USEFULNESS OF DUAL-ENERGY COMPUTED TOMOGRAPHY IN DETERMINING THE MINERALOGICAL COMPOSITION OF STONES INSIDE THE ORGANS*

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Computed tomography is a method of diagnostic radiology. The latest trend in the field of imaging using X-ray is multi-energy tomography, wherein a patient is scanned simultaneously by two energies: high (140 keV) and low (80 keV). In single-energy tomography, image in a given voxel is based on ascribing to that specific voxel value of Hounsfield Unit (HU). HU value is obtained from linear absorption coefficient in the patient's body. Hounsfield units may, however, imprecisely reflect the composition of the structure under study, due to the effect of beam hardening. This causes the scanned field, despite its homogeneous structure, to have different CT values for different layers. The aim of this study was to evaluate the usefulness of dual-energy CT in determining the mineralogical composition of organs stones. The results obtained from the dual-energy computed tomography (DECT) were compared with the effective atomic number calculated during the IR measurements. The research material were 11 kidney stones and 16 gallstones. They were divided into 18 groups. In order to perform tomographic scans, each of the stones was placed in a phantom made of plexiglass. Then, decomposition of the stones was analyzed using infrared spectrometry.

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1. Introduction

1.1. DECT — dual-energy computed tomography

Computed tomography is a diagnostic method that allows recording multilayer sections of a patient's body using an X-ray beam. The latest trend in

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the field of medical imaging using X-ray is multi-energy tomography, wherein a patient is scanned simultaneously by two energies: high (140 keV) and low (80 keV). The use of two energies during CT scanning (DECT — dual-energy computed tomography) allows determining the value of the linear absorption coefficient for a given material at different energies. This allows obtaining information on the average atomic number of the structure examined, which can be used to identify deposits and organ stones. In single-energy tomography, image in a given voxel is based on ascribing to that specific voxel value of Hounsfield Unit (HU). HU value is obtained from linear absorption coefficient in the patient's body. Hounsfield units may, however, imprecisely reflect the composition of the structure under study due to the effect of beam hardening. This causes the scanned field, despite its homogeneous structure, to have different CT values for different layers. In addition, it can be observed that in CT images, two materials differing in elemental composition can be characterized by the same HU. These inaccuracies appear for substances with similar values of the linear coefficient of radiation absorption.

1.2. Effective atomic number

The probability of occurrence of photon interaction with matter depends on the atomic number of the matter. The effective atomic number makes, thanks to the DECT, possible to calculate the average atomic number for a mixture of materials. In medical applications, it is a very useful concept that characterizes the response to the radiation of multi-component material. The dual energy tomographs scan the patient's body using simultaneously two energies, obtaining a set of data that allows to distinguish materials with a similar absorption coefficient (similar HU), but with different chemical composition. In this way, the physical property of tissues is used, for which the degree of radiation absorption is dependent on the X-ray energy. The coefficient of radiant attenuation depends on two phenomena: the Compton scattering and the photoelectric effect. To estimate the value of the effective atomic number (Z_{eff}) for multi-component material, it is necessary to apply a weighted average of atomic numbers of all chemical elements in the test substance. This dependence is described by the formula

$$Z_{\text{eff}} = \sqrt[a]{f_1 * (Z_1)^a + f_2 * (Z_2)^a + f_3 * (Z_3)^a + \ldots + f_n * (Z_n)^a}\,, \qquad (1)$$

where: f_n — the weight factor of the total number of electrons of the element constituting the compound, Z_n — the atomic number of the element. Exponent a is an energy-dependent constant. In medical diagnostics, it is averaged to 2.94 [1, 2].

1.3. Application of multi-energy tomography in the treatment of nephrolithiasis and biliary stones

Cholelithiasis and kidney stones are diseases of the biliary and urinary systems in which the occurrence of intra-organ stones is diagnosed. Both kidney stones and bile stones can be diagnosed using ultrasonography and tomography. DECT provides information on the mineralogical composition of the deposit. An example may be patients with kidney stones whose main component is uric acid. The crystals of this acid are too hard to be completely disintegrated by lipotrypsy. Therefore, the remaining fragments of the deposit are removed from the patient's body with the urine, what can be a very painful and unpleasant process. Prior knowledge of the composition of the deposit can allow the patient to be qualified for surgical removal of the stones instead of lipotrypsy.

2. Materials and methods

The research materials were 11 kidney stones and 16 gallstones. They were divided into 18 groups. The criterion for the division was the origin of the stones: whether they were kidney stones, gallstones (Fig. 1) or whether they came from one patient or many.

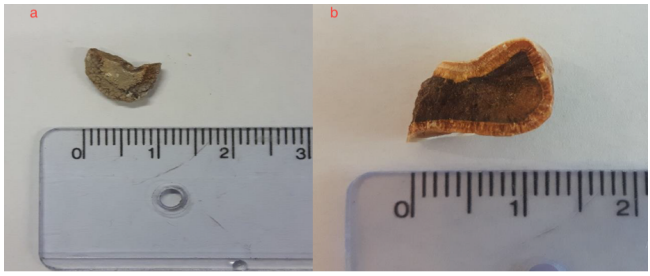

Fig. 1. Stones used in the measurements: (a) kidney stone, (b) gallstone.

2.1. Preparation: tomographic scans

In order to perform tomographic scans, each of the stones was placed in a phantom made of plexiglas (Fig. 2). It was necessary to attach a shelf in its interior, which made it possible to set the stones in the center of scanned area. During the test, the phantom was filled with water, which was a simulation of soft tissues. The phantom was placed on the scanner's table and inserted into the gantry. Tomographic scans of all stones were made using the GE 750HD Discovery CT by GE Heatlthcare. It is a single-source multi-energy tomograph with the capacity for fast switching of the X-ray tube

voltage that allows the scanning of the studied area almost simultaneously with high (140 keV) and low (80 keV) energy. For each rotation, two sets of data (up to 256 layers) are obtained, giving the possibility to determine the absorption coefficient. This scanner uses the Advantage Workstation software with the GSI Viewer application.

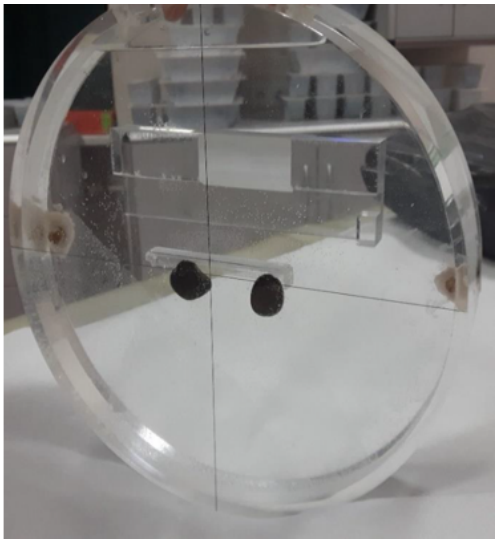

Fig. 2. Phantom with the stones.

2.2. Preparation: infrared (IR) spectroscopy

The scanned stones were then analyzed in mid-infrared. For this purpose, the FT-IR Nicolet 6700 spectrometer from Thermo Fisher Scientific and the tablet press combined with the Specac hydraulic press available in the Department of Medical Physics of the Jagiellonian University was used. The FT-IR spectrometer Nicolet 6700, thanks to the OMNIC software, allows to obtain high resolution spectra, their computer processing and analysis. In order to collect IR spectra, samples of the tested substances (Fig. 3) were prepared in the form of tablets.

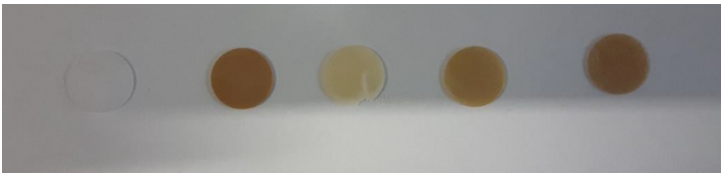

Fig. 3. Samples prepared for testing in an IR spectrometer.

3. Results

3.1. Determination of effective atomic number based on multi-energy computed tomography

Tomographic scans of the phantom filled with water with the stones placed inside were obtained. On this basis, using the Gemstone Spectral Imaging software of the Advantage Workstation (GE), the histograms of the effective atomic number were calculated. The Kidney Stones Analysis option enabled the selection of specific voxels on the CT scans intended for analyze. Then, the program calculated the histogram of the effective atomic number for selected voxels of CT scans for selected stone's areas (Fig. 4). On the x-axis were values of the effective atomic number (Z_{eff}), and on the y-axis the percentage of pixels corresponding to a given value of the Z_{eff} (Fig. 4). For weighted average of Z_{eff}, the following formula was used:

$$\bar{Z} = \frac{w_1 Z_1 + w_2 Z_2 + w_3 Z_3 + \ldots + w_n Z_n}{w_1 + w_2 + w_3 + \ldots + w_n}, \tag{2}$$

where: w_n — is the percentage of pixels, and Z_n — is the effective atomic number corresponding to the median of the interval.

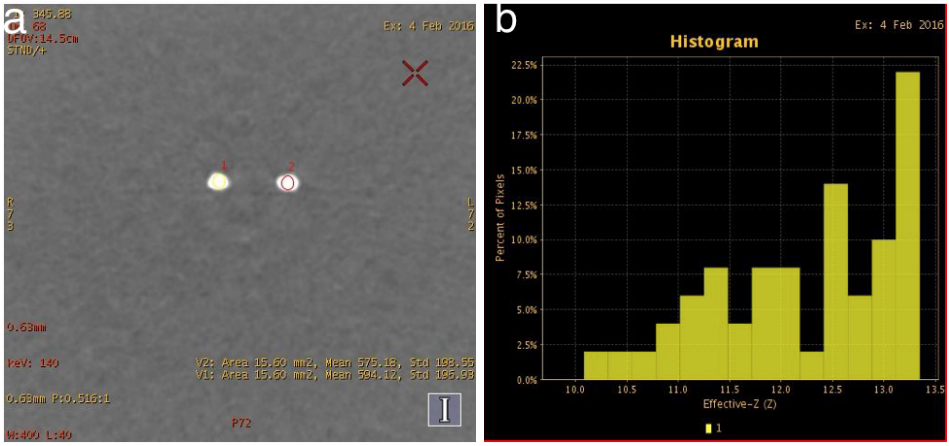

Fig. 4. Results of measurement of kidney stone n_1: (a) tomographic scan (b) histogram of effective atomic number.

3.2. Verification of effective atomic number based on infrared spectrometry

The tested material was divided into two groups: kidney stones and gallstones, which were analyzed separately. In both parts, it was necessary to

calculate the effective atomic number for materials that according to literature data form internal stones. The following compounds were used in the research: hydroxyapatite ($Ca_{10}(PO_4)_6 \cdot 6H_2O$, $Z_{eff} = 15.86$), bullite ($CaHPO_4 \cdot 2H_2O$, $Z_{eff} = 13.82$), struvite ($MgNH_4PO_4 \cdot 6H_2O$, $Z_{eff} = 9.56$), uric acid ($C_5H_4N_4O_3$, $Z_{eff} = 6.91$), L-cysteine ($C_6H_{12}N_2O_4S_2$, $Z_{eff} = 10.60$), calcium pyrophosphate ($Ca_2P_2O_7$, $Z_{eff} = 15.24$), calcium oxalate ($(COO)_2Ca$, $Z_{eff} = 14.02$), cholesterol ($C_{27}H_{46}O$, $Z_{eff} = 5.65$), bilirubin ($C_{33}H_{36}N_4O_6$, $Z_{eff} = 6.28$), calcium carbonate ($CaCO_3$, $Z_{eff} = 14.82$) [1–4].

The identification of gallstones was made using the OMNIC program included with the spectrometer software. The program, through attached library, matched most similar materials to the spectrum of the tested stones. Adjustment was made on the basis of the peak positions and spectrum shape. Spectrum measurements were performed both for the cortex and for the medulla of the stones (Fig. 5). Analysis of kidney stones was made using software OriginPro9. IR spectra were recorded for samples of reference compounds. Using the program, the position of the peaks of each compound was determined. They served to create a database. Then, the spectra of the examined stones were analyzed by determining the position of their peaks and by comparing them with the positions of the peaks of the reference compounds. This allowed to obtain information on the percentage of each reference compound in the tested sample. Next, using the formula for the weighted average, the effective atomic number was determined for each of the tested stone samples.

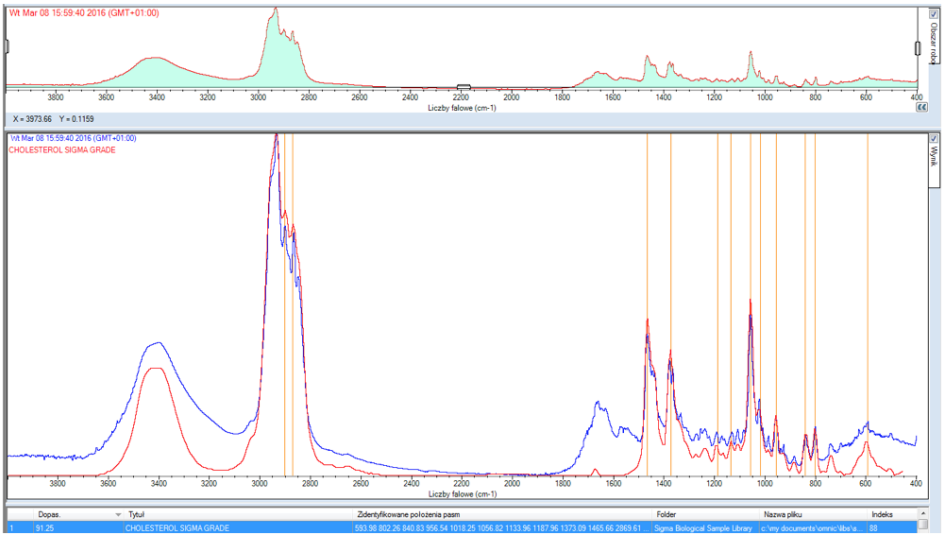

Fig. 5. Spectral analysis performed in the OMNIC system for the gallstone z_1.

In order to verify the received information, a graphical comparison of the corresponding IR spectra was made. Figure 6 shows an example spectrum for the n_1-stone sample compared with the calcium oxalate spectrum. On the basis of the analysis of shape of the spectrum, it can be concluded that the main component of tested stone is calcium oxalate.

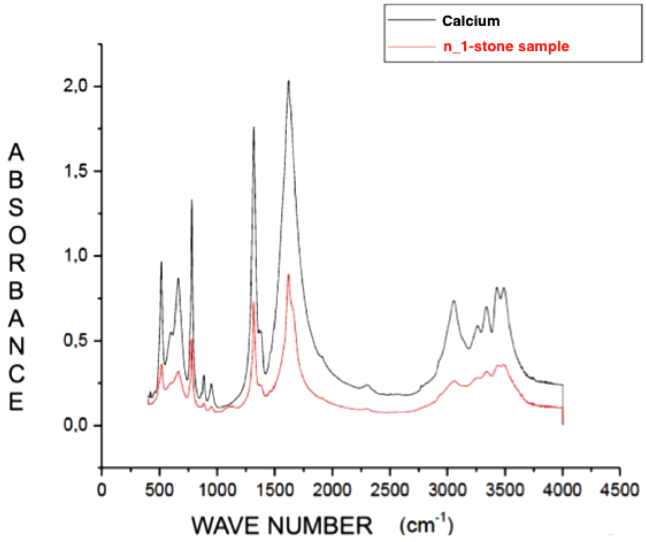

Fig. 6. Comparison of the IR spectrum obtained for the n_1-stone sample and the calcium oxalate sample.

4. Conclusion

Analyzing the results obtained, it can be concluded that DECT is useful in determining the mineralogical composition of intra-organs stones. For most cases (28 samples), the percentage difference between Z_{eff} calculated on the basis of the tomography (Z_{eff} CT) and Z_{eff} obtained on the basis of the infrared studies (Z_{eff} IR) does not exceed 10%. When cortex and medulla are investigated separately (5 samples), the percentage difference between Z_{eff} CT and Z_{eff} IR significantly exceeds 12.5%. The main reason for the divergence could be an inaccurate selection of the stone's voxels put to analyse by the CT scan.

The value of the effective atomic number determined on the basis of infrared spectrometry was used as the reference value. In the case of gallstones, the library included to the spectrometer software was used to determine the chemical composition. However, it only matched the main component, which was cholesterol. The presence of bilirubin and calcium was found by comparing the position of the oscillation peaks of the reference substance with the positions of peaks of the tested samples.

In the case of kidney stones, the analysis was made only by comparing the peaks positions. It should be emphasized that this method does not provide final information on the composition of the sample, but indicates what substance is most likely to be expected.

5. Summary

The aim of this study was to evaluate the usefulness of dual-energy CT in determining the mineralogical composition of organs stones using Advantage Workstation GE software available in Centre of Oncology, Maria Skłodowska-Curie Memorial Institute, Krakow Branch.

Multi-energy tomography is a perfect complement to the diagnostic methods of diseases related to the occurrence of intra-organs stones. Scanning the studied area simultaneously with two energies allows obtaining high resolution CT scans on which pathological structures of 0.5 cm are visible. The GSI Viewer application included to the physician's workstation calculates the histograms of the effective atomic number, thus providing information on the mineralogical composition of the stones, which can significantly affect the patient's treatment and their faster recovery.

Before considering the use of dual-energy tomography in determing mineralogical composition of intra-organs stones in clinical applications, its accuracy should be confirmed by means other than infrared studies such as x-ray spectroscopy. That is our next goal in developing our studies.

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