Assessment of the Homogeneity of Polymeric Materials Using Hounsfield Units

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Abstract. The X-ray transparency of various polymers and plastics is one of the most important factors in the choice of materials in the design of new medical robotic and mechatronic systems and complexes. Along with the radiolucency, such a parameter as material inhomogeneity is also one of the main ones. The inhomogeneity of the material can not only affect the radiolucency of individual areas of the product but also impose restrictions on the use of polymeric materials by changing the physical and mechanical properties of the products. In this work, a technique was proposed for determining the location of regions of interest with reliable values on a CT image. Data were obtained for the values of the parameter HU and standard deviation for various polymer materials. A technique was proposed for determining the degree of heterogeneity of polymeric materials. The values of the degree of heterogeneity were obtained for all investigated materials.

1. Introduction

Currently, robotic systems are being actively developed, which are used to support doctors during surgical operations [4,5,6]. The performance of these systems depends on many factors. These factors can come both from the characteristics of the entire system and from its individual elements. Evaluation of the characteristics of the developed robotic systems depends on a good understanding of the structure of the nodes of these systems, as well as their overall connection. For example, the accuracy of the robot's units can be assessed using automatic stands [3], and the accuracy of navigation of medical instruments can be assessed using specialized metrological equipment [1,2,7]. However, if, when designing a robotic system, it is found necessary to use intraoperative X-ray (EOP), CT, or MRI to navigate inside the patient's body, then there is an urgent need for a non-trivial selection of materials. Therefore, along with the assessment of the accuracy of robotic systems, the most important field for research is X-ray transparency and its assessment.

Radiodensity (or radiopacity) is the opacity for radio waves and the X-ray portion of the electromagnetic spectrum: that is, the relative inability of these types of electromagnetic radiation to pass through a particular material [8]. Materials that block the passage of electromagnetic radiation are called X-ray contrast materials, and those that allow the radiation to pass more freely are called X-ray transparent materials. Radiopaque materials on radiographs are white compared to relatively darker
radiolucent materials. For example, on typical radiographs, bones appear white or light gray (radiopaque), while muscles and skin appear black or dark gray, mostly invisible (radiolucent).

Although the term "radiodensity" is more often used in the context of a qualitative comparison, radiodensity can also be quantified using the Hounsfield scale, a principle that is central to X-ray computed tomography (CT) applications. The Hounsfield scale is a quantitative scale for describing radiodensity. It is often used in CT scans, where its value is also called CT number. The Hounsfield Units (HU) scale is a quantitative scale for describing radiodensity. It is often used in CT scans, where its value is also called CT number. The Hounsfield Units (HU) scale is a linear conversion of the original linear attenuation coefficient measurement to a scale in which the radiodensity of distilled water at standard pressure and temperature is defined as zero Hounsfield unit, and the radiodensity of air is defined as -1000. Thus, in a voxel with an average linear attenuation coefficient, the corresponding Hounsfield unit value is defined as follows:

\[ HU = 1000 \times \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}} - \mu_{\text{air}}} \]

where \( \mu_{\text{water}} \) and \( \mu_{\text{air}} \) are linear coefficients of attenuation of radio waves in water and air, respectively.

In medicine, the range of plastics and polymer mixtures used is extensive. The main parameter of material in medicine can be considered the parameter of the material's radiolucency (HU). However, the heterogeneity of the material is also not only one of the main parameters, but also an indicative characteristic. Plastics are a material consisting of a set of simple elementary elements interconnected. The value of the material's X-ray transparency parameter mainly depends on the concentration of these elementary elements in the composition of polymer mixtures and plastics. Consequently, the plastic of the same brand should have a specific value of the HU parameter and heterogeneity, however, analyzing the data presented in the articles on determining the value of the material's radiolucency, it can be seen that the values of these parameters differ and constitute a large range of values [9-21].

There may be several reasons for the occurrence of different values of the HU parameter of the same material:

1. Various concentrations of chemical elements in the composition of primary plastic.
2. Various technical conditions for the processing of virgin plastic.
3. Various methods for determining the value of the HU parameter. Various parameters of computed tomography scanning, the use of various algorithms and filters when collecting experimental data.

However, along with standardized and generally accepted methods for determining the concentration of chemical elements in polymers, the absence of a standardized method for determining the values of the HU parameter and the heterogeneity of polymer materials by CT image leads to different research results.

Investigated materials

A total of 45 samples from various materials were selected for our study (Table 1). Polymers (43 pcs.) and three types of stainless steel were used as materials. Samples 23-38 were produced by polymer layering.

For all samples, CT images were obtained using a CT-Scanner Aquillion 64 (Canon). The scanner power was 120 kV, and the slice thickness was 0.5 mm. Using the software (Vidar Dicom Viewer 3), the values of the HU parameter and the standard deviation in the regions of interest were determined. It should be noted that images of objects on CT images have the effect of blurring the edges. This effect does not allow to reliably determine the values of the HU parameter. Therefore, it is necessary to develop a methodology that allows you to unambiguously determine the location of the regions of interest with reliable HU readings.
Table 1. Investigated materials.

| №  | Material                                | №  | Material                                                      |
|----|-----------------------------------------|----|---------------------------------------------------------------|
| 1  | Polyacetal                              | 2  | SAN-based (styrene-acrylonitrile copolymer)                   |
| 2  | Glass fiber laminate                    | 3  | Nylon                                                         |
| 3  | Capron                                  | 4  | Carbon fiber nylon                                            |
| 4  | Polyurethane                            | 5  | ABS with added carbon fibers                                   |
| 5  | Polyvinyl chloride                      | 6  | Thermoplastic elastomer                                       |
| 6  | Polycarbonate                           | 7  | Polymethyl methacrylate (PMMA)                                |
| 7  | Graphite-filled capron                  | 8  | Nylon                                                         |
| 8  | Fluoroplastic                           | 9  | High impact polystyrene                                       |
| 9  | Stainless steel                         | 10 | Polyactide                                                    |
| 10 | Stainless steel                         | 11 | Polyethylene terephthalate glycol (PET copolymer)             |
| 11 | Stainless steel                         | 12 | Acrylonitrile styrene acrylate                                |
| 12 | Textolite                               | 13 | Copolymer of acrylic ether, styrene, and acrylonitrile        |
| 13 | Caprolon with MoS2                      | 14 | Polyurethane                                                 |
| 14 | Polyaniline sulfone                     | 15 | Polyethylene terephthalate glycol (PET-G)                     |
| 15 | Polyamide 6                             | 16 | Styrene-butadiene-styrene                                     |
| 16 | Polypropylene block copolymer           | 17 | Polymethyl methacrylate                                      |
| 17 | Polyetheretherketone                    | 18 | Fluoroplastic                                                |
| 18 | Ultra-high molecular weight polyethylene| 19 | Polyvinyl chloride                                           |
| 19 | Carbon fiber                            | 20 | Polymethyl methacrylate                                      |
| 20 | Carbon fiber                            | 21 | Polymethyl methacrylate                                      |
| 21 | Acrylonitrile styrene acrylate          | 22 | Smooth-Cast 205                                              |
| 22 | Polylactic acid                         |    |                                                               |

Method for determining the heterogeneity of polymer materials
An integral part of the method for determining material heterogeneity is an algorithm for determining the location of regions of interest with reliable values. As mentioned above, the blur effect of the edge contributes to the change in the values obtained in the regions of interest, therefore, these values should be considered unreliable and should be excluded from consideration.

Thus, the method for determining the heterogeneity of the sample material by CT-image includes 3 main points:

1. Determination of the location of the area of interest areas with reliable values.
2. Determination of the values of the HU parameter and the standard deviation of the HU parameter in at least 10 regions of interest on three or more tomographic slices.
3. Determination of the standard deviation of the values of the HU parameter of all areas of interest located in the zone of reliable values.

**Results**

To assess the effect of edge blurring on the HU parameter readings, it is necessary to determine the distance from the visible edge of the sample at which the values of the HU parameter are systematic and constant. To do this, we draw an imaginary coordinate system with the center located on the middle layer of the sample, the X-axis along the long side of the sample, and the Y-axis along with the short one. The intersection of the X and Y axes must coincide with the geometric center of the specimen on the CT image (Figure 1).

![Figure 1](image_url)

**Figure 1.** Location of the coordinate axes and characteristic areas on the CT-image of the sample.

Further, in the characteristic areas (1, 2, 3), which are the intersection of the X and Y axes of the visible edges of the material, it is necessary to measure along the X or Y coordinate axes of the values of the HU parameter. In our study, the regions of interest, in which the average values of the HU parameter and the standard deviation are determined, were located at a distance of 0.1 mm, and the number of regions of interest was equal to 70 for one characteristic region, provided that the sample size was sufficient.

By repeating this algorithm for all characteristic regions, three data sets were obtained: in characteristic regions 1, 2, and 3. It should be noted that a total of 131 values were obtained along the Y-axis.

Based on the data obtained, graphs were built showing the changes in the values of the HU parameter and the standard deviation depending on the distance from the visible edge of the sample on the CT image (Figure 2 - 4).
As can be seen from the graphs, the values of the standard deviation near the edges of the sample on the CT image are large. This is due to the effect of blurring the edges of the sample. Therefore, ROIs with these values should not be considered in further calculations and should be filtered out.
Each ROI is a set of voxels with average gray values, which are then matched by software to the HU value. Since the ROI is a set of values for the HU parameter of a certain number of voxels, the standard deviation shows homogeneity within one ROI. Therefore, having determined the standard deviation from the standard deviation of the set of obtained values, it is possible to determine the magnitude of this deviation depending on the distance from the edge of the sample on the CT image.

On the Y-axis, two ranges of values of standard deviations were considered for the corresponding numbers of regions of interest: from 4 to 129, from 7 to 126. Regions of interest with numbers 1, 2, 3, 130, 131 were excluded from the calculations, since the standard deviations of these regions of interest are large, which indicates the heterogeneity within these areas of interest, and the unreliability of these values. The standard deviation values of the standard deviations of the set of regions of interest numbered 4 through 129 and 7 through 126 were 11.879 and 3.393, respectively. Therefore, we can conclude that the range of regions of interest from 7 to 126 numbers more accurately characterizes the homogeneity of the sample material, since the values of the standard deviation of these two ranges differ by more than two times.

According to the proposed methodology, the ranges of reliable regions of interest for characteristic regions 1, 2, and 3 were determined. For characteristic region 1, this range is characterized by regions of interest numbered from 4 to 70, and for characteristic region 2 - with numbers from 5 to 70.

Therefore, by calculating the distance from the edges of the sample on the CT-image along the X and Y axes, it is possible to determine the location of the zones in which the values of all regions of interest will be reliable. The distance from the neighboring regions of interest was 0.1 mm, therefore, it can be concluded that at a distance of 0.4 mm in the characteristic region of 1 and 0.5 mm in the characteristic region of 3 CT - images of the sample, respectively, all values of the regions of interest will have reliable values, and in characteristic area 2 - from 0.7 to 12.6 mm.

It should also be noted that the zones with reliable values of the regions of interest differ in their size depending on the sample under study. So for sample number 17, they were 0.4 mm in characteristic area 1 and 0.5 mm in characteristic area 3 from the visible edges of the sample on the CT image and 0.7 to 12.6 mm in characteristic area 2. For sample at number 20 - from 1.2 mm to 6 mm in the characteristic area 2 and 0.6 mm and 2.9 mm in the characteristic areas 1, 3, respectively. For sample number 43 - from 1.4 mm to 3 mm in the characteristic area 2 and 2.1 mm and 1.3 mm in the characteristic areas 1, 3, respectively. The location of regions of interest with reliable values can depend on a large number of factors, such as shape and size, the method of manufacture and subsequent processing of the test sample, and many other factors. Therefore, it can be concluded that determining the location of the zone of reliable values of the regions of interest must be determined for each sample individually.

According to the method described above, for each sample, the location of the zone of reliable values of the regions of interest was first determined, and then the values of the parameter HU and the standard deviation were determined for three layers. Each layer had 10 regions of interest, in which the values of the HU parameter and the standard deviation were determined. As a result, the values of the HU parameter and the standard deviation were obtained in 30 regions of interest. Next, the arithmetic mean of the value of the HU parameter was determined for 30 regions of interest for each sample according to formula 1.

\[
\overline{HU} = \frac{1}{n} \sum_{i=1}^{n} HU_i = \frac{1}{n} \left( HU_1 + \ldots + HU_n \right)
\]  

(1)

Also, the standard deviation of the values of the HU parameter for each sample was determined according to formula 2.

\[
S = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( HU_i - \overline{HU} \right)^2}
\]  

(2)

The calculation results are presented in Table 2.
Table 2. Calculated values of HU parameters and standard deviation.

| №  | The arithmetic mean of the parameter HU | Root-mean-square deviation of parameter values | HU | The arithmetic mean of the parameter HU | Root-mean-square deviation of HU parameter values |
|----|----------------------------------------|-----------------------------------------------|----|----------------------------------------|-----------------------------------------------|
| 1  | 293,40                                 | 39,995                                        | 23 | -108,97                                | 61,567                                        |
| 2  | 967,43                                 | 334,378                                       | 24 | -91,00                                 | 87,468                                        |
| 3  | 80,10                                  | 14,625                                        | 25 | -179,10                                | 48,277                                        |
| 4  | 198,37                                 | 10,227                                        | 26 | -239,00                                | 42,119                                        |
| 5  | 1022,47                                | 37,088                                        | 27 | -328,83                                | 94,300                                        |
| 6  | 81,40                                  | 9,474                                         | 28 | -105,57                                | 36,622                                        |
| 7  | 74,33                                  | 8,277                                         | 29 | -294,40                                | 86,872                                        |
| 8  | 933,67                                 | 39,310                                        | 30 | -244,97                                | 33,885                                        |
| 9  | 756,07                                 | 37,633                                        | 31 | -96,53                                 | 39,107                                        |
| 10 | 1795,47                                | 511,662                                       | 32 | -232,20                                | 38,651                                        |
| 11 | 3263,40                                | 335,779                                       | 33 | -169,23                                | 93,076                                        |
| 12 | 2914,40                                | 446,369                                       | 34 | -205,70                                | 29,302                                        |
| 13 | 266,87                                 | 21,787                                        | 35 | -223,40                                | 44,946                                        |
| 14 | 77,33                                  | 6,865                                         | 36 | -347,57                                | 61,675                                        |
| 15 | 202,73                                 | 31,138                                        | 37 | -255,03                                | 77,611                                        |
| 16 | 52,17                                  | 12,540                                        | 38 | -263,27                                | 96,809                                        |
| 17 | -137,50                                | 14,481                                        | 39 | 60,45                                  | 14,581                                        |
| 18 | 128,90                                 | 15,266                                        | 40 | -138,97                                | 13,828                                        |
| 19 | -114,47                                | 14,422                                        | 41 | 546,43                                 | 176,255                                       |
| 20 | 223,50                                 | 33,118                                        | 42 | 81,23                                  | 8,270                                         |
| 21Б| -740,13                                | 39,123                                        | 43 | 44,20                                  | 9,521                                         |
| 21М| -182,47                                | 56,938                                        | 44 | -20,80                                 | 48,002                                        |
| 22 | -219,30                                | 58,392                                        |    |                                        |                                               |

According to GOST R IEC 61223-2-6-2001, material homogeneity is defined as the constancy of the HU parameter values throughout the CT image of the sample. Therefore, the standard deviation of the measured values of the HU parameter can indicate the degree of inhomogeneity of the sample material.

As can be seen from the obtained values, metal samples have high values of the arithmetic mean parameter HU. The values of the standard deviation of the values of the HU parameter, characterizing the heterogeneity of the material, also have high values. It can be argued that the high values obtained during the processing of CT images are distorted by the effect of flare. Based on this, it can be concluded that the methods for determining the X-ray transparency and inhomogeneity of the material must be corrected for metal measurement objects.

All polymer materials presented in this article can be roughly divided into two categories: materials that have a homogeneous structure and materials that have been obtained by layer-by-layer application of the material. All samples obtained by the method of layer-by-layer deposition of the material have negative values of the arithmetic mean parameter HU, which is characteristic of this method of making samples since during manufacturing the material is applied layer-by-layer according to a certain pattern. Thus, empty cavities filled with air are formed in the sample, which eventually affects the arithmetic mean parameter HU. When determining the arithmetic average parameter HU of material, two components are taken into account: the value of the HU parameter of the material itself and the value of the HU parameter of air, which leads to negative values of the arithmetic average parameter HU of the sample material.
2. Conclusion
In this article, 45 samples from various materials were examined for radiolucency. 42 grades of polymer materials and three types of stainless steel were used as materials. Samples 23-38 were produced by polymer layering. A technique was proposed to determine the location of the zone of reliable values of the areas of interest.

The values of the HU parameter were determined for all the samples under consideration. A method was proposed for determining the degree of inhomogeneity of the sample material by CT-image, which includes three main stages: determining the location of the zone of interest with reliable values, determining in at least 10 regions of interest the values of the HU parameter, and the standard deviation of the HU parameter on three or more tomographic slices, determination of the standard deviation of the values of the HU parameter of all areas of interest located in the zone of reliable values.

The degrees of heterogeneity were determined for all considered polymeric materials by calculating the standard deviation from 30 values of the parameter HU. The heterogeneity of polymeric materials can be conditionally divided into three categories: homogeneous, medium homogeneous, and heterogeneous materials. The samples under study can be classified as homogeneous materials, the values of the standard deviation of the HU parameter are in the range from 0 to 15. Samples with the values of the standard deviation of the HU parameter in the range from 16 to 100 can be considered homogeneous materials. And materials with the values of the standard deviation of the HU parameter more than 100 should be considered inhomogeneous.

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