

In this work, an EL DICOM image, representing the worker's lens, was acquired to give tailored anatomical structures as well as the ease to contour the EL. Computational Environment for Radiotherapy Research (CERR) and GAMOS have been utilized to contour and simulate the radiation dose to the nuclear medicine workers' EL, respectively [16-17].

Materials and Method

1. Simulation Scenario in NM Clinic

In NM departments ^{99m}Tc and ^{131}I are used in clinical routine. These two radionuclides are independently mixed with other compounds to target patient organs for diagnosis and treatment, respectively. The occupational exposure scenario simulated embodies both patient and worker standing at different distances for three consecutive minutes (Fig. 1). The duration of three minutes was selected to represent the maximum observable time a NM worker spends with a patient. The most important simulation for radiation protection purposes in NM is set at 30 cm anterior-posterior (AP) direction, which is the distance and direction for a close contact between the worker and the patient. The simulation also undergoes the change of patient height with respect to the worker (Fig. 1) [18].

2. NM Worker Representation

A DICOM Computed Tomography (CT) image of a healthy head and neck was

obtained. The DICOM image obtained is 145 slices and the eyes are pictured in 15 consecutive slices while the lenses appear in only 6 slices. Each slice is 512 by 512 pixels. The resolution of the image obtained is 1 mm in all directions. However, at this resolution, the EL can be contoured more confidently than images with bigger voxels sizes. Figure 2 shows the DICOM image, X and Y coordinates, slice number, as well as tissue densities. Each color corresponds to a density in the image. GAMOS assigns the densities with respect to their actual Hounsfield Unit (HU) automatically^[16]. The significant volume

of both lenses is 1cm^3 , which adds to 500 voxels per lens.

The EL in the image was contoured such that all lens pixels were contained in one structure and such that the left and right ELs are named “lens”^[2]. The contoured structure in the image is as per the ICRP recommendation about the EL significant volume, which is the average of both ELs (Fig. 3). The couch was also contoured because it is composed of materials other than air, which can affect the results of the simulation. The contour was done by using CERR toolkit built-in MATLAB R2016B, as shown in Fig. 3.

Fig. 1. Simulation scenario setting schematic diagram showing open Source (patient) (right), and the DICOM image (left) produced by GAMOS.

Fig. 2. Worker's DICOM image generated by GAMOS showing removed couch.

Fig. 3. EL significant volume and couch contour by CERR on MATLAB representing the worker image.

3. Open Source Representation

A GEANT4 water cylinder named “patient” is created in GAMOS such that it has 40 cm diameter and 40 cm height (Fig. 4). These dimensions are selected based on the dimensions of DICOM image healthy individual. The simulated open source has a 25 mCi [960 MBq] for ^{99m}Tc , and 150 mCi [5550 MBq] ^{131}I administered activity, which are the highest permissible activities administered to patients for diagnosis and treatment [5]. This water cylinder representing the open source has been located in the simulation at 5 different distances and at three different geometrical positions: AP, LAT, and PA, around the radiation worker as shown in Fig. 1. In addition, the cylinder was relocated vertically to foresee the effect of patient height (open source height) on radiation worker’s lens dose. The selection of vertical movement in the simulation is due to the fact that the DICOM image is a head and neck image, different from a whole body DICOM image simulation, where elongating the cylinder is feasible.

Fig. 4. A cylinder representing the open source in the simulation produced by GAMOS (not to scale).

4. GAMOS Simulation

The dose was scored in the DICOM image voxels named “lens” deriving from the exposure to ^{131}I , and ^{99m}Tc isotropic and cylindrical sources. The cylindrical source is simulated as a substitution to represent the

patient such that the radioactivity was distributed homogeneously in it (Fig. 4).

The photons that escape the EL deposit some of their energies on their way exiting the contoured lens volume. G4 tracking option has been used to account for photon attenuation within the voxels traversed in the lens structure. This option account for the scattering and energy deposition inside the voxels that are named “lens” [16]. The gradual change in photon energy inside the lens voxels is an essential GAMOS property. It enables simulating the dose to the lens even if the photons did not lose all of their energies in the lens.

Two GEANT4 physics lists named Standard Electromagnetic Physics along with Radioactive Decay Physics were used. Electromagnetic physics list tracks low energy photons down to 10 keV. The information of radioactive decay of ^{99m}Tc and ^{131}I were collected from the table of isotopes and were plugged in GAMOS manually [19]. Several GAMOS printers were used to score dose to the EL structure: PSPrnterG4Cout, and PSPrnterDoseHistos [16]. Each printed file gives the user some results, and each file can be analyzed differently. For instance, the text files printed from PSPrnterG4Cout could be processed in an Excel sheet and plotted. On the other hand, the PSPrnterDoseHistos printer could print information like the dose error and the number of runs. To reduce statistical errors to 1-5 %, the number of histories used is 40 million, which reduced the results error to 2 % and raised the simulation time to 45 minutes per simulation. One simulation per irradiation location per distance has been done; a total of 15 simulations for each irradiation direction were performed. Also, another 5 simulations were performed to find the lens dose with respect to patient height.

5. GAMOS Results Validation by VMC

Virtual Monte Carlo (VMC) simulation toolkit includes a DICOM image of a reference person [20]. This simulation toolkit is verified by International Atomic Energy Agency (IAEA), the ICRP and International Commission for Radiation Units (ICRU). Therefore, VMC can be utilized to check GAMOS results. However, the simulation scenario in VMC can only be built with a point source. Thus, it is essential to make both GAMOS and VMC simulations similar by choosing a point source of equal activity. The point source is placed at different distances from the DICOM image in VMC. Also, the point source was geometrically displaced in the AP, LAT and PA directions. The simulation results from VMC are compared to GAMOS results in the next section.

Results and Discussion

It should be noted that the difference between the simulation results from this simulation and the clinical EL dose values obtained from the literature (see introduction) is reasoned by the difference in the radiation exposure scenario (see results), and the clinical procedure (see introduction). This section will illustrate that the presence around an open source imposes a radiation dose to the worker more than the whole clinical procedure reviewed in the introduction. Also, this section will present the NM occupational EL dose change with respect to patient height relative to the worker.

1. GAMOS Results Verification

Radiation emitted by a point source travels directly to the worker without being attenuated in any other media than air. The EL dose from both simulation toolkits shows the inverse square law relation. Also, both toolkits result for AP, LAT and PA directions are consistent from highest dose to lowest, respectively (Fig. 5-9).

Although the resolution of the image is higher, the results from GAMOS show consistency within 10 % compared to VMC. The EL dose simulation result for close contact by GAMOS shows a dose of $231 \pm 3.51 \mu\text{Sv/Scenario}$. On the other hand, the EL dose result of VMC simulation for close contact is $270 \mu\text{Sv/Scenario}$ (Fig. 6). This difference is essentially because of the difference in contouring the EL. The cylindrical water open source result for close contact is $58.8 \pm 0.5 \mu\text{Sv/Scenario}$, which is way below the results from a point source (Section 4.2).

The irradiation by ^{131}I point sources that took place in GAMOS and VMC simulations from the LAT and PA directions showed a 4 % difference in radiation EL dose results. On the other hand, VMC showed 149 and 71 $\mu\text{Sievert/Scenario}$, for LAT and PA directions, respectively (Fig. 6).

2. GAMOS Open Source

Simulating or calculating the NM worker EL dose due to the exposure of an open source by using a point source is an overestimation of the dose because the radioactivity is condensed at one point. A more realistic simulation is done by GAMOS, which accounts for the scattering inside the patient and the distribution of the radiopharmaceutical inside the patient. Moreover, in this simulation the photons traverse the water cylinder and attenuate inside it (open source), then some of them reach the worker's lens.

The AP direction has the highest lens dose among all directions. This is because the EL is facing the open source. Figure 7 shows the EL dose from ^{131}I and ^{99m}Tc open sources for the AP and LAT directions. The lens receives a lesser dose from the LAT directions than the AP. This reduction is due to scattering and absorption of radiation in other head structures. The reduction is about half the value for the AP direction. The dose values at

close contact (30 cm) received in the lens by ^{99m}Tc for the AP direction is about half the value for the dose received by ^{131}I . ^{131}I AP lens dose is simulated as about 58.8 ± 0.05 $\mu\text{Sv}/\text{Scenario}$, while ^{99m}Tc dose to the lens is 24.4 ± 0.3 $\mu\text{Sv}/\text{Scenario}$. On the other hand, the lens dose from simulated ^{131}I and ^{99m}Tc from the LAT direction is 21 ± 0.54 and 7.93 ± 0.35 $\mu\text{Sv}/\text{Scenario}$, respectively (Fig. 7).

GAMOS simulation shows that the dose received from the PA direction is even less than the LAT direction. The reduction in the dose is about ten percent compared to the LAT direction (Fig. 8). This is explained by the distance that the radiation travels before depositing energy in the lens and by the scattering and the deposition of energy in the skull and brain, respectively. On the other

hand, the dose from ^{99m}Tc from the PA direction is simulated to be 9.08 ± 0.49 μSv per procedure for ^{131}I and 1.18 ± 0.33 $\mu\text{Sv}/\text{Scenario}$ for ^{99m}Tc .

3. Open Source Height

Patient height plays an important role in occupational EL dose in the NM department. If the open source is taller or shorter, the EL dose changes [18]. The simulation is performed with patient administered activity kept constant. Figure 9 shows the dose is changed by the increase or decrease in patient height with respect to the worker. The worker height in the clinic was assumed to be 170 cm. The zero point in Fig. 9 implies that there is no difference in height between the open source and the worker.

Fig. 5. Comparison between worker lens dose by VMC and GAMOS for ^{131}I point and open sources scenario with respect to distance from AP direction.

Fig. 6. Comparison between worker EL dose by VMC and GAMOS for ^{131}I , point and open sources with respect to distance from LAT and PA directions.

Fig. 7. EL dose from AP and LA directions per procedure with respect to distance to open source.

Fig. 8. EL dose per scenario with respect to distance of an open source from the PA direction.

Fig. 9. I^{131} EL dose per scenario with respect to open source height.

The dose is at a maximum when there is no difference in height between the worker and the open source. Then, the worker EL dose decreases gradually for shorter and taller open sources. This is explained by the longer distance that radiation travels from the open source to the worker EL. The farther the open source is the less exposure to EL. Moreover, decreasing the worker EL dose by changing height means that other body organs are irradiated.

Based on the simulation settings and the assumption listed in the material and method section, the number of patients that a worker can process to stay in the uncontrolled group is 300 patients for ^{99m}Tc patients or 130 ^{131}I patients per year. At this workload in clinics, it is feasible for workers to operate on patients ^{131}I and ^{99m}Tc safely and without placement in the control group. ALARA principle states that the lesser exposure to radiation is the better. This indicates that the selection and matching of patient and worker with respect to height are recommended, especially in ^{131}I procedures.

6. Conclusions

GAMOS and CERR constitute a feasible combination to create an EL phantom for simulations. Also, GAMOS and VMC point sources simulations results are in line with each other. Moreover, a complex geometrical scenario simulated by GAMOS reveals that the worker EL dose from an open source can reach 0.5 Gy depending on the workload.

The dose to the worker EL is not only composed of the exposure scenario in this simulation. Other exposures occur in NM clinics when sources are in closed shielded containers. The simulation performed illustrates the EL dose after radioactive material is transferred to patients. The results of the simulation reveal that the exposure from the AP direction exposes NM workers to higher radiation dose than the LAT and PA

directions. On the same line, the numerically calculated number of patients that can be processed by one NM worker is based on one exposure scenarios.

Shielding the eyes is done by using goggles. Goggles are one type of radiation protection used in radiation fields. The goggles that could attenuate the ^{131}I is heavy enough to fall down the worker's head. Therefore, it is rarely used in NM clinics. Performing a shielding simulation can be done for designing a goggle that is fit to stay still on the NM worker's face. The shape and curvature of the goggles, and its fitting on the worker's head, all constitute the effectiveness of shielding. Therefore, shielding simulation and measurements must be studied separately.

There are several steps that could be done on this topic like acquiring a higher resolution image of a reference EL phantom by a CT scanner. Also, to place two DICOM files in one simulation to foresee patient-worker radiation dose. Also, to utilize a DICOM Positron Emission Tomography (PET) image hot spots in simulation. On the same line, the GEANT4 collaboration is currently developing the .STL file format to fit into simulations. The new STL file format is promising to make this simulation feasible by reducing files size and GPU memory.

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محاكات الجرعة الإشعاعية من مرضى الطب النووي لأعين العاملين باستخدام الصور المقطعية الرقمية

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المستخلص. يعتبر مرض عتامة العين (المياه البيضاء) من الأمراض الشائعة بين المتعاملين مع المصادر المشعة. حيث إن نسبة ٣٠٪ من المتقاعدين من هذا المجال تعرضوا لهذا المرض، حسب ما تم إعلانه في أبحاث حديثة. فقد تمت دراسة تأثير الإشعاع على عدسة العين في حقول إشعاعية، منها مرضى العلاج الإشعاعي، والعاملين في الإشعاع، والناجين من القنبلة الذرية. الدراسات الحديثة تشير إلى أن هناك احتمالية كبيرة جداً بالإصابة بعتامة العين في حال التعرض لجرعة إشعاعية مقدارها ٠,٥ جراي، سواء على دفعة واحدة أو على جرعات متعددة. ونظراً لذلك، قامت ال آي سي آر بي بخفض الجرعة السنوية للعاملين في الإشعاع من ١٥٠ ملي سيفرت إلى ٢٠ ملي سيفرت، بحيث لا تتجاوز الجرعة السنوية ٥٠ ملي سيفرت خلال خمسة سنوات. ويوجد عدد محدود من البحوث التي تطرقت لهذا الموضوع في عيادات الطب النووي باستخدام مقياس الاتش بي ٣ للإشعاع. وتختتم هذه البحوث بأن الجرعات الإشعاعية لعينون العاملين في قسم الطب النووي تكون بين ٤,٥ و ٩ ملي سيفرت من خلال بعض الأعمال، مثل تحضير وحقق المواد المشعة. وفي عيادات الطب النووي كالمستشفى الجامعي، يعتبر البود ١٣١ والتكنيشيوم ٩٩ إم من المصادر المشعة المستخدمة، غير أن تأثيرهما يكون محدوداً حال تواجدها داخل الصناديق المدرعة، وإن البدء في إخراجها لتحضير الجرعات، وكذلك إعطاء الجرعة المشعة للمريض يحول المريض إلى مصدر مشع مفتوح، وبالتالي يزيد من احتمالية التعرض. ويعتبر مقياس الجرعات ال اتش بي ٣ جديداً وغير مألوف. عادة ما يستخدم بديل كال اتش بي ٠,٧، والاتش بي ١٠ لقياس الجرعة الإشعاعية لعينون العاملين. ومن اللازم حساب الجرعات تحت شروط معينة وباستخدام معادلات وثوابت معينة بهذين المقياسين للحصول على نتائج مقاربة. ومن الجدير بالذكر أن بعض الثوابت اللازمة لهذه الحسابات معلومات لا يمكن الوصول إليها بسهولة. ولهذا تمت عملية المحاكاة بالحاسوب في أكثر من عمل. وتكون هذه الأعمال إما باستخدام صور مقطعية ذات وضوح منخفض أو بأبعاد محدودة أو بنتائج مطروحة بوحدات معتمدة على طاقة الفوتون الصادر. وفي هذا البحث، تم

عمل محاكاة (جاموس) باستخدام صور مقطعية رقمية عالية الوضوح وبأبعاد هندسية مشابهة لوضع المتعاملين مع المصادر المشعة في عيادات الطب النووي. وتمت محاكاة المريض المحقون بمادة مشعة باستخدام أسطوانة مليئة بالماء، مع الأخذ في الحسبان المسافات بين المريض والعامل. وتم التطرق إلى تأثير طول المريض على الجرعة الإشعاعية لعيون العامل. وتكشف نتائج المحاكاة أن أعلى جرعة إشعاعية لعدسة عيون العامل في قسم الطب النووي عندما يكون المريض مواجهًا للعامل، يليها عندما يكون المريض بجانب العامل، ويليهما عندما يكون المريض خلف العامل. وبناءً على أعلى نتيجة من المحاكاة، تم حساب أعلى عدد من المرضى الذين من الممكن أن يديرهم العامل قبل حصوله على جرعة ثلاثة أعشار الحد السنوي ليكون ١٠٠ مريض (يود ١٣١) و ٢٦٠ مريضاً (تكنيشيوم ٩٩ إم).

كلمات مفتاحية: جرعة الإشعاع للعيون، يود ١٣١، GAMOS، محاكاة مونت كارلو، جرعة للعيون في مرجع الطب النووي، تكنيشيوم ٩٩ إم.