High Energy Electron Dosimetry by Alanine/ESR Spectroscopy

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Dosimetry based on electron spin resonance (ESR) analysis of radiation induced free radicals in amino acids is relevant to biological dosimetry applications. Alanine detectors are without walls and are tissue equivalent. Therefore, alanine ESR dosimetry looks promising for use in the therapy level.

The dose range of the alanine/ESR dosimetry system can be extended down to 1 Gy. In a water phantom the absorbed dose of electrons generated by a medical linear accelerator of different initial energies (6~21 MeV) and therapeutic dose levels (1~60 Gy) was measured. Furthermore, depth dose measurements carried out with alanine dosimeters were compared with ionization chamber measurements.

As the results, the measured absorbed doses for shallow depth of initial electron energies above 15 MeV were higher by 2~5% than those calculated by nominal energy C_E factors. This seems to be caused by low energy scattered beams generated from the scattering foil and electron cones of beam projecting device in medical linear accelerator.

Key Words: Electron spin resonance (ESR), Alanine dosimeter, Absorbed dose, Free radical dosimetry (FRD), Electron beam

INTRODUCTION

Dosimetry method in radiotherapy have to be based on radiation effects in living tissue and the solid organic compounds, particularly amino acids, are proper for dosimetry in the human body.

A biologically important and quantitatively accessible radiation effect in organic substances is the production of free radicals. Free radicals in crystalline biomolecules are relativity stable intermediate products of a sequence of events, which, as in tissue, are started by the initial absorption of radiation energy.[1]

Quantitative analysis of the free radicals may therefore be biologically relevant dosimetry and indicate the biological damage of cellular components. The crystalline organic substance, amino acids, proved to be particularly suitable for dosimetry. The radical concentration can be quantified by electron spin resonance (ESR) measurements. The application of ESR dosimetry in the medical field has been attempted on high energy radiation therapy. The alanine dosimeters which are small size and almost tissue equivalent have ideal preconditions for the dosimetry in the therapeutic field and for measurement of electron dose distribution inside of tissue. For electron energies in the range 6~21 MeV, the dose response curves for alanine and depth dose curves were measured. The applicability of the alanine/ESR dosimetry for electron beam irradiation in the therapeutic dose range was demonstrated.[2,3]

MATERIALS AND METHODS

The ESR dosimeters were made by polycrystalline alanine pellets which were composed of alanine and paraffin, with an alanine content up to 90% by weight. The pellet demensions for electron dosimetry were 4.5 mm in diameter and 8 mm in length. The pellet mass was 200 mg containing 180 mg of alanine and the specific gravity was close to soft tissue (Table 1). The alanine generated the radical species by irradiation.[2]

$$CH_3\text{-}\underset{\displaystyle NH_2}{\underset{|}{CH}}\text{-}COOH \xrightarrow{\text{Radiation}} CH_3\text{-}\dot{C}H\text{-}COOH$$

The paramagnetic absorption spectra of microwave in the radicalized alanine dosimeter was recorded with different amplification factors. The ESR measurements in this experiments was performed with Bruker ESP-300 spectrometer operating in the X-band at constant microwave power level. All measurements were made at room temperature. For evaluation, the samples were inserted in a

Table 1. Comparison of Tissue Equivalent Materials

Materials	Density (g/cm³)	Proportion of element (weight) H	C	N	O	Other	Z/A	Remark
Muscle	1.05	10	12	4	73	1	0.549	*
H_2O	1.00	11			89		0.555	*
Paraffin	0.88	15	85				0.573	
Mix. D	0.99	13	78		3	6	0.565	*
Alanine	1.25	8	40	16	36		0.539	
Alanine 85% Paraffin 15%	1.2	9	47	14	30		0.457	**
Alanine 80% Paraffin 20%	1.2	9	48	13	29		0.546	

(Z/A) : For Compton Process
* : Graphic for use in radiology ; F. Wachsman
** : Alanine/ESR dosimeter

Table 2. Results of Depth Dose Measurements

Energy (MeV)	Ref. depth (cm)**	Depth (cm)	Alanine absorbed dose (gy)	Ion chamber: Exposure reading	Ion chamber: Absorbed dose (Gy)*	Dose difference
6	1	1	0.99	1.00	1.00	−0.01
		2	0.56	0.50	0.56	0.00
15	2	2	1.02	1.00	1.00	+ 0.02
		3	1.00	0.99	0.99	+ 0.01
		5	0.79	0.77	0.80	−0.01
18	2	2	1.04	1.00	1.00	+ 0.04
		4	1.00	0.96	0.99	+ 0.01
		7	0.60	0.53	0.59	+ 0.01
21	2	2	1.04	0.99	0.99	+ 0.05
		4	0.99	0.99	0.99	0.00
		6	0.88	0.82	0.88	0.00
		8	0.52	0.45	0.51	0.00

** At the reference depth a nominal dose of 2Gy was calculated
* Calculated from exposure measurement by C_E factors from ICRU—21

quartz tube and positioned in a magnetic field of high homogeneity.[4,5]

The magnetic field was scanned linearly and in addition was modulated by an radio frequency (RF) field, for the resonance condition, the absorbed energy from the sample will change the balance of the microwave system. Normally, the first derivative of the absorption curve is registered by an X-Y recorder as a function of the magnetic field yielding the typical ESR spectrum. The spectra were recorded with different amplification factors, each ESR spectrum consists of several lines (hyperfine structure) caused by the hyperfine interaction of the unpaired electron with hydrogen nuclei (Fig. 1).

Representative of a given dose is the spin concentration which can be determined from the ESR spectrum by appropriate analysis. The calibration of the alanine/ESR dosimeters were performed at cobalt-60 source of the teletherapy unit, in the dose range between 1 Gy to 60 Gy and the dose rate is 1

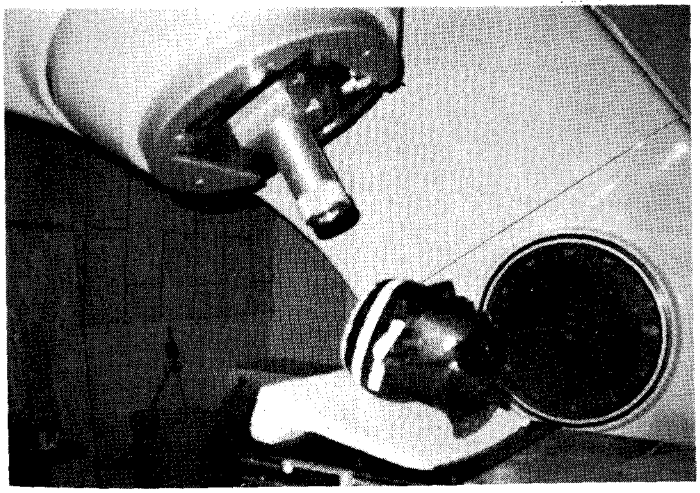

Fig. 1. Alanine/ESR spectrum for absorbed doses of 15 MeV electron.

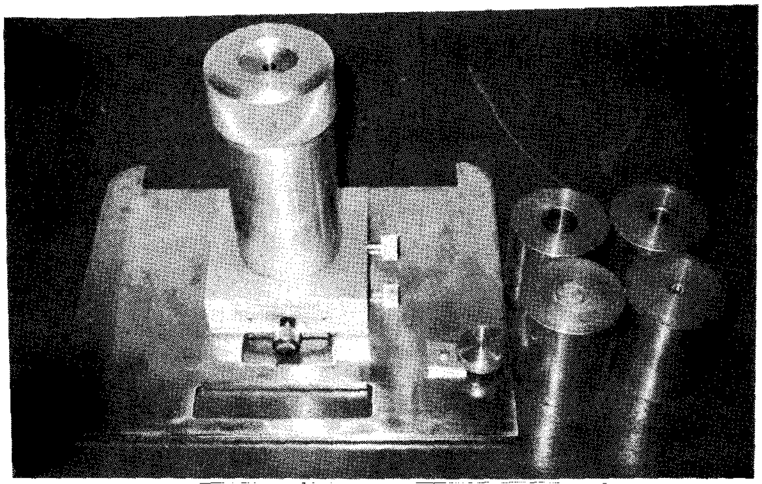

Fig. 2. Alanine dosimeters and holder for insert in water phantom in different depth.

Gy per minute. Calibration dosimetry was based on secondary standard ionization chamber dosimeter calibrated by substandard check source.

Alanine dosimeter and holder were placed in water phantom at different depths (Fig. 2). The nominal absorbed doses are calculated from exposure measurements, at the position of the alanine dosimeters, with an ionization chamber, Capintec PR-06 probe, and conversion factors C_E from the table in the ICRU-Report 21. Alanine/ESR dosimetry was performed with a Bruker ESP-300 spectrometer calibrated in terms of absorbed dose in water for Co-60 radiation. Electron beam was generated by medical linear accelerator (Siemens, Mevatron KD 7767) and alanine dosimeter holder was set in the water phantom to be 100 cm from target and beam was collimated by 10×10 cm electron cone (Fig. 3).

RESULTS

1. Dose Effect Curve

The relationship between ESR signal and absorbed dose is shown in Fig. 4 for high energy

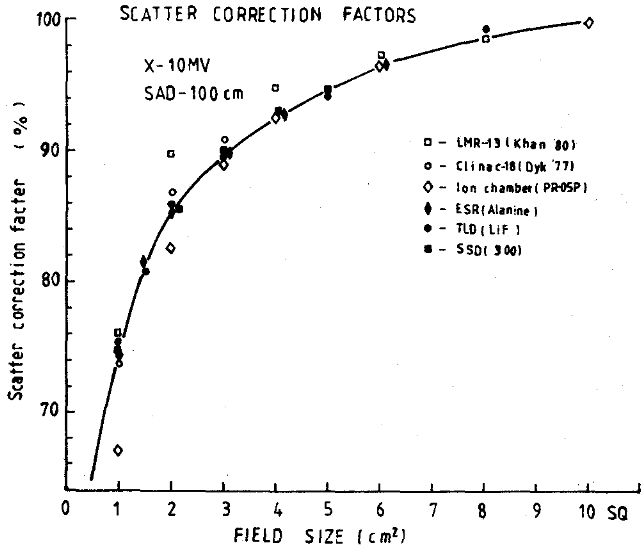

Fig. 3. Irradiation method of alanine dosimeter in water phantom from medical linear accelerator, SSD 100cm, 10x10cm∅ cone, 19x19cm² jaws.

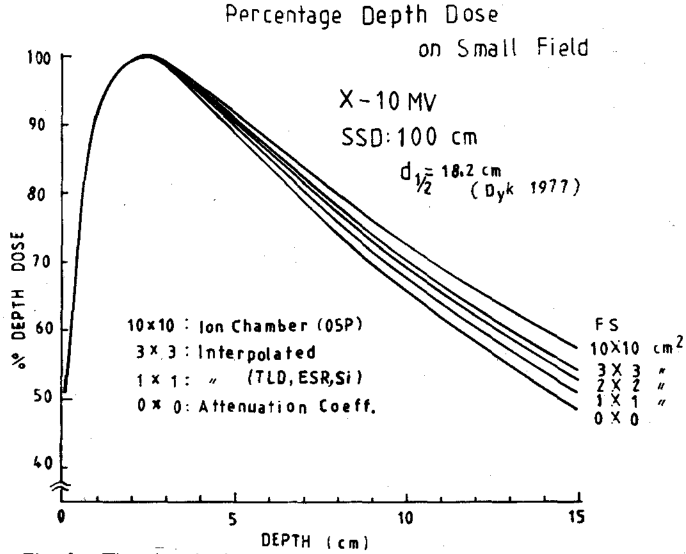

Fig. 4. The absorbed dose measured with alanine dosimeters versus the calculated nominal dose for irradiation of electrons.

electron beam with useful range for the alanine/ESR system from 1 Gy to 60 Gy. The magnitude of zero dose reading and its fluctuations are caused by reproducibility of readout geometry of the sample and stability of the lower detection limit of the method. The magnitude of the zero dose depend on detector material and sample preparation. The zero dose limit may be extendable down to 0.1 Gy or even less with improvements in detector material and readout technology.

The ESR signal increases linearly with dose up

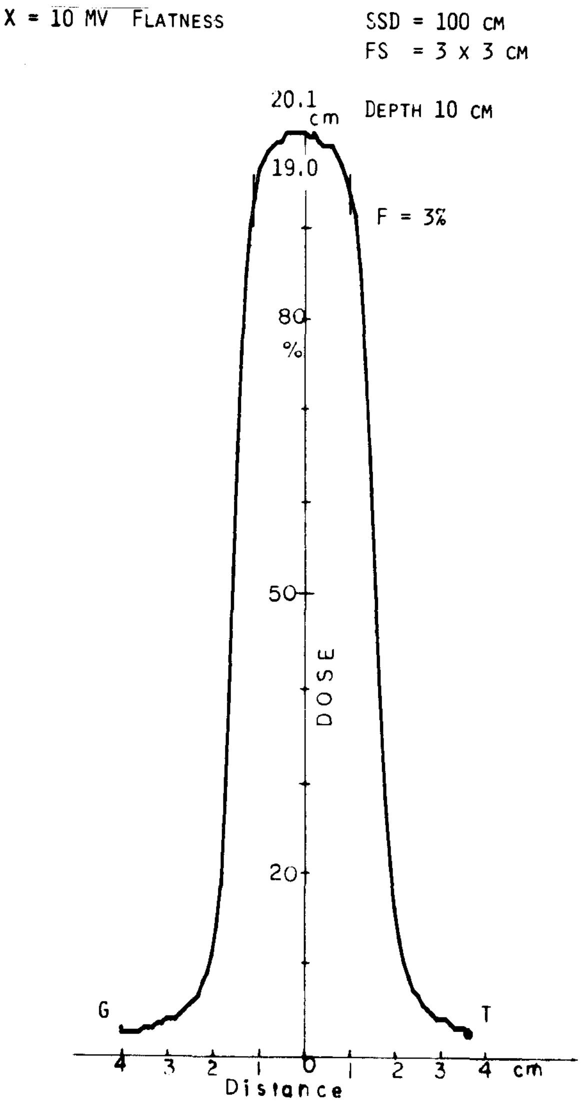

Fig. 5. The uniformity of alanine dosimeter for 15 MeV electron.

to 60GY. Over this dose range, the ESR system can be calibrated in terms of absorbed dose with a single standard sample. The dose reliability of alanine dosimeter was±2% (standard deviation) at lower dose and the uniformity was±2~4% under 4 Gy and decreased to±1% error above 4 Gy electron (Fig. 5).

2. Energy Dependence

Due to the low effective atomic number, the calibration factor of alanine samples varies only slightly with electon energy relative to the response in biological tissues. The experimentally determined electron energy dependence of ESR response normalized to Co-60 gamma radiation calibrated with ion chamber and the response function slightly increased between 6 MeV and 21 MeV electron as much as C_E factors (Fig. 6).

3. Electron Depth Dose

Relative depth doses measured with the ionization chamber and alanine dosimeters were compared. At increasing depths, the measured and calculated doses are in good agreement as shown in table 2 and Fig. 7. The measured absorbed dose at a depth of 2 cm is higher by 2~5% compared to the calculated values for initial electron energies of 15 MeV and above.

4. Long Term Stability

The free radical species were found to have long term stability at room temperature. This was verified by measurements over a period of 24 months. When stored at 20℃ remained constant to within 1 % (Fig. 8).

DISCUSSION

Free radical dosimetry (FRD) based on ESR analysis, initially developed for intralaboratory use, has recently reached a status for applications of interlaboratory dosimetry intercoparisons. It may even replace some of the currently used reference methods, e. g. Fricke dosimetry, for reasons of sufficient radical stability and system precision. For the moment, the main limitation is the relatively high cost of suitable ESR spectrometers.

Numerous studies have been made of free radicals in X-and γ-ray irradiated crystalline organic substances. Among them amino acids proved to be particulary suitable for dosimetry. The radical concentration can be quantified by electron spin resonance (ESR) measurements. On the basis of quantifying ESR spectral signals, a metrology for highlevel dosimetry in the range between 1 Gy and 60 Gy has been developed.[2,5,6,7]

FRD using ESR analysis of radiation-induced free radicals in alanine is promising for many applications of radiation dosimetry.[8,9,10] It combines high accuracy and reliability with a small, rugged, and low price detector that is relatively insensitive to ambient physical parameters and handling. Contrary to most other solid state techniques, a primary

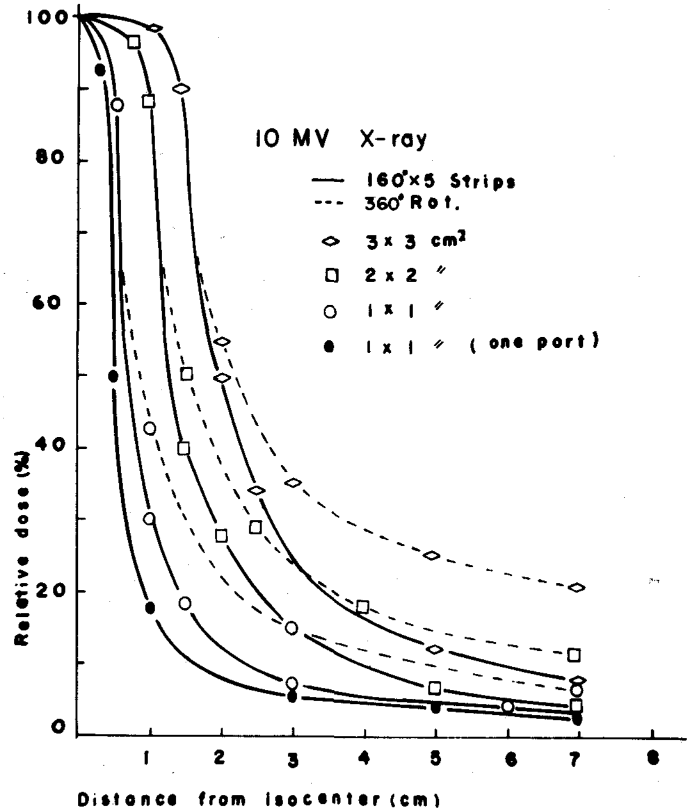

Fig. 6. Electron energy response of Alanine/ESR dosimeter.

radiation effect in a biological medium is used to determine the radiation dose. No readout treatment of the detectors is needed as in the cases of TLD (annealing) or lyoluminescence (dissolution). The new method gives reliable tissue equivalent dose readings, and the ESR signal readout is non-destructive, allowing for repeated evaluations. It is this repeatability of evaluation together with the relatively broad dose range and low overall uncertainty, which gives the ESR readout technique advantage over such methods of free radical dosimetry as lyoluminescence. Alanine responds linearly over a wide dose range to ionizing photons.[11]

Because of its reliable dosimetric properties, free radical ESR dosimetry is suitable for many applications. Although a sophisticated and expensive ESR spectrometer is required, the main future of this dosimetry technique probably lies in large volume reference dosimetry. It is very useful to apply ESR dosimetry for the radiotherapy fields. This study have proven applicability of the alanine/ESR dosimetry system for therapy level electron dosimetry. Up to initial electron energies of 12 MeV, the alanine dosimetry is in good agreement with the calculated nominal doses at all depths. The higher absorbed dose value obtained by alanine in a depth within 2cm for initial electron energies above 15 MeV may be explained by a field contamination of scattered electrons of lower energies generated in the scattering foil or in the cone of the accelerator. The unusual shape of the ionometric depth dose curves may also be indicative of additional scattered low energy electrons which would cause a shift of the maximum dose towards lower depths with increasing initial electron energies as observed in the curves. Due to the presence of lower energy electrons, the tabulated C_E factors valid only for monoenergetic incoming electrons lead to an underestimation of the calculated absorbed doses which is observed by alanine/ESR dosimetry.

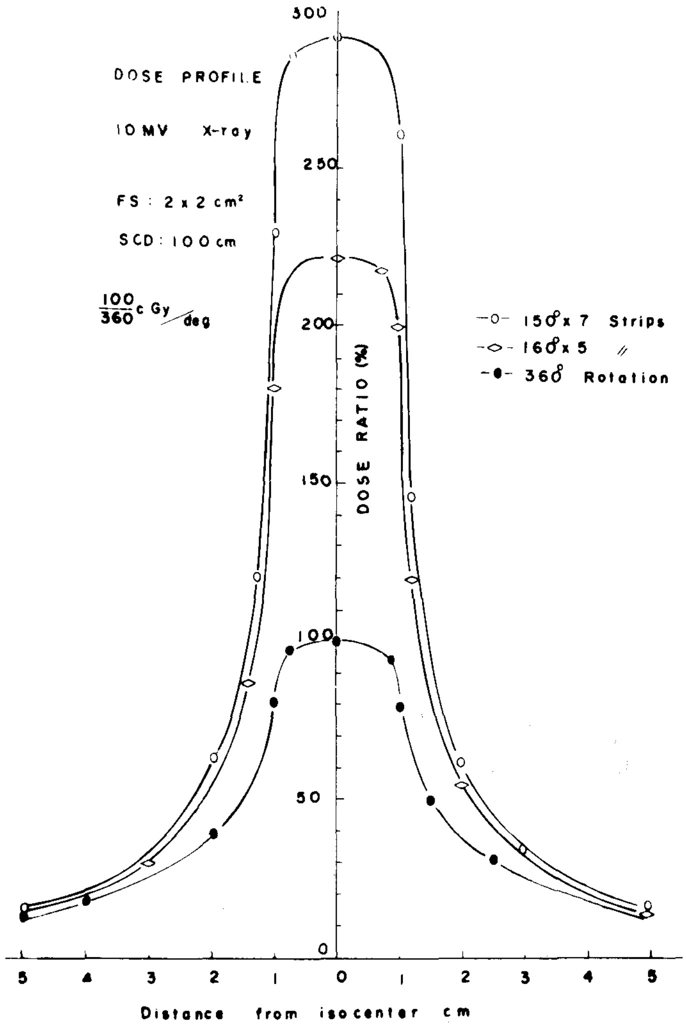

Fig. 7. Comparison of relative depth dose as measured with ionization chamber and alanine dosimeters for 6–21 MeV electron energies.

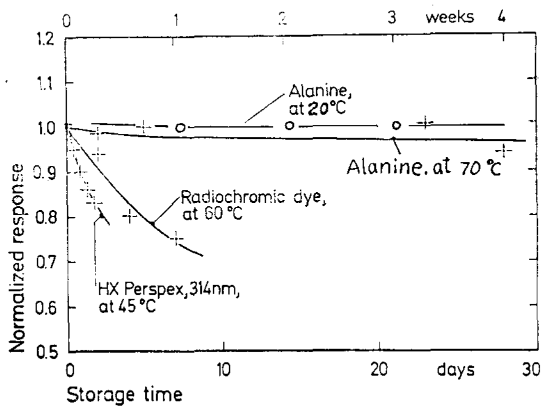

Fig. 8. Time response of alanine/ESR dosimeter and radiochromic dye.

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=국문초록=

Alanine/ESR Spectroscopy에 의한 고에너지 전자선의 선량측정

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물질에 방사선을 조사시키면 구성원자 또는 분자의 일부분이 전리되며 특수한 유기화합물은 장기간 free radical 상태로 존재하고 그 밀도는 조사된 방사선량에 비례한다. Free radical 상태의 물질에 마이크로파와 같은 전자파를 투과시키면 free radical된 전자의 고유진동과 일치된 전자파를 흡수하는 전자스핀공명(Electron Spin Resonance)이 일어나며 흡수된 전파의 강도를 측정함으로서 조사된 방사선량을 추측할 수 있다.

ESR를 이용한 free radical dosimeter로서 가장 잘 알려진 물질이 아미노산 alanine이므로 이것과 파라핀 10%를 혼합하여 0.4×1cm의 alanine dosimeter를 제작하였다.

측정 방법은 방사선 흡수선량을 직접 측정할 수 있도록 조직등가인 물 팬텀과 방수된 Alanine dosimeter holder를 제작하고 의료용 선형가속기에서 발생되는 6~21MeV 전자선을 조사하면서 최대 흡수 선량과 깊이에 따른 선량분포를 측정하였다. 전자선 조사선량은 1 Gy에 60 Gy까지의 방사선 치료선량 범위을 선택하였으며 측정결과 전자선량 증가에 따라 ESR 신호의 진폭이 선형비례적으로 증가하였다. 그러나 전자선량이 4 Gy이하에서는 alanine dosimeter의 선량 균일성이±2~4%(표준편차)의 오차가 있었으며 4 Gy이상에서는±1%이하의 오차를 나타냄으로서 환자에 대한 전자선 조사량 범위인 1 Gy에서 60 Gy까지의 흡수선량을 정확히 측정할 수 있었다. 측정한 결과 전자선 에너지 12 MeV이하에서는 전리상으로 측정 계산된 선량과 일치하였지만 15 MeV이상에서는 표면에서 깊이 2 cm까지의 흡수선량이 약 2~5%가 높았다. 이와 같은 현상은 의료용 선형가속기의 전자선 방출구에 장착된 산란판과 조사면을 조정하는 cone에 의하여 발생되는 저 에너지 산란전자선이 alanine dosimeter에 측정된 것으로서 에너지가 증가될수록 오염 정도가 증가되었다.

본 실험을 통하여 지금까지 고에너지 전자선량계측에서 전리상에 의한 전기량 측정과 산란선이 없는 단일 에너지로만 간주하여 계산하였던 전자선 흡수선량 측정방법을 직접 흡수선량 측정이 가능한 Alanine/ESR dosimetry로서 교정하는 것이 바람직하다고 생각한다.