Composition of CT Lung Density Reference Using Prompt Gamma Activation Analysis

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INTRODUCTION

The Computed Tomography (CT) density measures in Hounsfield Units (HU) have been used as a quantitative image biomarker for the diagnosis and monitoring of lung density changes due to emphysema, a feature of chronic obstructive pulmonary disease (COPD) [1]. To reduce variability in the density metrics specified by CT attenuation, measured in Hounsfield Units (HU), phantom studies in a variety of scanner models were conducted to provide assessments of the accuracy and precision of the density metrics across platforms solely due to machine calibration [2]. To provide a calibration reference for these phantoms, NIST has developed a suite of lung density reference foams, Standard Reference Material (SRM) 2088, which are certified for the absolute density [3-5]. The SRM is aimed at establishing the HU-electron density relationship and removing scanner dependence for the CT lung density measures. However, the composition of the polyurethane foam material (LAST-A-FOAM® FR-7100 series, General Plastics, USA) is not well known. We employed Prompt Gamma-ray Activation Analysis (PGAA) to determine the elemental composition by measuring the characteristic energies and intensities of prompt gamma rays emitted from H, N and C following neutron capture by nuclei [6].

DESCRIPTION OF THE ACTUAL WORK

PGAA was performed on SRM 2088 polyurethane foam blocks with five different nominal densities: 0.060 g/cm^3, 0.120 g/cm^3, 0.185 g/cm^3, 0.230 g/cm^3, and 0.325 g/cm^3. Each was cut into about 4 cm × 2 cm × 1 cm block, and mounted by Teflon® strings in an evacuated sample chamber for neutron beam irradiation and for gamma-ray spectroscopy with a high-purity germanium detector. The collection time varied from 1 h to 16 h. The relative atom fractions were determined by taking the ratio of the numbers of atoms, obtained from Eq. 1.

$$n_{x,\gamma_i} = \frac{A_{x,\gamma_i}}{\varepsilon_{\gamma_i}\ \sigma_{x,\gamma_i}\ \varphi_{th}} \qquad (1)$$

The quantities of interest in Eq. 1 are defined as:
n_{x,γ_i}: the number of atoms for element x (i.e., H, C, or N) for gamma ray γ_i.
i: peak index, in cases where there are multiple gamma-ray peaks for the element. (For H, $i = 1$.)
A_{x,γ_i}: count rate of the characteristic gamma-ray peak i from element x.
σ_{x,γ_i}: partial gamma-ray production cross section for gamma ray γ_i from element x.
ε_{γ_i}: detection efficiency for gamma ray γ_i.
φ_{th}: thermal-equivalent neutron flux in sample.

By taking the ratio the number of atoms determined by Eq. 1, the neutron flux characterization is bypassed for homogenous samples since it is the same for elements in the same sample. Thus, the resulting ratio is independent of sample characteristics (mass, composition, shape, etc.).

RESULTS

Gamma-ray spectra were acquired for the foam blocks with five different density. Fig.1 shows a comparison of the resulting gamma-ray spectra from the highest and lowest density samples. The peak analysis was performed using PeakEasy (Los Alamos National Laboratory). Energies of prompt gamma-ray peaks used for the analysis are:

- C: 1,261 keV; 3,684 keV; 4,945 keV
- H: 2,223 keV
- N: 5,269 keV; 5,298 keV; 5,533 keV; 10,829 keV
- Cl: 1,164 keV (not labeled)

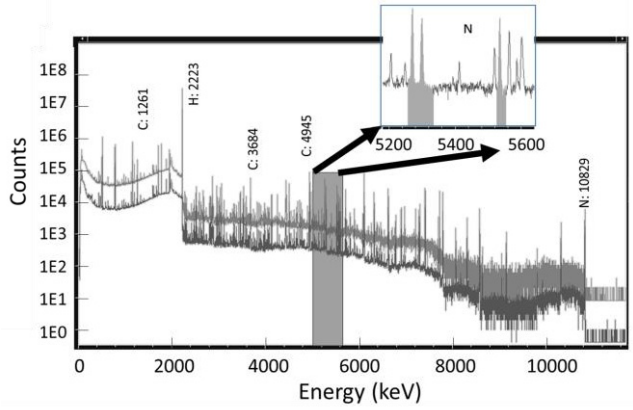

Fig. 1. Gamma-ray spectra acquired (normalized by detector live time) from the (top) highest density sample and from the (bottom) lowest density sample.

The number of atoms determined using Eq. 1 (with an arbitrary neutron flux value) were plotted (Fig. 2) for C and N versus H. The uncertainties due to counting statistics are small in comparison to the different values obtained from the different peaks for C and N, the average and the standard deviation (over i) of which are plotted in Fig. 2.

The number of atoms increased proportionally to the density of the sample, as expected. The slope of each linear trendline represents Eq. 2 and can be used to determine the stoichiometry of the material because the samples are considered to have identical compositions but varying physical density.

Of the many possible "polyurethane" compositions, only two, or possibly three, have the H/C and N/C ratios that simultaneously fall within or close to the 95% confidence interval of the ratios determined by PGAA (Fig. 3). This information will be useful for CT number calibration using the SRM 2088 in a lung density phantom. Future directions include the investigation of sources of uncertainties and analysis of other minor elements in the matrix that have effects on x-ray attenuation.

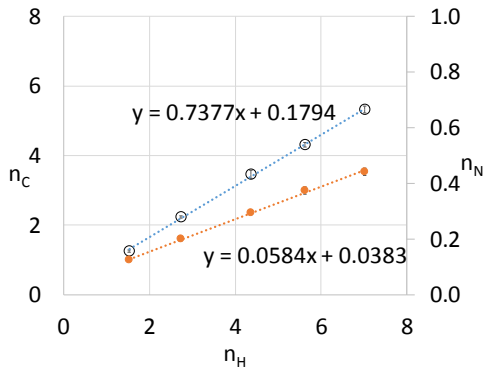

Fig. 2. Determination of atom ratios of C, H, and N based on Eq. 1. The slope and uncertainty are used to create the 95% confidence intervals of the most likely ratios in Fig. 3.

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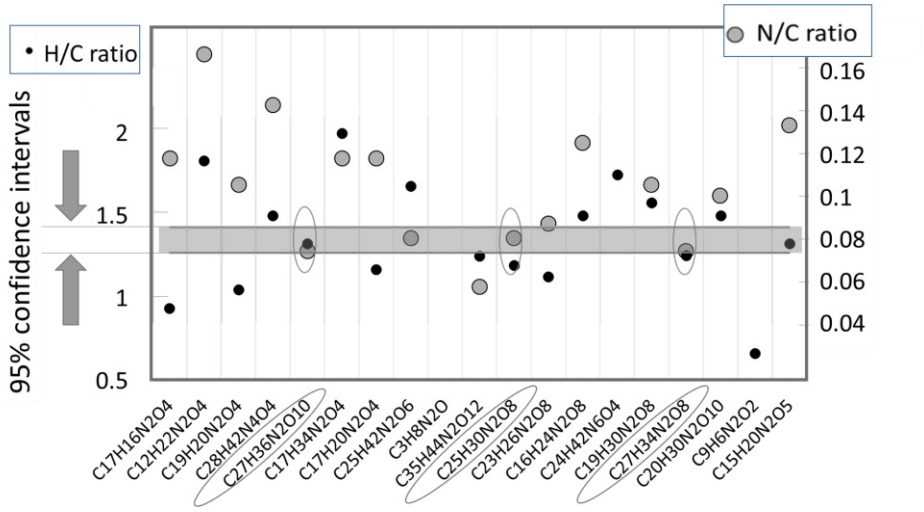

Fig. 3. Summary of the H/C and N/C ratios from the possible polyurethane compositions, with the ones closest to the ratios (circled) determined by PGAA.