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Determination of Linear X-Ray Attenuation Coefficients of Pathological Brain Tissues and Use of Filters in Tissue Contrast Enhancement in Computed Tomography

Bazı Patolojik Beyin Dokularının Lineer X-ışını Azaltma Katsayılarının Belirlenmesi ve Bilgisayarlı Tomografide Filtrelerin Doku Kontrastını Artırmak için Kullanılması

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Abstract

Objective: X-ray attenuation coefficients are used in common radiological, pathological and spectroscopic examinations and in the determination of the radiation dose distribution in biological tissues. In radiology, these coefficients enable diagnosis by differentiating the abnormal tissues from the normal ones using their morphological structure and contrast differences. In this study, our aim is to precisely determine the linear x-ray attenuation coefficients of pathological brain tissues and to use x-ray beam filters to enhance the tissue contrast in computed tomography.

Materials and Methods: To directly measure the relative linear attenuation coefficients, an energy dispersive x-ray spectroscopy system (EDXRS-Canberra, Si(Li) with DSA-1000 spectrum analyzer 1998; CT, USA) was used with collimators and a medical-purpose x-ray tube (Siemens, Siremobil, 1985; Erlangen, Germany) in a linear geometry.

Results: Using a Mo filter with Computed Tomography CT and photon energies from 15 to 25 keV, EDXRS acquisitions were found to significantly distinguish grades of brain tumors ($p<0.05$). For the data acquired from CT systems with the decreasing filtered photon mean energy, the x-ray attenuation coefficients (i.e., the Hounsfield units) show that the ratio of EDXRS to CT for water's attenuation coefficient are increased. With our suggested x-ray filters, the tissue contrast has been found to be increased in ex vivo brain tumor slices compared with slices scanned in conventional CT scanners.

Conclusion: X-ray attenuations measured with the EDXRS are found to be statistically more reliable because of the length of acquisition times in this study.

Key Words: Computed tomography, X-ray tube, X-ray attenuation coefficient, X-ray spectral filters

Özet

Amaç: Temel değişkenler olarak x-ışını azaltma katsayıları radyolojik, patolojik ve spektroskopik incelemelerde ve biyolojik dokularda radyasyon doz dağılımının belirlenmesinde yaygın olarak kullanılmaktadır. Özellikle radyolojide anormal dokuların normal olanlarından biçimsel yapı ve kontrast artışından faydalanarak tanılanmasını sağlar. Bu çalışmada patolojik beyin tümörlerinin lineer x-ışını azaltma katsayılarını hassas bir şekilde tespit etmeye ve bilgisayarlı tomografide (BT) doku kontrastını x-ışını demet filtreleriyle artırmaya çalıştık.

Gereç ve Yöntem: Bu çalışmada numunelerin bağıl lineer x-ışını azaltma katsayısının doğrudan ölçümünde enerji ayrımlı bir x-ışını spektroskopi sistemi (EDXRS-Canberra, Si(Li) dedektörü DSA-1000 spektrum analizörüyle, 1998, CT, USA) ile lineer geometride kolimatörler ve bir tıbbi x-ışını tüpü (Siemens, Siremobil, 1985, Erlangen, Almanya) kullanılmıştır. Ayrıca bilgisayarlı tomografi sistemi (Toshiba, XVision/GX, 1994, Nasu, Japonya) Hounsfield birimi (HU) ölçümleri için kullanılmıştır. Önerilen x-ışını demet filtreleri için yapılan ölçümler patolojik olarak tanılanmış çeşitli numunelerde tekrarlanmış ve istatistiki metotlarla değerlendirilmiştir.

Bulgular: BT ölçümlerinde Mo filtre kullanılarak, EDXRS ölçümlerinde 15-25 keV aralığındaki enerjiye sahip fotonlarla beyin tümörlerinin greydleri arasındaki farklılığın daha iyi ayırt edildiği tespit edilmiştir. BT sistemlerinden alınan verilerde filtrelemeyle ortalama foton enerjisinin azaltılması sonucunda x-ışını azaltma katsayıları ya da bu katsayıların suyun azaltma katsayısına oranını gösteren HU artmıştır. Önerdiğimiz x-ışını demet filtreleriyle elde edilen çıkarılmış beyin tümörü kesitlerindeki doku kontrastının konvansiyonel BT tarayıcılarından alınan kesitlere nispeten artmış olduğu bulunmuştur.

Sonuç: EDXRS ile elde edilen lineer x-ışını azaltma katsayıları veri alma sürelerinin uzun olması sebebiyle istatistiki olarak daha güvenilir bulunmuştur.

Anahtar Kelimeler: Bilgisayarlı Tomografi (BT), X-ışını azaltma katsayısı, X-ışını spektral filtreleri, X-ışını tüpü

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Introduction

Medical imaging, the principal method for noninvasively obtaining anatomical and physiological information about the human body, has experienced considerable advances in technology and clinical applications over the past 25 years [1]. X-ray computed tomography (CT) is one modality that has developed in both technique and application. CT imaging of the brain can help in the early diagnosis of malignant tissue abnormalities by distinguishing grades of disease and avoiding invasive interventions into the skull.

The CT x-ray beam spectral shape has been studied by many researchers because the reduction of the radiation dose and an enhancement of the contrast could be achieved in various fields of diagnostic radiology [2]. Using different filter combinations, the contrast and dose have been studied in soft tissues using the x-ray tube photon attenuation, both experimental and theoretical [3, 4]. If the contrast agent enhancement can be increased while using x-ray beam filters, then angiographic examinations may yield more [5].

The spectral shape of the x-ray tube was adjusted by changing the anode and filter materials to obtain maximum image quality and minimum dose delivered to the tissue [6]. Image quality is increased and radiation dose is decreased because the photon energy where the detector efficacy is maximized is incident to the detector's surface. A 2- to 3-fold reduction in radiation dose delivered to the tissue has been measured when the x-ray tube spectrum was optimized [7, 8]. Also, the signal-to-noise ratio (SNR) of acquired images could be optimized using this approach [9]. These studies can also be expanded to CT because the x-ray photon attenuation data at different energies also enhances the cross-sectional image quality. Currently, with the help of digital technology, radiodiagnostic image processing and enhancements tend to focus on the spectral analysis and elemental composition of the body region of interest [10]. In a separate study, single and dual-energy CT images with monochromatic synchrotron x-rays were compared [11]. This technique was used to develop quantitative dual-energy x-ray imaging [12] (e.g., fluorescent x-ray computed tomography (FXCT) with synchrotron radiation). One phantom study reported that FXCT could clearly image the distribution of both iodine and xenon agents, and the contrast ratio was significantly better than that of the transmission CT images [13]. To quantitatively select the iodine concentration in the slice, one study's scans used three heavily filtered x-ray beams: two had mean energies that straddle the iodine K-edge (33 keV) and the third energy was slightly higher. The results were independent of tissue and bone attenuation over a broad range of projection path lengths. It was shown for slice diameters up to 30 cm that, to separate iodine from one other material, a two-beam K-edge approach requires less integral dose than a two-beam technique with conventional CT energies. For selective iodine imaging in the presence of more than one other material, the three-spectrum K-edge technique is necessary. The exposure requirements and beam-hardening corrections were discussed in detail, and a computer-simulated CT image, generated by the proposed scheme, was presented in that study [14]. Phase-contrast x-ray imaging is a promising technique for observing the structure inside biological soft tissues without the need for staining or serious radiation exposure. Phase-contrast x-ray CT was able to clearly differentiate the cancer lesion from the normal tissue and the fine structures, which correspond to cancerous degeneration and fibrous tissues [15].

Commercial results of these studies are being used to differentiate soft tissues shaded by bone structures. In these systems, dual photon energy techniques produce effective detected energy spectra that result in much lower noise for a given patient radiation dose. [16, 17]. Some studies have done ex vivo attenuation measurements of x-rays with normal and abnormal breast tissues. It was found that differences between normal and cancerous tissues exist in the linear attenuation coefficients of monochromatic x-rays between 14.15 and 18 keV, but there was some degree of overlap. [18]. In a separate study, infiltrating duct carcinomas and fat were well-differentiated by measuring x-ray attenuation. For photon energies used with film-screen mammography, infiltrating duct carcinomas were found to be more attenuating than fibrous tissue, and above 31 keV, the ranges of attenuation overlapped for the two tissue types [19, 20].

As previously reported by various researchers, x-ray spectral analysis in CT is a useful tool for distinguishing pathological soft tissues from normal ones. The materials and methods for exploiting this differentiation are noteworthy.

Materials and Methods

In our study, we used conventional CT scanners to obtain similar results to those from dedicated energy-differentiating scanners. Filters were placed in front of the x-ray tube beam aperture to shape the x-ray beam spectrum. The energy distribution of photons obtained after the filters were applied is shown in Figure 1.

We measured linear attenuation coefficients as Hounsfield Units (HU) by using the CT scanner's software (Toshiba, XVision/GX, 1994; Nasu, Japan; Figure 2), manually evaluating the peak areas of the x-ray tube's filtered continuous x-ray region, and manually evaluating the attenuated peak areas in the exponential attenuation formula. In general, the linear attenuation coefficients were determined by source-sample-detector linear geometry (Figure 3); the x-ray tube source's linear attenuation coefficients of water and paraffin were immersed in tissues (Table 1). Two high purity metal foils and two cellulose matrix pellets were selected as x-ray filters to measure the x-ray tube's continuous energy spectrum.

Experienced pathologists with standard microscopy methods diagnosed and classified pathological brain tissues in three groups:

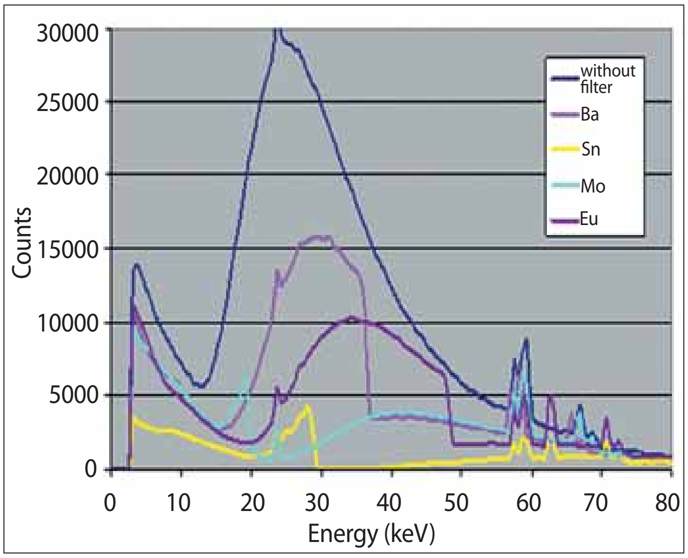

Figure 1. *Energy distribution of photons obtained with different filters.*

TEST ERD

06. 09. 15 15:20:04.7

120kV/300mAs

31Y/M

+6.0mm

+0.0D

— ROI 1 —
Area: 16.5
Mean: -80.77
SD : 25.82
— ROI 2 —
Area: 16.5
Mean:-186.12
SD : 76.65
— ROI 3 —
Area: 16.5
Mean:-295.65
SD : 166.20
— ROI 4 —
Area: 16.5
Mean: -67.52
SD : 47.88

5 4
(411, 118)
0.0
5 4
WL = -111
WW = 1448
39516:12

Figure 2. Calculation of linear attenuation coefficients (HU) using the CT scanner's software (Toshiba, XVision/GX, 1994; Nasu, Japan).

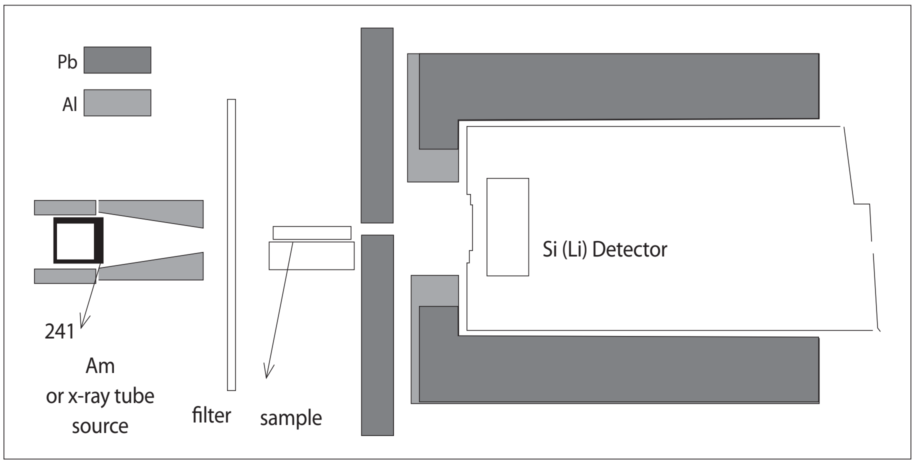

***Figure 3.** Source-sample-detector linear geometry.*

Table 1. X-ray beam-shaping filters, the corresponding mean photon energies after filters, and the linear attenuation coefficients of water and paraffin at these energies (WinXCom database)

Filter	Mean Energy (MeV)	Water μ (cm^{-1})	Paraffin μ (cm^{-1})
Mo	$1.80\ 10^{-2}$	1.042	0.389
Sn	$2.70\ 10^{-2}$	0.443	0.231
Ba	$3.70\ 10^{-2}$	0.289	0.187
Eu	$4.70\ 10^{-2}$	0.236	0.170
W Kα	$5.95\ 10^{-2}$	0.207	0.158
W Kβ	$6.80\ 10^{-2}$	0.195	0.153

Table 2. Statistical analysis showing photon energies that are successful at differentiating samples (by EDXRS)

	15-25 keV photons		Tungsten K photons	
	Mean	Standard deviation	Mean	Standard deviation
Group1	0.153^{b}	0.028	0.149^{ab}	0.028
Group2	0.196^{ab}	0.030	0.198^{a}	0.030
Group3	0.273^{a}	0.034	0.074^{b}	0.035
(a,b) distinguishable; (ab) indistinguishable				

astrocytoma LG (Group 1), astrocytoma G3 (Group 2), and glioblastoma (Group 3).

The linear attenuation coefficients calculations and evaluations were blind to the pathological classification. Statistical tests, including one-way analysis of variance (ANOVA) and Duncan's MRT, were done using SPSS 9.0 software (Chicago, IL, USA).

Results

Although the number of samples was not adequate for an accurate statistical analysis, our results showed similar contrast enhancements of soft tissues as lower x-ray energies. Also, our materials were modified by fixing in paraffin blocks. Water content of these tissues was replaced with paraffin. As seen on Table 1, the linear attenuation coefficient of paraffin was lower than water for all x-ray energies. It was expected that the average linear attenuation coefficient would decrease when a component was replaced by another with a lower density, but the linear attenuation coefficients also increased in contrast.

There was significant ($p<0.05$) enhancement in brain tumor linear attenuation coefficients (Table 2) of the energy dispersive x-ray spectroscopy system (EDXRS) attenuation measurements for lower energies that were obtained by both physically filtered and computationally filtered continuous x-ray tube spectrums. Compared to tungsten's characteristic x-ray's (W Kα,β) attenuation, the lower energetic x-rays could be used to distinguish two grades of same astrocytoma (Groups 1 and 3). W Kα,β x-rays were less affected by filtering, but these energies were basically used for diagnostic purposes in CT scanners. These energies were able to distinguish Group 1 from Group 3. Although the standard variations of these measurements were small enough, the results may be false because the number of samples was less in Group 3. Although an insignificant finding, Groups 1 and 2 could be distinguished for both energy intervals.

Discussion

Similar results are acquired when the same (Mo, Sn, Ba, Eu) filters are used in conventional CT scanners. The Mo filter's effective photon energy is approximately 18 keV, and at this region of the x-ray tube's spectrum, abnormal soft tissues can be distinguished more significantly ($p=0.16$) (Table 3). In our Xe detector scanner, the maximum quantum efficiency is near the K-absorption edge of Xe gas, which is about 35 keV. The general background enhancement of slices can be referred to the uncalibrated scanner for specific filters. Our measurements show contrast differences in the same slice, so the differences between groups are significant.

Additionally, it can be inferred from our results that the Ba filter with a cellulose matrix will increase the iodinated agent's contrast enhancement because its effective energy is slightly higher than iodine's absorption edge. However, this should be the subject of another study.

Although there are efforts to add x-ray spectral analysis into conventional imaging units, no commerical prototype currently

Table 3. Capability of Sn and Mo filters to distinguish study groups with CT scanner data

		Mean	Std. Deviation	N
Without filter	1	-20.909	23.855	11
	2	-41.666	70.689	12
	3	-51.666	37.103	6
	Total	-35.862	50.675	29
Sn Filter	1	64.545	38.305	11
	2	86.666	46.774	12
	3	60.000	56.213	6
	Total	72.758	45.739	29
Mo Filter	1	88.181	42.618	11
	2	114.166	48.889	12
	3	80.000	50.596	6
	Total	97.241	47.576	29
Group	N	No filter	Sn Filter	Mo Filter
3	6	-51.666	60.000	80.000
1	11	-41.666	64.545	88.181
2	12	-20.909	86.666	114.166
Sig.		0.243	0.259	0.160

Duncan's test Type III (error)=2097.669. a-Harmonic mean sample size = 8.800. b- Alpha = 0.05

exists. We believe dedicated CT scanners that are equipped with energy dispersive detectors and/or energy selective x-ray sources will contribute to the early detection of tissue abnormalities and other diseases.

Conflict of interest statement: The authors declare that they have no conflict of interest to the publication of this article.

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