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Comparative Analysis between Different Methods for Estimating Volumes of Non-Traumatic Intracranial Intraparenchymal Hematomas

Luiz Fernando Cannoni, Henrique Zuleta de Barros Couto*, Euro de Barros Couto Junior and José Carlos Esteves Veiga

Department of Surgery, Discipline of Neurosurgery, Irmandade da Santa Casa de Misericórdia de São Paulo, Brazil

***Corresponding author**: Henrique Zuleta de Barros Couto, Academic of Medicine, 40 Francisco Mainardi Street, Lapa, São Paulo - São Paulo, Brazil, Tel: +551199903-4404; E-mail: henriquezuleta@gmail.com

Abstract

Objective: We propose a more accurate method for calculating the volume of non-traumatic intracranial intraparenchymal hematomas.

Materials and methods: Data of 16 patients admitted to Hospital da Santa Casa de Misericórdia de São Paulo, in São Paulo. The selection was made solely because they were patients diagnosed with intraparenchymal hematomas. The data collection period was from February 1, 2022 to March 7, 2022.

Results: Three proposed methods for calculating hematoma volume were compared with the traditional formula. Also, the three proposals were compared with each other. We observed that the values of the three proposals are similar to the values of the traditional formula; when the three proposals were compared with each other, we obtained the following results: 'MED' and 'POND', p = 0.679; "MED' and 'SCA', p = 0.026 (the values of 'SCA' are effectively lower than those of 'MED'); lastly 'POND' and 'SCA', p = 0.063 ('SCA' values tend to be lower than 'POND' values).

Conclusions: The proposed method 'SCA', despite costing more time to obtain its volume, uses mathematical calculus devices (integrals) and is very close to one of the methods for volumetric estimation of non-traumatic intraparenchymal hematomas; the formula a.b.c/2 (LIT) seems to come very close to the

real value of the volume of a lesion, and even of any object that its volumetric study might be of interest.

Introduction

Interest in the medical field

The interest in estimating lesion dimensions is immense in the medical field. Generally, the volume of a lesion can help the healthcare professional to plan a surgical procedure, or even predict a prognosis for a certain case. Therefore, knowing the value of the volume of a given lesion as accurately as possible is necessary. Several models have already been proposed to obtain the desired value. The following method would be one of the most accepted in the medical literature:

I) Assume that the intracranial lesion has an ellipsoid shape;

II) Analyze the tomographic sections of the three axes (axial, sagittal and coronal) and obtain the following measurements (using the Ruler tool (from Xero Viewer®), or similar for other operating systems):

a: the biggest antero-posterior diameter of the lesion;

b: the biggest lateral-lateral diameter of the lesion;

c: the biggest cranial-caudal diameter of the lesion;

III) With these values in hand, one of the following formulas is used:

$$V_A = \frac{a.b.c}{2} \text{ and } V_B = \frac{2}{3}.a.b.c.$$

Comments and initial observations on the V_A and V_B models

From this model, regardless of the formula used, it is possible to notice that there are several inconsistencies:

1) an intracranial hematoma-type lesion (whether intraparenchymal, subdural, epidural or subarachnoid) does not necessarily have an ellipsoid shape; a three-dimensional reconstruction of this blood accumulation (by Computer Tomography Angiography (CTA) or Magnetic Resonance Imaging (MRI)) makes this quite evident, despite the extremely high costs of doing so; 2) as already systematically reviewed by Zhao et al. (2019) [1], the volume value obtained by the a.b.c /2 method (LIT) overestimates the real value between 8.53% and 29.3%; 3) any of the "simple formulas" ignore defects and amorphous sectors of the lesion.

As previously mentioned, the work of Zhao et al. (2019) [1] compared different methods for calculating the volume of a type of hematoma; while some methods underestimated the values, others overestimated them. The "gold standard" of Zhao et al. (2019) [1] was the volume estimated by the 3D Slicer software, and the formulas that the researchers used fit the same inconsistencies mentioned previously. It seemed necessary to accept the challenge of proposing a new method for calculating volume, in such a way that it comes as close as possible to the real value and that takes into account the imperfections present in the lesion of interest. The team of Ishisaka et al. (2021) [2] researched the validity of the a.b.c/2 method (called "XYZ/2" by the authors) for chronic subdural hematomas, using computerized analysis as the "gold standard" (somewhat similar to our proposed method). Our analysis, on the other hand, assumes that two methods (a.b.c/2 and 2.a.b.c/3) are the "gold standards" and we compare the values obtained by the computerized analysis method, reformulated in such a way as to try to overcome some inconsistencies from the work of Ishisaka et al. (2021) [2]. An inconsistency that we detected

was the fact that only one of the three available axes was used to carry out the volumetric analysis, instead of using the three available axes (as we did use in this very method). A second inconsistency was assuming that the average distance between two consecutive slices of a tomographic machine was equal to 5 millimeters, a value that we did not find in our analysis; it is interesting to note that the software Hospital da Santa Casa uses assumed values that differed from 5 millimeters of distance between consecutive slices for each axis (it is therefore inconsistent to assume that the distance between two consecutive images 'h' was the same for the three axes). Our method tried to overcome this inconsistency and proposed an alternative for this, using the values of the largest diameter and the number of slices for each axis.

The prospect of a new proposal

This paper proposes a method for estimating the volume of intraparenchymal hematomas, or even of any given object of interest, knowing only the parallel and equidistant slices of such, with its orthogonal axes, the surface area of each slice, the distance between each slice or the diameters of each slice. We started our analysis from intraparenchymal hematomas and we would propose the extrapolation of such method to other areas of Medicine, and even to other areas of knowledge.

Mathematical concepts

Obtaining the volume of regular solid objects such as cubes and prisms is obtained by applying formulas that involve the three spatial dimensions (length, width and height).

The volume of the cube (regular hexahedron) is easily obtained when the measurement of one of the sides is entered. As it is a regular solid figure, that is, the length, width and height measurements have the same dimensions, simply raise the side measurement to the cubic power ($V_{cube} = side^3$), obtaining the result in cubic units.

A prism is a solid that has all congruent plane sections in the shape of a polygon. Therefore, it does not matter where the section is made parallel to the base, as the section always has the same area.

To calculate the volume of a prism, simply multiply the area of its base by the height of the solid ($V_{prism} = _{base\ area.}$ H). The result will also be in cubic units. This formula is also applied to calculate the volume of cylinders, which are prisms with a circular base. Therefore, for the cylinder applies $V_{cylinder} = \pi . R_{base}^{2.} H$. It is known that a prism with a triangular base comprises 3 pyramids. For this reason, the $V_{pyramid} = 1/3 . area_{base} . H$.

The volume of the pyramid corresponds to 1/3 of the volume of the prism. A prism has a volume corresponding to 3 pyramids.

So far, we have calculated volumes of regular solids, as the cross-sectional area does not differ along the height of the solid.

However, the area across the solid can vary, making the solid no longer regular. Let us look at this irregular solid in **Figure 1**.

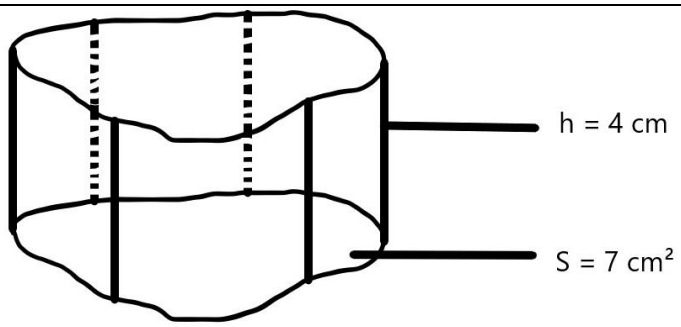


Figure 1: Irregular solid (Source: the authors).

In this case, the volume of the irregular solid in question is 28 cm **[3]**.

Even if the cross-sectional area is irregular, as in the figure above, the volume is calculated by the product of this cross-sectional area and the height of the solid, as long as this does not vary along the height.

A good example is the calculation of the volume of a cooling tower at an atomic power plant **(Figure 2)**. In this case, the areas of the central circles are smaller than the areas of the outer circles.

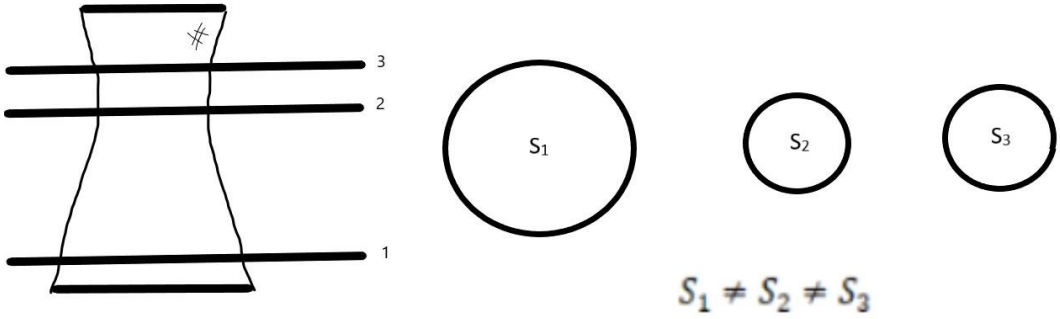


Figure 2: Sketch of an atomic power plant cooling tower and 3 slices on different heights along it (Source: the authors).

Therefore, if we calculate each circumferential cross-sectional area and add them all together, we will have the final volume of the tower (this is known as an integral calculus principle). Logically, the greater the number of circumferences (named in this paper as 'slices') and the smaller their thicknesses, consequentially the greater precision in calculating the volume of the tower will be. The greater the number of 'slices' added together, the more accurate the calculation will be, because if the number of slices tends to infinity, it means that the thickness of each slice tends to zero. The same effect happens in regular figures, but because there are defined formulas for calculating the volumes of these solids, we apply them directly for the calculation. In mathematical terms, the representation of the area calculation through a defined integral of the function f(x) is shown, where 'S' corresponds to the surface area, '0' and 'b' correspond to the starting and ending point of the measurement of

the area (also known as its extension) and 'f(x) dx' represents the function that describes the area to be calculated:

$$S = \int_0^b f(x)\,dx$$

Now, we intend to calculate volumes of solids which cross section constantly varies throughout the solid. This is because intraparenchymal hematomas generally have very irregular cross-sectional surfaces. Let us imagine, then, how to calculate the volume of a bell or a paraboloid. They are geometric solids whose cross-sectional area varies as the solid is traversed, that is, along its height. In such cases, we need to determine the equation (function – f(x)) that determines the solid of revolution, and then multiply by the largest number of possible slices (d(x)), to obtain the most accurate volume possible.

In **Figure 3**, below, it can be seen that by rotating the function f(x) 360 degrees along the x axis, we will obtain the calculation of the volume of a solid bell.

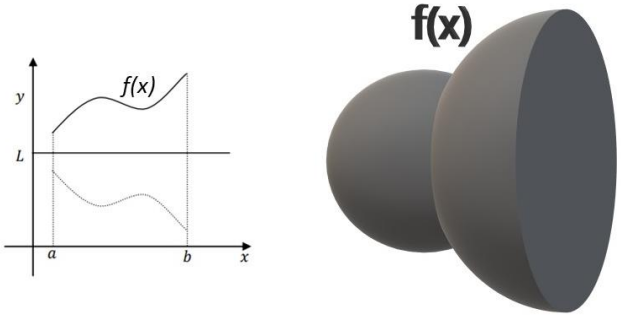


Figure 3: Solid bell volume (Source: the authors).

In **Figure 4**, to calculate the volume of the paraboloid, we use the same principle as calculating the volume by integral, that is, we rotate the function f(x) around the x axis.

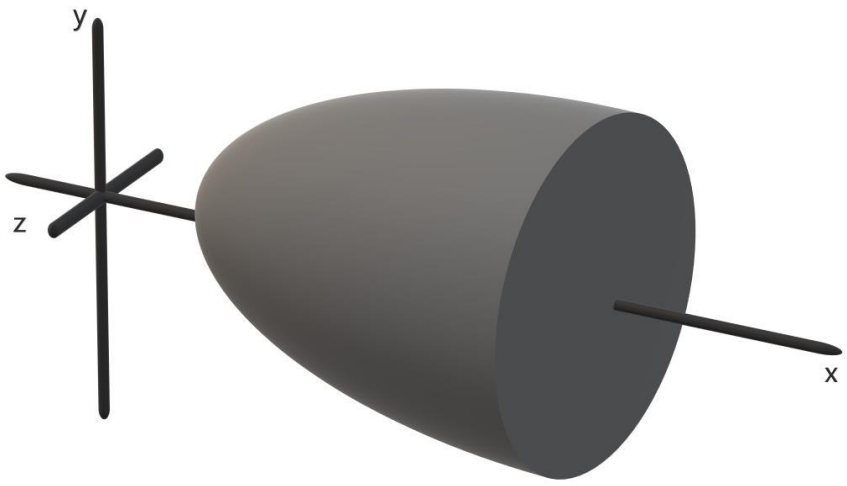


Figure 4: Paraboloid (Source: the authors).

By rotating the function f(x) above by 360 degrees, the volume of the paraboloid is obtained.

Thus, we can also obtain the volume of a sphere ($4/3.\ \pi.\ R^3$).

In this paper, we measured volumes of non-traumatic intracranial hematomas, using the principle of dividing the solid figure (hematoma) into the largest possible number of cross-sections in order to obtain the best approximation for calculating the volume of the lesion, which was done by the apparatus of the computerized tomography machine of our Hospital. We made a comparison with the formulas offered in the literature for calculating the volume of hematomas, although these formulas have been developed to calculate the volume of epidural hematomas, with a certain extension to subdural hematomas. These hematomas tend to have a more regular geometry when compared to intraparenchymal hematomas, making it easier to use these formulas to calculate the volume of those lesions.

Inclusion and exclusion criteria

Inclusion: only non-traumatic, lobar intraparenchymal hematomas that did not maintain dural contact with the bony surface of the skull were included, due to the possibility of overestimating the slice area of surface.

Exclusion: epidural and subdural hematomas were not candidates for volume calculation, as the calculation of hematoma surfaces could include bone surface or partial effect of bone structures which, as highlighted above, would overestimate its values.

Materials

Images from Computed Tomography (CT) scans of 16 patients who were admitted and treated at the Hospital da Santa Casa de Misericórdia de São Paulo were used. Data collection was carried out between February 1, 2022 and March 7, 2022. Patient data, exam reports and images of interest are stored in the Institution's database.

The program used to create **Figures 1 to 6** is Paint 3D, a free software available from Microsoft Corporation for Windows' computers.

The software used to observe tomographic

images is XERO Viewer® version 8.1.2, together with its "Ruler" and "Polygon" tools, which can provide us with linear and superficial measurements. The hardware used is: two Siemens® tomographs model SOMATOM go. All with 32 channels, volumetric and with no definition of slice thickness, which provide us with sections of the lesion, in three orthogonal axes (axial, sagittal and coronal); a Windows 10 desktop computer from Microsoft Corporation. The CT scanners were configured equally. The citation of brands was made necessary, as other healthcare institutions could have other apparatus and software's available to them.

Method

The method for obtaining the defined measurements was established prior to the start of data collection. The steps used in our work are described as following:

- With the CT exam available, we opened the file in the XERO Viewer® software.
- The hyper-attenuating region was identified, characterizing the presence of the lesion.
- The contours of the lesion were manually drawn, with the help of the 'Polygon' tool of the software. The precision of fitting each point to the margins of the hyper-attenuating image and the distance between them was up to each examiner.
- With the contour drawn and the area of surface calculated by the software, we used the "Ruler" function of XERO Viewer® program to obtain the values of the largest observable dimensions of that section, as long as this measurement is parallel to one of the axes studied.
- Therefore, let us call this measurement the diameter of a slice, for a given axis. For each slice, then, there will be 2 diameter values that will be obtained, and they are as follows:

a. For an axial slice, both antero-posterior and lateral-lateral diameters are obtained;

b. For a coronal slice, both lateral-lateral and cranial-caudal diameters are obtained;

c. For a sagittal slice, both antero-posterior and cranial-caudal diameters are obtained.

2. Once the values of all areas and diameters are obtained, we carry out the following operations:

3. The values of the areas of all cuts for a given axis are added:

a. For the axial axis, let us call the value of the sum of the areas S_{axial};

b. For the coronal axis, let us call the value of the sum of the areas $S_{coronal}$;

c. For the sagittal axis, let us call the value of the sum of the areas $S_{sagittal}$.

4. For each axis chosen for the study, the largest value of the diameter corresponding to it should be chosen in such way that this diameter is perpendicular to the studied axis and parallel to one of the axes of interest, with the relationships being as following:

a. For the axial axis, one should choose the biggest value of cranial-caudal diameters (let us call this value $D_{cranial-caudal}$).

b. For the coronal axis, one should choose the biggest value of antero-posterior diameters (let us call this value $D_{antero-posterior}$).

c. For the sagittal axis, one should choose the biggest value of lateral-lateral diameters is chosen (let us call this value $D_{lateral-lateral}$).

5. We then perform the following generic operation: $\boxed{V_{axis} = D_{perpendicular} * \frac{S_{axis}}{n_{axis}}}$

a. For the sagittal axis, we have: $V_{sagittal} = D_{lateral-lateral} * \frac{S_{sagittal}}{n_{sagittal}}$

b. For the coronal axis, we have: $V_{coronal} = D_{antero-posterior} * \frac{S_{coronal}}{n_{coronal}}$

c. For the axial axis, we have: $V_{axial} = D_{cranial-caudal} * \frac{S_{axial}}{n_{axial}}$

With three volume values obtained, three methods were developed to work with them:

I. Calculate the arithmetic mean between the values (MED):

$$V_{final} = \frac{V_{sagittal} + V_{coronal} + V_{axial}}{3};$$

II. Make the weighted average between the values, given that the weights of each axis are equivalent to the number of slices obtained for such axis (POND):

$$V_{final} = \frac{V_{sagittal} * n_{sagittal} + V_{coronal} * n_{coronal} + V_{axial} * n_{axial}}{n_{sagittal} + n_{coronal} + n_{axial}};$$

III. Perform the following operation (SCA):

$$V_{final} = \frac{b * S_{sagittal} + c * S_{sagittal} + a * S_{coronal} + c * S_{coronal} + a * S_{axial} + b * S_{axial}}{2 * n_{sagittal} + 2 * n_{coronal} + 2 * n_{axial}}$$

6. We compared the values obtained in each of the proposals with the values that models accepted in the literature would obtain.

The method for obtaining the diameter for a given axis

The measurement of the diameter of an axis ($D_{cranial-caudal}$, $D_{lateral-lateral}$ or $D_{antero-posterior}$) must be carried out adopting the following steps and conditions:

1. Choose the axis that will be worked on;
2. The diameter of interest ($D_{cranial-caudal}$, $D_{latero-lateral}$ or $D_{antero-posterior}$) must be visible in at least one of the sections of the piece;
3. The diameter of interest must be parallel to one of the other axes studied;
4. The diameter measurement takes into account the extremes of each slice of each axis, which is the distance between the points in relation to the axis of interest.

This measurement of the diameter of a cut for a dimension of interest is already used in methods accepted in the literature. We simply extended the concept to all sections in the three axes available to the observer (axial, coronal and sagittal).

The deduction of the generic formula for calculating the volume of a hematoma

For a given axis, the CT provides us with 'n' slices filled by the lesion. Thus, we will have three values of 'n': $n_{sagittal}$, n_{axial} and $n_{coronal}$ (we used n_{axis} as a generic notation).

It is known that the distance between two consecutive slices is 'h'. Also, we will have three values of 'h': $h_{sagittal}$, h_{axial} and $h_{coronal}$ (we used h_{axis} as a generic notation).

Therefore, to estimate the volume of this lesion using our method, we do the following:

- We identified the first image that shows the typical hyper-attenuation of a hematoma; this is our number 1 slice.
- Then, for this slice number 1, we drew the contours of the lesion with the software "Polygon" tool. This gave us the value of the area of our drawing, so that the area of the lesion is equal to the highlighted area. Let us call the value of this area S_1.
- We admit that there is a very thin "straight prism" between two consecutive cuts, which base is equivalent to the contour drawn by us and which height is equal to the distance between the slices (h). Let us call it prism 1.
- Using Cavalieri's principle, we calculate the volume of prism 1 (V_1), using the formula:

$$V_1 = h * S_1$$

We then repeat the procedure for slice 2, obtaining the value of S_2 and V_2, and so on, until the last slice (number 'n'), which eventually presents us the typical hyper-attenuation of the lesion, obtaining the value of S_n and V_n.

For the generic slice number 'z', the volume of this prism is calculated, taking into account Cavalieri's principle:

$$V_z = S_z * h.$$

Our solution ends when we add all the 'n' volumes obtained, obtaining the final volume value (V_{final}):

$$V_{final} = (V_1 + V_2 + \cdots + V_n) = \sum_{z=1}^{n} V_z, z = 1, \ldots, n$$

However, there is a very interesting alternative to this method, and it is done as follows:

$$V_{final} = V_1 + V_2 + \cdots + V_n = h * S_1 + h * S_2 + \cdots + h * S_n = h * (S_1 + S_2 + \cdots + S_n) \ (I)$$

To calculate the average distance between each slice, assuming that they are all parallel and equidistant, we must previously know the diameter of the part for a given axis (the values of $D_{cranial-caudal}$, $D_{latero-lateral}$ or $D_{antero-posterior}$, in millimeters) and the number of slices the tomography machine made for such axis (our 'n'). Thus, the ratio between these two factors should provide us with the distance between each slice 'h' (in millimeters/cut):

1) For a given axis, we must determine the diameter of the part for this particular axis, using a slice from another axis, orthogonal to the one being worked on (which can be obtained with the Ruler tool in XERO Viewer®). Like this:

- By choosing the axial axis, we can obtain the measurements $D_{latero-lateral}$ or $D_{antero-posterior}$ to obtain $h_{latero-lateral}$ or $h_{antero-posterior}$, respectively ;
- By choosing the coronal axis, we can obtain the measurements $D_{latero-lateral}$ or $D_{cranial-caudal}$ to obtain $h_{latero-lateral}$ or $h_{cranial-caudal}$, respectively ;
- By choosing the sagittal axis, we can obtain the measurements $D_{crânio-caudal}$ or $D_{antero-posterior}$ to obtain $h_{cranial-caudal}$ or $h_{antero-posterior}$, respectively.

2) The number of cuts, as already discussed, can be obtained by observing the first and last cuts that have the typical hyper-attenuation of bleeding (and these indices are shown by the

XERO Viewer® itself).

3) The ratio previously described is made, using the generic formula:

$$h_{axis} = \frac{D_{axis}}{n_{axis}} \ (II)$$

However, we know that:

$$V_{final_{axis}} = h_{axis} * (S_1 + S_2 + \cdots + S_n) \ (I)$$

Therefore, substituting II into I, we will have our final volume for an axis (V_{final}):

$$\boxed{V_{final_{axis}} = \frac{D_{axis}}{n_{axis}} * (S_1 + S_2 + \cdots + S_n)}$$

Illustrations of the method for clarifications

Figure 5 shows a scheme of three geometric shapes. The image on the left represents any section of a hematoma that can be obtained in the tomographic study. The letter S represents the surface area of this cut, which is obtained using the "Polygon" function of the XERO Viewer® software. The middle image represents the same section, but in three dimensions, as if there was a straight prism of height 'h' and base equal to S, from the section obtained by CT. The image on the right represents this same three-dimensional piece, highlighting both parallel bases and the height 'h' of the straight prism. Now, **Figure 6** shows the method for estimating the diameters for two randomly drawn objects. In the leftmost sector of the image, two axes perpendicular to each other can be seen. In the central part of the image, an object is shown with two of its diameters highlighted. In the rightmost part of the image, another object with an important convexity is shown. It is shown that the diameter estimation depends only on the errand of finding the extreme points of the part for the axis of interest and estimating the distance between these extremes only in relation to the axis of interest. All these schematics seemed to be necessary, as **Figure 7** shows a real application of all things discussed so far, on an intraparenchymal hematoma in the axial section. In it, its contour is already circumscribed by the "Polygon" function and the area is available for viewing on the screen. It is interesting to note that the hematoma has a somewhat chaotic shape, making demarcating its contours a very challenging task. As for the estimation of a diameter, **Figure 8** shows another example of an intraparenchymal hematoma, in which one of the diameters (the latero-lateral) is measured.

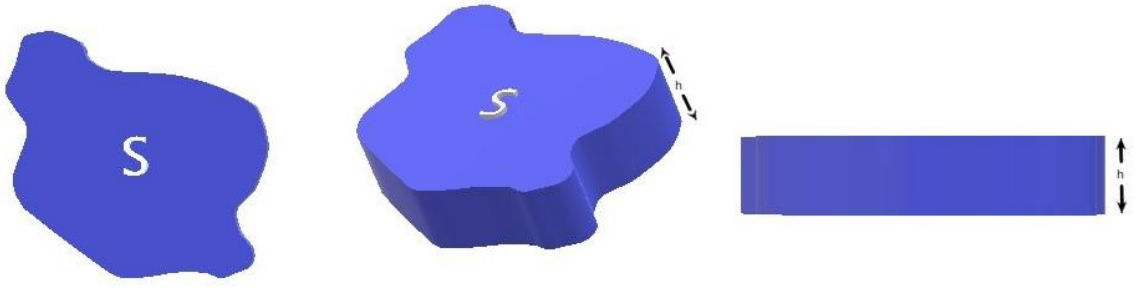


Figure 5: three perspectives of the same object. Note that it is a straight prism, of which parallel faces have an area 'S', and its height is 'h' (Source: the authors).

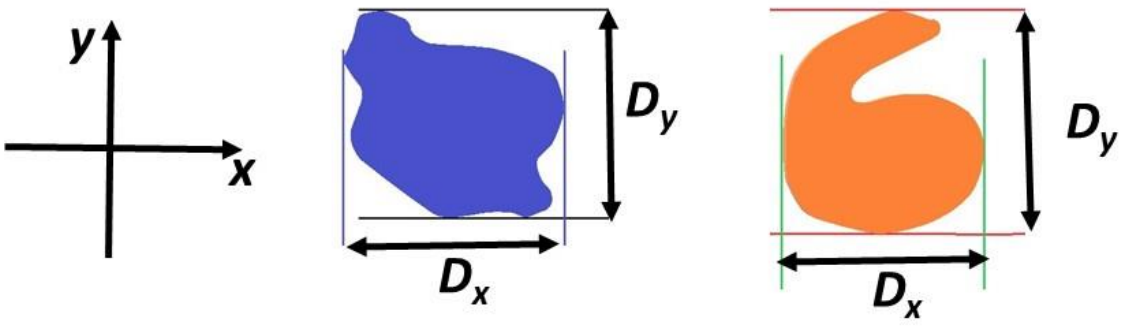


Figure 6: Estimation of two diameters (D) for each cut. Note that important convexities (as in the object on the right) are surpassed if we only take into account the extremities of the piece in relation to the axis of interest (Source: the authors).

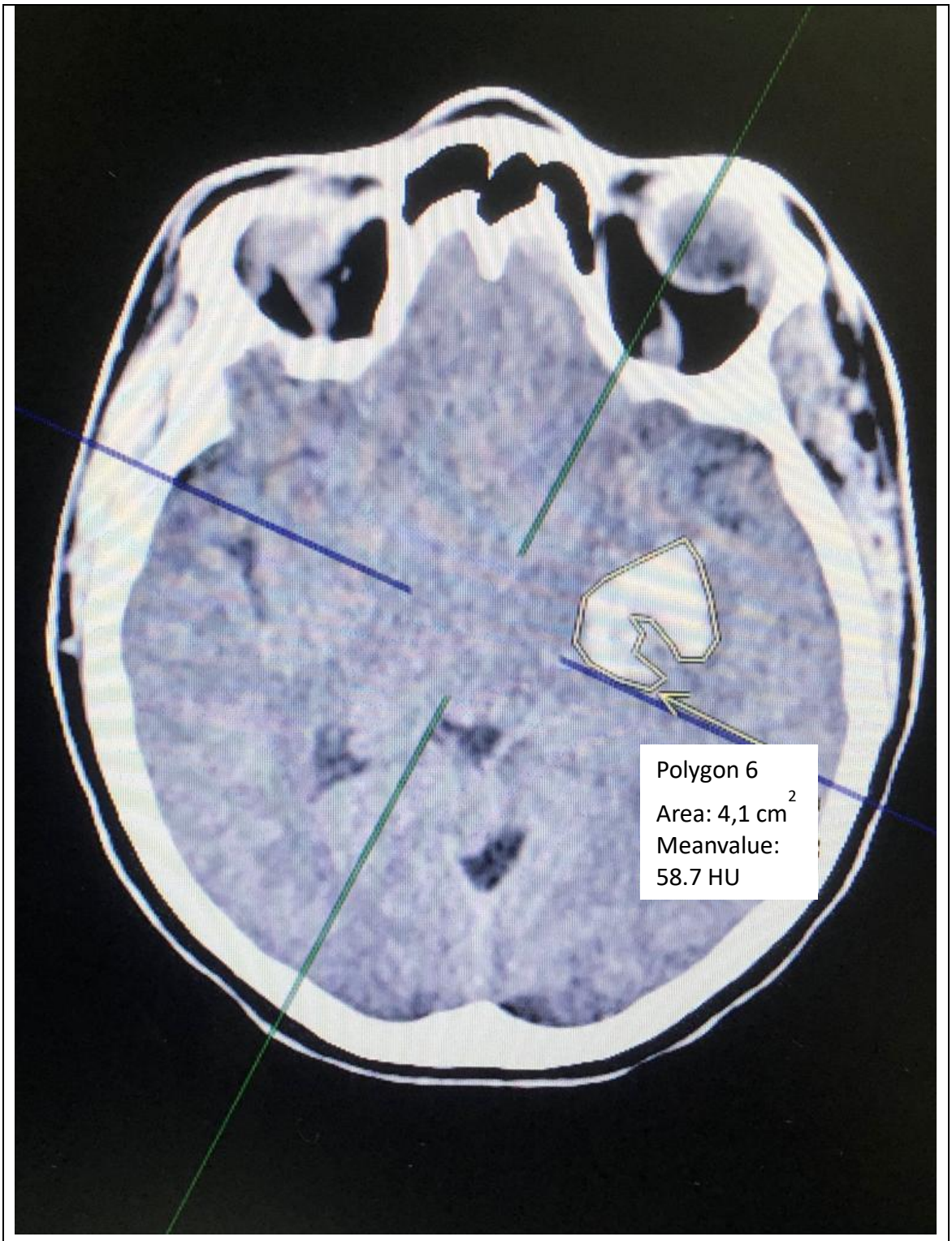


Figure 7: Demarcation of the margins of the intraparenchymal hematoma using the Polygon function. The XERO Viewer® software itself provides the delimited area in square centimeters. Yellow arrow highlights the 'polygon' and shows its information's (translated from Portuguese to English in the white square). Blue and green lines are auxiliary lines used by the software itself. (Source: the authors).

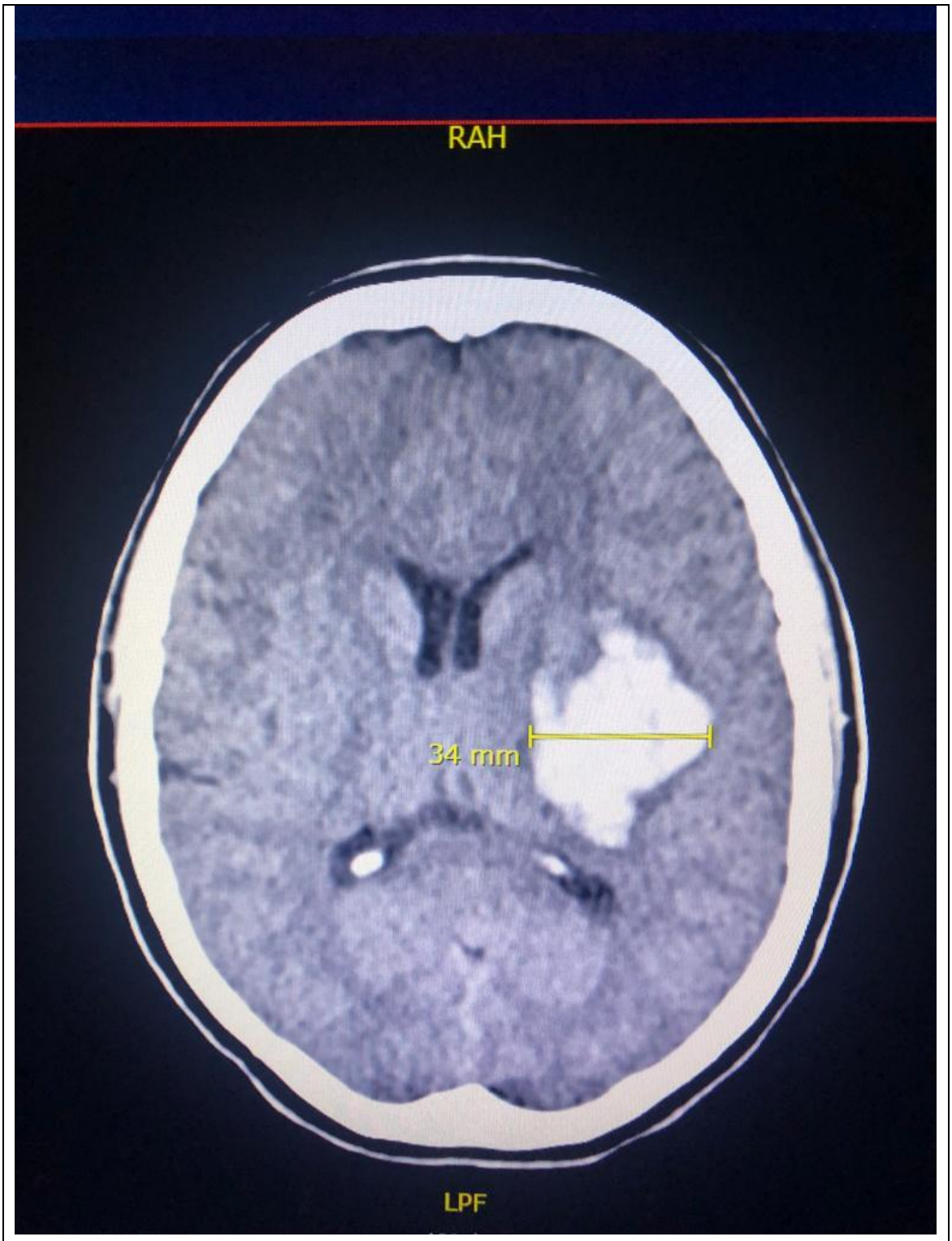


Figure 8: Yellow segment shows demarcation of one of the diameters of an intraparenchymal hematoma using the 'Ruler' function. The XERO Viewer software provides the measurement value in millimeters. (Source: the authors).

Discussion

We sought to propose a mathematical model for calculating volume, using only slices of parallel sections of the part of interest, in three orthogonal axes, without the use of expensive tools and exams from a hospital system. There may be some relationship between the volume of a hematoma immediately before it is drained and the patient's prognosis, as suggested by Broderick et al. (1993) [3]. We do not seek to investigate this possible volume-prognosis relationship; we also do not propose any algorithm of any kind to be developed that makes use of the hematoma volume value to decide whether or not to perform a neurosurgical procedure, especially since several protocols are already well established and disseminated.

A hematoma (whether intraparenchymal, subdural, epidural or subarachnoid) is an important type of injury to the intracranial circulation. It is a large blood accumulation, located in the patient's intracranial region, which interrupts blood circulation in that affected region and damages the brain through compression (and consequent mass effect) and lack of supply of oxygen and nutrients to neurons and glial cells in such region.

The damage that its presence causes to the brain can therefore be irreversible. Therefore, the neurosurgeon needs some information from the patient and their history to make an appropriate decision.

Several authors such as Peres et al. (2017) [4], Van Ornam et al. (2018) [5], Yu et al. (2018) [6], Bobeff et al. (2019) [7], Paranathala et al. (2019) [8], Kulesza et al. (2020) [9], Aromatario et al. (2021) [10], Ragaee et al. (2021) [11], Siddiq et al. (2021) [12], studied and suggested that there are several informations that must be obtained from the patient and that are equally relevant for making a decision and predicting a prognosis, some of which are as follows: age, history of the injury (whether traumatic or spontaneous), the existence of comorbidities (such as diabetes or Systemic Arterial Hypertension (SAH)), whether there is a previous history of Cerebrovascular Accidents (CVA), the patient's continuous use of medications, intoxication by alcohol, tobacco or other drugs on admission, the patient's vital signs on admission, the patient's glycaemia at the time of admission, the Glasgow Coma Scale (GCS) score at the time of admission or its worsening, the presence of focal deficits on examination neurological, the presence of active bleeding, the presence of signs of cerebral edema, the presence of coagulopathies, the blood ionic concentration, the presence of direct damage to the brain, the volume of the lesion, the location of the injury, the presence of skull fractures (and the types of fractures).

The exhaustive citation of some of these information shows that there is a large set of data that is very relevant for decision-making and prognosis prediction. Each author cited suggested the weights that each factor had in determining operational risk and prognosis. It turns out that Broderick et al. (1993) [3] took the risk of trying to correlate in isolation the estimated volume of hematomas immediately before the resection operation and the patients' prognosis and produced a work of great relevance, suggesting that there is some relationship between the volume of the lesion and the prognosis. The work therefore suggests that estimating the volume of these injuries (however laborious it might be) is not an innocuous action, and can predict some information about what would happen to a

patient. If there is still any doubt about whether or not the procedure should be carried out, even after collecting and analyzing all the information and other information not previously mentioned, it is advisable that the hematoma should be drained, regardless of the possible prognoses.

Therefore, it is reiterated that this work aims to study the estimated volume of the hematoma in isolation and propose a method that does so more precisely, comparing it with two other methods accepted in the literature. A second important remark is that, to calculate the volume of blood accumulated in a cavity of an injury, we cannot simply drain the hematoma or even "touch" it with surgical instruments. If this happens, we can unclog injured vessels, which blood flow was partially or completely interrupted by the clot, and the injury would re-bleed. If more blood enters the substrate, then the lesion volume value will increase and end up overestimated. It may be that mere contact with ambient air causes the lesion to expand, or even blood leaks into the operating environment through the surgical lesion, leading to a distortion of the real volume value. In short, to study an injury of this type, we must assume that the hematoma is an "intangible object", since it can be deformed when reached, and its properties would change. Therefore, imaging exams should be used to study this piece of interest and its properties. CT is performed recurrently in hospital services for various cases, including the study of intracranial hematomas; as it is an accessible exam from a financial and temporal point of view, we decided to use CT to study the hematoma injuries. A third point of emphasize is that it can be proposed that the method in this particular paper could be used after the lesion has been drained, and before the surgical site is properly sealed, as the surgeon could compare the value of the volume estimated by CT (using this method) with the actual volume of the lesion (estimated in some way available in the surgical center). This can help him/her to make a second decision: whether the lesion was entirely drained or not, and whether he/she should review the operation site, as there is a possibility that there are remains of the hematoma that have not been yet removed. Therefore, the estimated value of the volume can serve as a parameter for comparison with the actual volume of the piece, and the surgeon can make a sure decision about the effectiveness of his/her procedure, deciding whether the site should be revised or if it should be sealed shut.

With the lesion removed, the real volume can be measured in several ways, as long as the physician remembers what was previously stated: the drained blood and clots were disfigured, and they had undergone changes in their properties, whether expanding or shrinking, or even being re-absorbed or had re-bled. This would be an alternative to having to seal the surgical lesion and wait for new CT images to verify if the lesion had been completely resolved, as this would spare the patient from one extra X-ray radiation exposition from the post-operative CT scan. More in-depth studies would be needed to find out whether this is suitable as a cheap and applicable neurosurgical procedure that could be implemented in healthcare services. The use of imaging methods to identify the location and dimensions of a lesion is already carried out on a recurring basis in the Hospital da Santa Casa de Misericórdia de São Paulo service and in other healthcare services. CT is the most accessible imaging modality financially and in

terms of examination time; it should be highlighted that other modalities such as CTA and MRI provide excellent study models. It is known, however, that they are much more expensive for healthcare services. Also, the time required to carry out these exams is very long compared to the time required to perform a CT scan: while the first ones take from minutes to hours (making them not recommended for emergency cases), the latter takes from seconds to minutes. Although the CTA and MRI modalities provide the information we seek with great ease and precision, subjecting each patient in a neurosurgical urgency/emergency situation to an examination that takes longer than necessary would mean putting his/her quality of life at risk. Therefore, taking images with any other imaging methods (even if the non-expansion/stabilization of the lesion was confirmed and guaranteed) would be unethical from the authors' point of view. Thus, the choice to use CT and only this method to study the volume of lesions would be justified. The fifth topic is that we propose that the method used in this work can be used in other areas of knowledge, mainly in volumetrics. In order to do this, we must propose a general problem: whether "would it be possible to calculate the volume of an intangible object", given that the hematoma follows the nuances previously mentioned to classify it as such. Perhaps in this way, we can extrapolate this method beyond the limits of neurosurgery, or even Medicine itself and estimate the volume of any object, however complex, amorphous and intangible it may be, as long as there is equipment similar to a CT machine available for this purpose.

Generally, the images shown on the desktop computer are plains of helical sections that the CT created. We postulate, therefore, that these images are flat and equivalent to what is observed through the desktop computer. Let us also assume that consecutive cuts are parallel to each other and the distance between them is constant (the value of which is 'h' for each axis worked on), which may vary between the axes (i.e., the value of $h_{latero-lateral}$ may be different from $h_{antero-posterior}$).

For a specific case, only one researcher drew the contours and took measurements for all slices in the three axes. This is justified by the subjective criteria of each researcher to determine the exact contours of the figure in the program and thus biases would be reduced. It is interesting to assume that this work of obtaining data for each section and each axis is quite exhaustive, which is something correct to assume. The measurements must follow the rigor of being parallel to one of the studied axes: therefore, patience was a prerequisite to carry out a study of this type; this should also serve as an explanation to why our paper has such limited number of cases: we worked on tens, even hundreds of slices per axis per particular case.

The XERO Viewer® software provides the surface of the area drawn in square centimeters, with precision up to three decimal places. However, if the area is greater than a certain value (determined by the software itself), the program only provided one decimal place of precision.

If any of the intermediate cuts (from indices '2' to 'n-1') have an area equal to 0, it is postulated that there are more than one piece, separated by the distance of one cut ('h').

It must be noted that the accuracy of the method described previously depends directly on the distance between two consecutive cuts ('h'). Therefore, mathematically, the smaller 'h' is, the more slices there will be to be accounted for,

and more accurate the final value of the estimated volume will be, as the same object is divided more times into thinner slices. Thus, if the three 'h' values of the CT are known, the smaller they are, the more accurate the estimates of the volumes of interest using this method will be.

Based on the deduction of the generic volume formula, it is not necessary to know the average distance between the cuts ('h'), since this value is pre-programmed into the CT machine. The 'h' factor was a device used to demonstrate that it itself is not necessary to be known (although knowing it is very much appreciated for greater precision in the results, as already explained).

Based on the last mathematical formula presented (final volume of an axis), it is correct to state that the final volume depends, ultimately, on the diameter of the part in a given axis (D), on the number (n) of slices that have the typical hyper-attenuation of the hematoma and the values of each area of each axis (S, which are obtained by the exhaustive work of contouring the lesions slice by slice).

For each particular case, one must proceed with caution in the first and last slices, as they generally showed attenuation of very close heterogeneities, which are suggestive of cerebral edema surrounding the hematoma of interest. Cerebral edema is not of interest to our work and therefore should not be accounted for.

For this study, the following cases were excluded from the analysis: subarachnoid hematomas, with or without ventricular flooding, subdural hematomas, epidural hematomas and cases in which multiple hematomas occurred. This is because:

- Subarachnoid hematomas, with or without ventricular flooding, present blood dilution by the Cerebrospinal Fluid (CSF), making a volumetric precision study of this type practically unfeasible.
- Subdural and epidural hematomas present blood collection very close to the skull bones, and the attenuations of the images are very similar; therefore, the volumes of these two types presented important discrepancies from the values obtained in the literature.
- For cases with multiple hematomas, the resolution of a hematoma (in the order that best suits the neurosurgeon) causes the rest of the intracranial material (brain, vessels, CSF and other hemorrhagic lesions) to expand and occupy the now-empty space. This dilation of the other hemorrhagic lesion(s) would alter its (their) volume(s), causing this method to underestimate it(them).

Results

Applications of mathematical and statistical evaluation methods

Each case of intraparenchimal hematoma produced the data present in **Table 1**, by observation:

Table 1: Data inputs.

case	record	[SAG] sum area [cm^2]	[COR] sum area [cm^2]	[AXI] sum area [cm^2]	[SAG] number of cuts	[COR] number of cuts	[AXI] number of cuts
1	HSC937196	614.575	583.149	305.251	79	103	46
2	HSC1658422	596.320	685.806	389.961	95	105	40
3	HSC867997	392.047	420.802	226.787	67	84	38
4	HSC1658422B	645.291	665.694	338.969	101	107	36
5	HSC1520209	367.681	342.661	163.749	100	73	29
6	HSC1458417	733.058	712.048	333.889	103	123	45
7	HSC2447833	1264.441	1207.489	682.664	76	132	54
8	HSC2430355	1573.155	1554.926	796.804	103	194	67
9	HSC2350797	77.678	73.016	28.653	49	49	18
10	HSC2356526	872.738	925.785	389.896	111	124	53
11	HSC2481478	305.494	316.044	171.112	91	65	42
12	HSC2481425	345.428	339.724	140.558	73	89	30
13	HSC2485960	426.053	464.077	240.756	84	72	43
14	HSC1513242	986.936	881.569	356.909	123	101	48
15	HSC2356526	391.003	478.530	214.448	81	84	31
16	HSC2496517	1422.712	1373.705	710.285	113	114	50

Table 1 continued

case	record	‘a‘ l-l [mm]	‘b‘ a -p [mm]	‘c‘ c -c [mm]	[SAG] cut height [mm]	[COR] cut height [mm]	[AXI] cut height [mm]	[SAG] estimated volume [ml]	[COR] estimated volume [ml]	[AXI] estimated volume [ml]
1	HSC937196	38.0	47.0	35.1	0.481	0.456	0.763	29.562	26.610	23.292
2	HSC1658422	46.4	54.5	34.7	0.488	0.519	0.868	29.126	35.597	33.829
3	HSC867997	32.3	38.1	33.9	0.482	0.454	0.892	18.900	19.086	20.232
4	HSC1658422B	45.2	51.8	31.9	0.448	0.484	0.886	28.878	32.227	30.036
5	HSC1520209	43.4	35.5	26.4	0.434	0.486	0.910	15.957	16.664	14.907
6	HSC1458417	26.6	41.3	31.5	0.258	0.336	0.700	18.931	23.909	23.372
7	HSC2447833	42.9	67.9	49.1	0.564	0.514	0.909	71.374	62.113	62.072
8	HSC2430355	34.1	72.9	39.1	0.331	0.376	0.584	52.082	58.430	46.500
9	HSC2350797	18.6	11.7	14.1	0.380	0.239	0.783	2.949	1.743	2.244
10	HSC2356526	36.9	35.2	39.4	0.332	0.284	0.743	29.013	26.280	28.985
11	HSC2481478	24.6	20.4	33.7	0.270	0.314	0.802	8.258	9.919	13.730
12	HSC2481425	28.0	35.0	28.8	0.384	0.393	0.960	13.249	13.360	13.494
13	HSC2485960	36.9	29.2	39.5	0.439	0.406	0.919	18.716	18.821	22.116
14	HSC1513242	37.5	37.2	44.3	0.305	0.368	0.923	30.090	32.470	32.940
15	HSC2356526	47.3	37.8	29.6	0.584	0.450	0.955	22.833	21.534	20.476
16	HSC2496517	48.0	55.2	43.8	0.425	0.484	0.876	60.434	66.516	62.221

Abbreviations: SAG — sagittal; COR — coronal; AXI — axial; ‘a‘ — dimension ‘l-l‘ (sagittal axis); ‘b‘ — dimension ‘a-p‘ (coronal axis); ‘c‘ — dimension ‘c-c‘ (axial axis); [ml] – milliliters.

Table 2 shows the calculations of each volume, using the literature formulas and our three proposed algorithms.

Table 2: Volume calculations.

case	record	[LIT] a.b.c /2 [ml]	[LIT] 2/3* a.b.c [ml]	[MED] est volume [ml]	Rel Volume 1	Diff Volume 1	[POND] est volume [ml]	Rel Vol 2	Diff Vol 2	[SCA] est volume [ml]	Rel Volume 3	Diff Volume 3
1	HSC937196	31.344	41.792	26.488	18.33%	4.856	26.963	16.25%	4.381	26.244	19.43%	5.100
2	HSC1658422	43.875	58.500	32.850	33.56%	11.024	32.741	34.01%	11.134	30.866	42.14%	13.008
3	HSC867997	20.859	27.812	19.406	7.49%	1.453	19.251	8.36%	1.609	19.061	9.43%	1.798
4	HSC1658422B	37.345	49.793	30.381	22.92%	6.964	30.518	22.37%	6.827	28.323	31.85%	9.022
5	HSC1520209	20.337	27.116	15.843	28.37%	4.495	16.062	26.62%	4.275	14.752	37.86%	5.586
6	HSC1458417	17.303	23.070	22.071	-21.60%	-4.768	21.928	-21.09%	-4.625	21.662	-20.12%	-4.359
7	HSC2447833	71.512	95.349	65.186	9.70%	6.326	64.791	10.37%	6.721	63.868	11.97%	7.644
8	HSC2430355	48.599	64.799	52.337	-7.14%	-3.738	54.438	-10.73%	-5.839	51.548	-5.72%	-2.949
9	HSC2350797	1.534	2.046	2.312	-33.65%	-0.778	2.330	-34.16%	-0.796	2.248	-31.75%	-0.714
10	HSC2356526	25.588	34.117	28.093	-8.92%	-2.505	27.831	-8.06%	-2.243	28.355	-9.76%	-2.767
11	HSC2481478	8.456	11.275	10.636	-20.49%	-2.180	9.964	-15.14%	-1.508	10.771	-21.49%	-2.315
12	HSC2481425	14.112	18.816	13.368	5.57%	0.744	13.339	5.80%	0.773	13.070	7.97%	1.042
13	HSC2485960	21.280	28.374	19.884	7.02%	1.396	19.489	9.19%	1.792	20.261	5.03%	1.019
14	HSC1513242	30.899	41.199	31.833	-2.93%	-0.934	31.476	-1.83%	-0.577	32.943	-6.20%	-2.044
15	HSC2356526	26.462	35.282	21.614	22.43%	4.847	21.903	20.81%	4.558	20.776	27.37%	5.685
16	HSC2496517	58.026	77.368	63.057	-7.98%	-5.031	63.260	-8.27%	-5.233	61.618	-5.83%	-3.591

Abbreviations: [LIT] – literature; [MED] – formula MED; [POND] – formula POND; [SCA] – formula SCA; SAG — sagittal; COR — coronal; AXI — axial; ‘a‘ — dimension ‘l-l‘ (sagittal axis); ‘b‘ — dimension ‘a-p‘ (coronal axis); ‘c‘ — dimension ‘c-c‘ (axial axis); rel – relation; est – estimated; vol – volume; [ml] – milliliters.

Formulas:

[A] Literature formula (LIT):

‘a’ — dimension ‘l-l’ (latero-lateral diameter)

‘b’ — dimension ‘a-p’ (antero-posterior diameter)

‘c’ — dimension ‘c-c’ (cranial-caudal diameter)

[LIT] $V = \frac{a*b*c}{2}$

[LIT] $V = \frac{2*a*b*c}{3}$

[B] Denominations of variables to the proposal of the formulas:

Abbreviations:

[SAG] number of slices — $n_{sagittal}$

[COR] number of slices — $n_{coronal}$

[AXI] number of slices — n_{axial}

[SAG] cut height [mm] — height of a slice on the sagittal axis — $h_{sagittal} = \frac{a}{n_{sagittal}}$

[COR] cut height [mm] — height of a slice on the coronal axis — $h_{coronal} = \frac{a}{n_{coronal}}$

[AXI] cut height [mm] — height of a slice on the axial axis — $h_{axial} = \frac{a}{n_{axial}}$

[SAG] area of each sagittal slice — $area_{sagittal\ slice}$

[COR] area of each coronal slice — $area_{corte\ coronal}$

[AXI] area of each axial slice — $area_{corte\ axial}$

[SAG] sum area [cm^2] — sum of areas in the sagittal axis — $S_{sagittal} = \sum area_{sagittal\ slice}$

[COR] sumarea [cm^2] — sum of areas in the coronal axis — $S_{coronal} = \sum area_{coronal\ slice}$

[AXI] soma área [cm^2] — sim of areas in the axial axis — $S_{axial} = \sum area_{axial\ slice}$

[SAG] vol est [ml] — sagittal estimated volume — $V_{sagittal} = h_{sagittal} * S_{sagittal}$

[COR] vol est [ml] — coronal estimated volume — $V_{coronal} = h_{coronal} * S_{coronal}$

[AXI] vol est [ml] — axial estimated volume — $V_{axial} = h_{axial} * S_{axial}$

[C] ‘MED’ formula:

[MED] vol est [ml] — estimated volume of hematoma — simple aritmetic mean

$$V_{final} = \frac{V_{sagittal} + V_{coronal} + V_{axial}}{3}$$

[D] ‘POND’ formula:

[POND] vol est [ml] — estimated volume of hematoma — ponderated mean

$$V_{final} = \frac{V_{sagital} * n_{sagital} + V_{coronal} * n_{coronal} + V_{axial} * n_{axial}}{n_{sagital} + n_{coronal} + n_{axial}}$$

[E] ‘SCA’ formula:

[SCA] vol est [ml] — estimated volume of hematoma — moderated mean

$$V_{final} = \frac{b * S_{sagittal} + c * S_{sagittal} + a * S_{coronal} + c * S_{coronal} + a * S_{axial} + b * S_{axial}}{2 * n_{sagittal} + 2 * n_{coronal} + 2 * n_{axial}}$$

Statistical analyzes — description and comparison between the three types of calculated volumes

Note 1: we chose to apply non-parametric tests, due to the small number of observations (16), and due to the considerable variability in the number of cuts, and the measurements of width, length and height of the selected hematomas.

Note 2: the Literature formula II (2/3 x a.b.c) was not used in these assessments. Only the a.b.c/2 formula from Literature was used, as it appears to be more appropriate for estimating the calculated volumes. According to Zhao et al.

(2019)[1], the volume value obtained by the a.b.c/2 method overestimates the real value between 8.53% and 29.3% and, as the literature formula 2/3 x a.b.c is numerically greater than the other a.b.c/2, then the overestimation of the first formula will be even greater than these percentages.

Table 3 shows the application of the *Wilcoxon Signed-Rank Test*, to check possible differences between the Literature values and the other proposed volume values.

Table 3: Statistical testing between literature formulas and our three proposed methods

Variable Pair	n	Mean	Standard deviation	Minimum	Maximum	25th percentile	50th percentile (Median)	75th percentile	Sig. (p)
[LIT] a.b.c/2 [ml]	16	29.846	18.396	1.534	71.512	18.061	26.025	42.242	0.326
[MED] est vol [ml]	16	28.460	17.862	2.312	65.186	16.733	24.279	32.596	
[LIT] a.b.c /2 [ml]	16	29.846	18.396	1.534	71.512	18.061	26.025	42.242	0.379
[POND] est vol [ml]	16	28.518	18.071	2.330	64.791	16.859	24.446	32.424	
[LIT] a.b.c /2 [ml]	16	29.846	18.396	1.534	71.512	18.061	26.025	42.242	0.255
[SCA] est vol [ml]	16	27.898	17.507	2.248	63.868	15.829	23.953	32.424	

Abbreviations: [LIT] – literature; [MED] – formula MED; [POND] – formula POND; [SCA] – formula SCA; vol est – estimated volume; sig. – statistical significance; [ml] – milliliters.

We observed that the Literature formula I presents a statistically non-significant difference when compared with the three formulas proposed in this study.

Table 4 shows application of the *Wilcoxon Signed Rank Test*, to check possible differences between the proposed volume methods:

Table 4: Statistical testing in-between our three proposed methods.

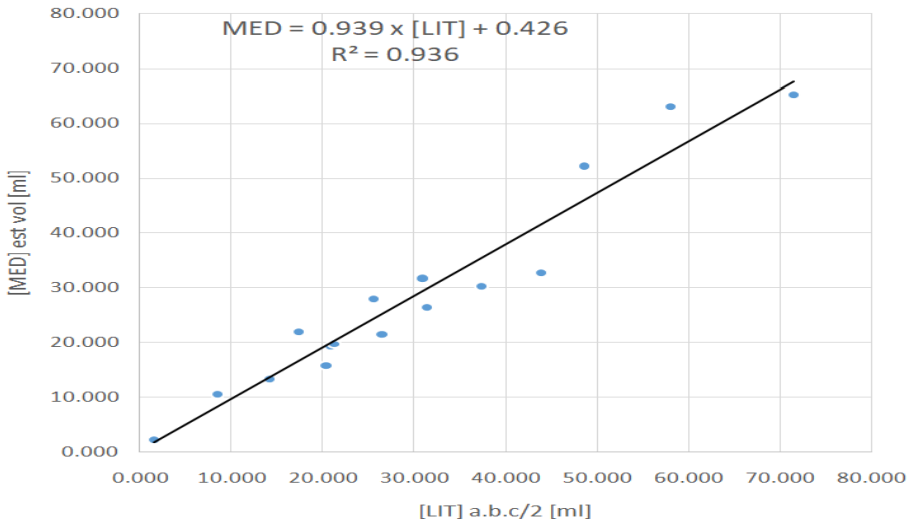
Variable Pair	n	Mean	Standard deviation	Minimum	Maximum	25th percentile	50th percentile (Median)	75th percentile	Sig. (p)
[MED] est vol [ml]	16	28.460	17.862	2.312	65.186	16.733	24.279	32.596	0.679
[POND] est vol [ml]	16	28.518	18.071	2.330	64.791	16.859	24.446	32.424	
[MED] est vol [ml]	16	28.460	17.862	2.312	65.186	16.733	24.279	32.596	0.026
[SCA] est vol [ml]	16	27.898	17.507	2.248	63.868	15.829	23.953	32.424	
[POND] est vol [ml]	16	28.518	18.071	2.330	64.791	16.859	24.446	32.424	0.063
[SCA] est vol [ml]	16	27.898	17.507	2.248	63.868	15.829	23.953	32.424	

Abbreviations: [LIT] – literature; [MED] – formula MED; [POND] – formula POND; [SCA] – formula SCA; vol est – estimated volume; sig. – statistical significance; [ml] – milliliters.

We observed that the 'SCA' volume presents a statistically significant difference ($p = 0.026$), when compared to the 'MED' volume; and presents a weak similarity [almost-difference ($p = 0.063$)] when compared to the 'POND' volume. Both volumes ('MED' and 'POND') present a statistically non-significant difference ($p = 0.679$).

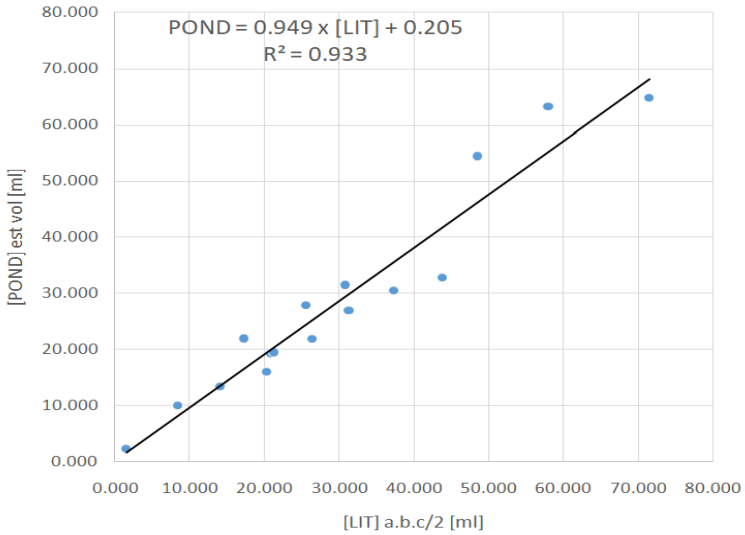
Graphics 1-3 show graphical representations and estimation of the regression equation between the 'LIT' volume and the 'MED', 'POND' and 'SCA' formulas:

Graphic 1: Representation and estimation of the regression equation between the 'LIT' volume and the 'MED' formula



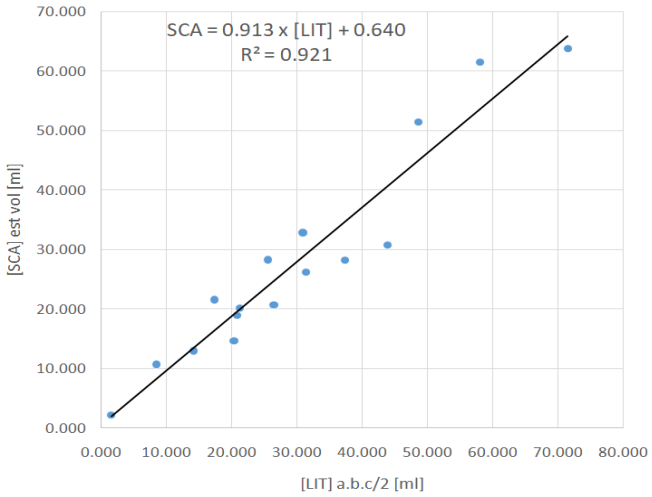
Abbreviations: [LIT] – literature; [MED] – formula MED; est vol – estimated volume; [ml] – milliliters.

Graphic 2: Representation and estimation of the regression equation between the 'LIT' volume and the 'POND' formula



Abbreviations: [LIT] – literature; [POND] – formula POND; est vol – estimated volume; [ml] – milliliters.

Graphic 3: Representation and estimation of the regression equation between the 'LIT' volume and the 'SCA' formula



Abbreviations: [LIT] – literature; [SCA] – formula SCA; est vol – estimated volume; [ml] – milliliters.

Conclusions

This work aimed to investigate a new method for estimating the volume of intraparenchymal hemorrhagic lesions. Our method makes use of mathematical calculus and integral devices, uses a lot of information made available by image visualization software (in three axes) and seeks to relate them in different ways. Therefore, it seems to get closer and closer to the real value of the lesion volume. In our study, we suggest that, as simple as the a.b.c/2 formula may seem, it is very close to the actual volume of a part, which leads us to suggest that the a.b.c/2 formula is a "gold standard" formula for volumetric estimation for both of intracranial hematomas and any non-hollow parts for which volume calculation is desired. The suggested mathematical method allows estimating the volume of the hematoma with an 'average' reduction of 6.5% in relation to the usual formula (a.b.c/2), and a 'median' reduction of 8.0% in relation to the volume estimated by the usual formula. Therefore, we suggest that the method proposed in this work could be used for volumetric estimation of any parts, mainly when it is not available to obtain such volumetric measurement by automatic means.

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