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(別紙様式 2)
(Separate Form 2)

論文内容の要旨
Summary of thesis contents

In workplaces near radiation-generating devices and radioactive sources, such as accelerators, X-ray tubes, and radioactive nuclei, radiation dose must be controlled properly to prevent hazards caused by exposure to radiation. Photon dosimetry is required in these situations because photons are easily produced as secondary radiation of energetic charged particles and neutrons, and emitted from materials activated by irradiation of primary particles. Concerning photon dosimetry, many dosimeters, methods, and standard fields have been developed that involve the energy region of interest in the present research.

Following the nuclear reactor accident in Fukushima in 2011, a concern for Cs-137 contamination has increased alone with an interest in radiation safety. From distributions of Cs-l37 during the Fukushima accident, many detected photons have energies of ～200 keV as a result of the multiple Compton scattering. This is also an energy region of interest for medical dosimetry researches including γ sources used in nuclear medicine and diagnostic radiology. The dosimetry for photons with energy of hundreds keV is very important in various fields, but the appropriate detector for this range is limited almost only to an ionization chamber and there is no mono-energetic source which is suitable to the low energy region around the energy of 200 keV.

In the present research, studies of photon dosimetry up to several hundred keV of energy were performed by the following two approaches. One is to measure the response of plastic scintillator for various photon energies, and the other is the development of a mono-energetic low-energy photon field. These are used to further improve dosimetric reliability of the existing employed dosimeters.

For photon (γ/X) detectors and dosimeters, the energy of incident radiation is a major factor that may distort their responses. The dosimeters are normally calibrated at high-energy photons using a radioactive source such as Cs-137 (662 keV), but they are used in the majority of cases at a lower energy region. The variation of the response of a dosimeter as a function of photon energy must be examined. Especially, the region around 200 keV is critical for the response of a dosimeter owing to the transition point of photon interaction from photoelectric effects to Compton scatterings. Some dosimeters such as NaI(Tl) are known to have an excess response for ～200 keV photons. Currently, the best way to evaluate the photon dose is by measuring it with a properly calibrated air ionization chamber, which is a common reference for dose measurements in various fields since it has a flat response independent of photon energy. In medical applications such as interventional radiology or depth dose measurements in phantom, the dose measurements for narrow photon fields drive the needs of a smaller size dosimeter with high accuracy. A small-size ionization chamber is possibly used under the limitation of low efficiency due to the low density of air.

A plastic scintillator is a good candidate for photon dosimetry because its effective atomic number approximately equals to that of human soft tissue. The plastic scintillator has also several advantages as a detection material such as higher detection efficiency, lower cost, flexibility in shape, and independence of atmospheric factors like pressure, humidity and temperature. Because of its 863 times higher density than that of air, a small size of detector is possible using plastic scintillator.

If a linear relation between absorbed energy and light output exists, an absorbed dose in the scintillator is obtained from the measurement of light output through direct summation of the energy deposition spectra. But the light output as a function of photon energy is not linear and decreased significantly below 150 keV. The light yields (the light output per the deposit energy) were obtained experimentally as a function of energy using the Compton coincidence technique in this study, because it is necessary in obtaining precisely the absorbed dose from the light output spectra. The decrease of light yields in low energy region could be explained with the quenching effect in scintillator by using the model developed by Birks, where the high ionizing density along the particle track in scintillator would be responsible for the reduction of light yields, i.e. quenching. The light yield were well fitted with the results obtained by the equation derived by Birks, and a value of quenching parameter could be obtained. Using the quenching parameter obtained and the resolution in a photo-peak measured for 59.5 keV γ–rays from Am-241, the pulse height distributions due to light outputs were well reproduced by EGS5 Monte Carlo calculation. The absorbed doses obtained experimentally from the light outputs were confirmed to be in agreement with those evaluated by EGS5 within errors of 3-13% for photons of energies from 59.5 to 835 keV. To examine the response of scintillators as a dosimeter, the ratios of the absorbed dose in scintillators and that in a soft tissue were calculated using EGS5, where scintillators doped with high Z materials were taken into consideration because the difference in the response comes from the difference of effective atomic numbers between scintillator and tissue. The calculation suggested that decrease of the ratio in the low energy region could be compensated by doping heavy materials such as lead into the plastic scintillator. These were also confirmed by the experiments using plastic scintillators doped with several concentrations of lead. As a result, the scintillator doping with 0.5% lead was found to show an approximately flat response.

Another method for ensuring the accuracy of photon dosimetry involves calibration of dosimeters which are actively carried out at several laboratories such as at the Facility of Radiation Standard, JAEA (Japan) and at National Institute of Standard and Technology, NIST (US). Mono-energetic photon fields are preferable for this purpose since the energy response of dosimeters becomes more obvious. Several radioactive sources with known activities have been used for this purpose, of which the primarily photon energies exceed 600 keV. Between 30 and 400 keV, filtered X-rays are also candidates though they are broader in energy width and are less affordable to prepare. Around 200 keV is a missing energy region for calibration. Several short half-life radioactive sources that suit this energy range are inadequate as references. As such, a stable mono-energetic field with approximately 200 keV of energy was most desirable for study purposes.

In the present research, a mono-energetic photon field with energy of ～200 keV was developed using a radioactive source with a backscatter layout. The backscatter layout allows the calibration of dosimeter for two different energies with a single radioactive source. The setup was optimized through calculations and experiments to minimize the low energy component and to obtain field uniformity. The optimal backscatter layout was found to comprise a 1 x 1 m^2 steel floor, a radioactive source placed 20 cm above the floor, and a 10 cm cubic lead block placed above the source. Under the proposed layout and using a 208-MBq Cs-137 source, a mono-energetic photon field with 190 ± 9.6 keV (FWHM) and a dose rate of 3.18 ± 0.18 μSv/h was obtained within an area of 10 × 10 × 10 cm at distance of 15 to 25 cm above the lead block. The energy width of the field was half of that of the existing field as shown by an X-ray generator using a cadmium zinc telluride detector.

There were two major issues which prevent utilizing plastic scintillator for low energy photon dosimetry; one issue is the existing of obvious non-linear relationship between absorbed energy and light output, another issue is the lack of appropriate calibration field. This study deals with both of these issues and obtained substantial progress. Thus, applicability of plastic scintillator for low energy photon dosimetry is substantially improved by this research.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

光子線に対する線量計測は広く行われているが、光子エネルギーが 400keV 以上の領域に比べて、30-400keV の低エネルギー領域に対する線量計測手法は未だに十分とはいえない。この領域は、X 線発生装置からの光子線エネルギー域で、医療や放射光での利用が盛んに行われている重要な領域であるが、単色の線源が少なく特に 200keV 前後で適切な線源がないとの理由から、標準放射線場が形成し難く、またこの領域に適切な線量計は一般に電離箱しかない現状である。
本論文では、低エネルギー光子線ドシメトリーの確立を目的として、そのためのアプローチである 200keV 前後の低エネルギー光子線場の構築と低エネルギー領域における新しい線量計の開発について、実験やシミュレーションの手法、結果、考察が述べられている。
本論文では、低エネルギー光子線場として、鉄やコンクリートで散乱させた光子のみを利用する放射線場が提案され、EGS5 による詳細なシミュレーションと低エネルギー光子測定器として CZT(CdZnTe)半導体検出器を用いた実験から種々の照射条件を決定し、結果として単色に近い放射線場を得ることに成功した。さらに、従来からの確立された手法である X 線管フィルター法との比較を行い、十分に有用であることを確認した。本論文で提案された方法はユニークであり、線源とコンクリートや鉄等の遮蔽体あるいは散乱体のみで実現できるので実用性が高く、さらには低コストかつ簡便であるため、今後の利用が期待される。
一方、低エネルギー用光子線量計として、生体組織と組成の近いプラスチックシンチレータ(PLS)を使用した線量計を開発するため、光子エネルギーに対する PLS の応答を実験的に詳しく調べている。線量は吸収エネルギーから算出されるため、エネルギー応答は線量計の性能を決定づける重要な要素である。現状では出力応答が低エネルギー域でもほぼ一定な電離箱がよく用いられるが、気体を媒体とするために感度が低く低線量域の測定には難があり、小型化にも限界があることなどから、PLS が着目された。しかしながら、PLS にはエネルギー応答の非直線性という問題があり、適用可能な光子エネルギーが限られていた。本論文では、Compton コインシデンス法による散乱光子とコンプトン電子の同時計数から光子エネルギーに対する PLS の発光量を測定し、低エネルギー域での吸収エネルギーあたりの発光量の減少を定量化し、実験結果が半理論式と一致することを確かめ、そこからクエンチング(消光)係数を求めている。この係数を用いることにより、測定によって求められた PLS の発光量が 60keV から 835keV の範囲で 3-13%の差で計算値と一致することを示し、手法の検証と共に正確な発光特性の掌握につながった。さらには、PLS の組成に起因するクエンチング効果の影響を同時に補正するために、添加物を加えたいくつかの PLS の応答について計算等で調べている。　微量の鉛を添加した PLS では、無添加のものに比べて、低エネルギー側の応答を平坦に近づけることが可能であることを見出し、実験により確認している。これらにより、PLS の発光特性の詳細が明らかになり、PLS を低エネルギー光子用線量計として応用するための基礎はほぼ確立された。
以上、本論文は低エネルギー光子線ドシメトリーのための放射線場の構築と電離箱に代わる新たな検出器の開発について具体的な提案を行い、実験やシミュレーションにより、その新規性や妥当性、有用性を明確に示し、重要かつ新しい知見を与えている。研究手法は適切に考えられ、導かれた結論も妥当であり、それらは明快かつ平易な英語で記されている。これらのことから、本論文は、学位論文として十分にふさわしい内容であると結論された。