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Estimation Of Cranial Volume-an Overview Of Methodologies

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Abstract. *Cranial volume is an important measurement in the study of racial differences and in clinical practice for the study of abnormalities of cranial size and shape. There are a number of methods available for the estimation of the cranial capacity of both macerated skulls and living using anthropological and radiological techniques. This paper presents an overview of these methodologies.*

Key words *: Anthropology, Cranium, skull volume.*

Introduction :

Knowledge of the volume of the cranial cavity of either a dry skull or of a living being may be important to the study and comparison of the crania of populations with various fundamental differences like racial, geographic , ethnic, dietary, etc.This information is useful in correlating cranial capacity with other cranial measurements and in studies of primate phylogeny. Medically , an analysis of cranial capacity exposes another aspect of growth and development and permits critical evaluation of unusually large, small, or misshapen crania *(Haack and Meihoff-1971*).

Various methods of measuring cranial capacity have been known for some time, up till now craniologists have not possessed a precise technique for ascertaining this very important measurement which would be a very simple procedure but at the same time an exact one *(Uspenskii-1954)*. An overview of the methodologies available for the investigator in the field of craniometry is presented here.

I. cranial capacity of the dry skulls : A number of accurate methods of determining the cranial capacity of the macerated skulls are available.

A) Linear measurements : Cranial volume can be calculated by using three principal dimensions of the cranium. 1) Maximum antero-posterior length (measured between glabella and the inion). 2) Maximum breadth (biparietal diameter ; measured between two parietal eminences). 3) Cranial height (basi-bregmatic height, measured between the internal acoustic meatus to the highest point of the vertex i.e. the bregma).

The first two measurements are carried out by using the spreading caliper and the cranial height is measured using the Todd's head spanner. The skull has to be placed in Frankfurt plane using a cubic craniophore (see- fig 1: -a, b, c, d) . Usually the measurements should be made at least three times and the average of the three should be considered for calculations. Using the following formula derived by Lee-Pearson the cranial volume can be computed:

Males : 359.34 + 0.000365 x L x B x H

Females : 296.40 + 0.000375 x L x B x H

Although this method is easy to carryout it is by no means accurate since the skull thickness varies between individuals. Any amount of corrections and allowences do not remove the inaccuracies associated with this method.

Dekaban & Liberman (1964) have modified the method of estimating the cranial volume by linear dimensions. The following formula was applied to estimate the cranial volume of 28 skulls : 0.5238x LxBxH. The results were compared to control volumes obtained by Lee-Pearson's, packing method using mustard seeds and X-ray measurements .The spheroid method gave results close to X-ray measurements and that of Lee-Pearson's close to anthropological methods.

(B) Packing/Filling methods : ***i) Manual packing method***- Another method in wide usage for determining the cranial volume of the skull is to pack the interior of the skull with filling materials and then measure it. Many packing materials like gunshots, sand, paraffin wax and mustard and millet seeds have been used *(MacDonell -1904 , Hrdlicka -1920, Mollison-1932, Stewart-1934*). The best filling material used so far has been the millet and mustard seeds. First all the foramina of the skull are plugged with cotton or wax. Next the cavity is filled through the foramen magnum by means of a funnel with mustard or millet seeds of uniform size. The skull is shaken from time to time to fill the cavity entirely. When the skull cavity has been filled to the brim , the seeds are pressed gently with the right thumb at the foramen magnum, next the seeds are poured to a volumetric jar through a funnel. Reading can now be taken on the jar. *Breitinger (1936)* has devised a cylinder with a graduated piston. The reading is taken after gently placing the piston on the seeds in the cylinder. There is a greater probability of personal error in taking this measurement but with proper precautions and controls the error can be reduced to about 10 cc. Use of a control skull measured before determining the capacity of a new skull is advised, to get an accurate measurement.

ii) Use of cranial capacity machine (see fig-2a) **:** In the method with packing done with hand there is naturally a chance of large personal error, increasing as the element of fatigue enters. To minimize this error use of a cranial capacity machine is recommended. One such device was designed by Goldstein during 1928-31. Figure 2a shows the machine. Essentially, it consists of a horizontal table, attached to which is a cradle in which the skull is fastened with base upward and rocks from side to side by a vibrating mechanism. A jointed tube of 14mm internal diameter and fitted with sliding valve, leads the seeds down in to the skull from a suspended container (capacity-5ltrs; base a 120 funnel). Similar machines have been devised by *Jarricot (1906) and Bushkovitch (1927)*.

The entire operation of the capacity determination consists of two parts viz; - the filling of the skull (''le jaujeage '') for which the machine is used and the second part is the measuring of the seed (''le cubage'') . The second part may give as great error as the first. The volume of the filling material can be determined in two ways: 1) it may be poured from the skull into a graduated cylinder and the reading made directly, or 2) the filing material may be weighed and the volume can be calculated indirectly by density factor. The change in the internal surface of the skull may affect packing leading to an error.

iii) Rubber balloon method **(see fig-2 b)** : One of the most satisfactory method of measuring cranial capaity of a dry skull is with the aid of water poured into a balloon which has been lowered into the cranial cavity through the foramen magnum. The first effective attempt by this method was made by *Poll (1896)*. Earlier attempts made by others using thin walled balloons resulted in bursting of the balloons upon touching the clinoid process. Thicker balloons result in the formation of air pockets between it and the cranial walls, this reduces the precision of the measurement. *Bochnek (1900)* found the Poll's method unsatisfactory with an error of nearly 29cm^3. Secondly the rubber balloon wears out too quickly bursting at various intervals. *Uspenski (1954)* modified this method on the following basis:

1. The mediating substance has to be liquid , so that a constant volume of any mass of the substance can be assumed during the course of the experiment.
2. The liquid mediator is to fill the cranial cavity under a high pressure so that the walls of the ballon fit tightly against the cranium and all air spaces are removed through the pores of the skull.
3. The balloon is to be of sufficient strength to withstand the puncture.
4. The process of filling the cranial cavity with liquid is to be controlled , by some apparatus which will make it possible to judge the course of filling and the point of termination.

The utilization of water from the tap meets the first two difficulties. The third requirement is settled by use of thicker balloons. The solution for the fourth condition is to use a second balloon ''B'' -a piece of tubing thicker than the measuring balloon ''A'', which acts as a compressor and pressure gauge. It dosen't undergo noticeable change during the filling of ''A''; the latter tightly fits in to the cranium. But as soon as this point is reached the excess water will expand the walls of ''B''. In effect the ''B'' functions as a sort ''pressure gauge ''. The author tested the accuracy of the method by measuring the cranial capacity ten times of the same cranium, the difference between separate measurements varied between 1-6cm^3. Next it was verified by measuring the volume of a hollow endo cast of the same cranium. The greatest difference between the individual measurements amounted to 7cm^3.

The capacity of the same crania was measured using millet seeds and the difference between the two methods was 65.4cm^3. The inadequacy of the millet seed technique is self evident.

(C) Estimation of cranial capacity by cephalometric Roentgenograms

Mackinnon (1955) has demonstrated a method of estimating the cranial capacity by using the cranial length (measured between glabella & oposthocranion) measured on the lateral Roentgenograms: the capacities of 52dry adult skulls were measured by filling with lead shots. The average ratios of the capacities to the length was found to be 78 to 1. An estimated capacity of each skull was therefore obtained by multiplying its length by 78. The greatest difference between the estimation and true capacity of any one skull was 17.2% or ± 241cc in a 1,400cc skull. This difference diminished as the number of skulls in the group was increased.

Mackinnon, Kennedy and Davies (1956) in their further studies derived a reliable method for estimating cranial capacity from Roentgenograms : A lateral and anteroposterior Roentgenograms of 52 skulls of known capacity were obtained with a measuring bar above the midline. Their internal lengths (L) , internal height (H), diameters from bregma to posterior cranial fossa (B) and breadth (W) were measured. The optimum estimate of the capacity of any one of the skulls from the combination of L, H, B andW was obtained from:

{½ (LxHxW)-½ (LxBxW)} X 0.51,

with an error of 0.618% (0.87cc in a 1400cc skull). It was further suggested by the same authors that, in anthropological investigation , a reasonable estimate of the averge capacity of 50 or more skulls can be obtained from one linear Roentgenologic measurement the bregma- posterior cranial fossa diameter B-in cms)- by the formula : (Bx100) /N , where N=the number of skulls (see fig-3).

Bergerhoff (1957) recommends the following formula for Roentgenologic measurement of the cranial capacity, which is a general formula for the calculation of volume of an ellipsoid:

V=L/2xH+B/4xW/2x4p/3

According this author the results of *Mackinnon et al (1956)* are based on the arithmetical average of a sample test of 52 skulls. A sample test of different composition could of course yield other averages. The assessment of cranial capacity should therefore in any particular individual case, remain free from any such factor. They have modified the *Mackinnon et al (1956)'s* formula as follows:

V= L/2x H+B/4 x W/2 x0.51x8

Haack and Meihoff (1971) have defined a method of estimating cranial capacity of either living subjects or cadavers or dry skulls.This method requires a lateral and AP cephalogram .The area of projection of the crainal cavity on the lateral cephalogram , (Al) is determined by use of planimeter and the breadth (b) is directly measured on the AP-cephalogram . This data is applied to the formula $V=KA_lb$: where the K is a constant which has to be determined by tests of similar population of skulls of known volume. Ten or 12 skulls should be sufficient for the purpose of determining K. The method is simple and direct and offers accuracy and reliability.

A radiographic method combining tomography, planimetry, and simplified calculations for determining the cranial volume has been described by *Kaufman and David (1972)* (see- fig -5 a, b, c). This method is based on direct measurements of tomograms of a given skull and is independent of extracranial mesurements or the use of indices. Variations in the age , sex or race of patients do not influence the calculations : Using a tomographic apparatus (Philips polytome) with a standard magnification factor, a lateral film and a midsagittal tomogram of the skull were obtained. The skull was divided into six volume units by seven parallel planes perpendicular to the canthomeatal line on the sagittal tomograms as follows-1) frontal 2) canthal 3) spenoid ridge 4) sella-turcica 5) external auditory canal 6) posterior fossa 7) occipital.

By tracing the inner table contours of planes 2 through6 on the coronal tomographic sections with planimeter calibrated in Cm^2 the area of each plane can be accurately measured. The thickness of each section (h) of each volume unit is determined by measuring the values between the planes directly on the midsagittal tomogram. The volume of each unit is calculated by averaging the areas of the two planes bounding it, multiplied by distance (h) between the planes. The frontal and occipital units require a different approach : their area is calculated by the formula: $A = p\ (d/2)^2$ These areas are averaged and multiplied by their (h) to give the volume of these units.

These findings were compared with actual cranial volume obtained by filling each of the skull with sand three times and measured in a graduated jar. All the skull orifices were sealed before filling the sand. The mean difference of cranial volume was 34.4 cm^3

Muke, Homann and Kellner (1976) have an alternative method of skull volume determination: for this purpose first the direct measurement of the skull volume was carried out using latex method on 20 macerated skulls. Later the same skulls were X-rayed in the usual manner and stereoscopically also. Form this they arrived at the formula-that the skull volume can be determined most accurately from the product of greatest width (TD) and the area of the median plane.

II. Cranial volume in the living :

Lee-Pearson (1901), have devised a number of formulae for the estimation of cranial capacity from the external measurements of the skulls and living heads.The best of these formulae combine the product of length, breadth and height with one multiplicative and one additive constant. They reported a mean error of 3-4% *(Haack and Meihoff-1971)*.

Cranial capacity can be calculated in the living subject by three principal dimensions as mentioned under the calculation for dry skulls. The cranial volume can be computed using the Lee-Pearson formula:

Males : 0.000337 (L-11) (B-11) (H-11) + 406.01cc

Female : 0.000400 (L-11) (B-11) (H-11) + 206.60cc

Dekaban (1977) has evolved a modified formula based upon spheroid principle for estimating the cranial volume in the living using the same linear dimensions . He has estimated the cranial volume in living subjects of 7 days to 20 years of age by the following formula:

V= 0.523 (length -2t) x(breadth -2t) x(height-t)

Where"t" is skull and scalp thickness. The value of ''t" was determined by using skull X-rays of different age groups.

III. Estimation of skull volume in infants :

In paediatric practice, the size of the head or precisely , the volume of the cranium is a measure of considerable interest *(Jorgenson, Paridon and Quade-1959).*

i) The water displacement method : *Jorgenson and Quade - 1956* in their preliminary experiments with dry skulls and later with autopsy material tried a simple volumetric method based upon water displacement by immersing the part of the head above the glabella-inion. This measure of water displaced by immersion (termed as external cranial volume-ECV) could be clearly correlated with the isolated brain. The authors could establish at the same time an accurate estimate of the same measure (ECV) could be arrived at by using the head circumference.

Later same authors *(Jorgenson et al -1959)* tried the water displacement method to estimate the ECV on 215 normal children of 0-7 years of age : the head of the child was gently immersed in a container with water filled to the brim, until the head reached the glabella-inion plane. The displaced water was collected in a measuring cylinder and the quantity was directly recorded (see fig-2 c).

ii) *Fuchs and Bayer (1954)* have experimented on the estimation of cranial volume with the assumption that the crainal cavity is an ellipsoid and that the volume of any body can be calculated from the cross sections of equal thickness in parallel planes. *Menchini and Auiu (1960)* have estimated the cranial volume of infants using the skull X-rays by the following formula:

$$V = h/12\ (f_1+4f_2++2f_3++4f_4+f_5)$$

Where h stands for the greatest diameter , in sagittal direction in the lateral view of the skull; f stands for the parallel, equidistant, cross-section. On account of ventral and dorsal curvature of the skull f_1 becomes equal to $f_5$and equal to 0; hence

$f_1= f_5= 0$.So that for determination of the volume of the cranium only three cross sections of radiographs and one lateral radiographs are required.

(iii) In the interpretation of radiographs of children's skull, there is often a need for some kind of standard skull size, especially where the possibility of cerebral atrophy or mild hydrocephalus or abnormality in the shape of the skull is in question . This is particularly so in the first four years of life, when the skull is growing rapidly *(Gordon-1966)*. A simple method by which deviations from the normal cranial capacity can be assessed from radiographs of skull of children of different ages has been described by Gordon (1966) :

The author made measurements on the series of skull X-rays of 213 children (104 boys and 109 girls) of 0-15 years of age according to *Mackinnon's (1956)* formula. Comparative curves of mean values obtained from this method and from the data obtained by direct measurement of cranial capacity at autopsy in chidren of various ages by *Todd and Williams (1933) and by Siwe (1931)* (both quoted by *Gordon (1966)* were constructed . These curves showed that they can be made to coincide by the use of simple conversion factor. Therefore the author has modified the original formula as follows:

V=[(LxWxB) + (LxWxH)]x 0.1594.

Abnormalites in the shape of the cranial vault such as brachycephaly, dolicocephaly or plagiocephaly do not appear to cause significant variation in the estimation values for capacity.

(iv) Estimation by occipitofrontal circumference (OFC) / Head circumference (HC) :

a) *Buda, Reed and Rabe (1975)* have demonstrated that there is a positive correlation between OFC and the skull volume in infants with normally shaped skulls. Using a steel tape the OFC was measured in 53 normocephlaic infants (head circumference between 10^{th}-90^{th} precentile) of 0-24 months of age.Four principal measurements from the skull X-rays of these infants were taken to calculate the cranial volume by formula derived by *McKinnon et al (1956)*:

$$V(cm^3) = 0.51\ (\ ½L \times H \times l) + ½(\ L \times B \times l)$$

(three measurements viz; Lm, Hm, Bm from lateral X-rays and one diameter (lm) from AP X-rays). Using the regression equation V= 59.1 x OFC the cranial volume could be accurately estimated. In seven infants with abnormally shaped skulls, the relation between OFC and skull volume differed from infants with normal shaped skull. The authors suggest serial determination of skull volume as a method for following the brain growth in such infants (see fig-4).

(b) *Epstein and Epstein (1978)* have demonstrated a relationship between the HC and the brain weight determined during autopsy. According to them it is possible to use HC as a means of estimating brain weights of both normal adults and children in the wide variety of pathological condition.

It is evident from the descriptions of the methodologies given above that none of the methods are completely perfect, hence it is advisable to use more than one technique on a sample for comparison ie., for dry skulls-linear dimensions/packing method/ radiological method ; for living subject- linear dimensions/ radiological methods.

IV. Latest methods of estimation of cranial volume :

Magentic resonance imaging techniques make it possible to abstract quantifiable information from the slices taken through different parts of the living body. This image slicing approach is directly comparable to the physical or mechanical slicing which is routine in anatomy and pathology both at macroscopical and microscopical levels *(Mayhew and Olsen-1991)*. Two such new techniques are described here.

i) Estimation of brain volume Using Cavalieri Principle :

Using Cavalieri principle which has been employed on physical slices of brain and other organs *Mayhew and Olsen -(1991)* have tried an application on the human brains. A complete set of parallel (coronal) slices through a fixed human forebrain was generated by magnetic resonance imaging (MRI) and the Cavalieri Principle, combined with point counting , was used to estimate brain volume. Alternative sampling schemes for estimating volumes were then assessed by taking systematic random selection of slices. Later , the brain was weighed and its fixed volume determined by fluid displacement.

For the complete set of n=28 MRI slices the volume was estimated with a coefficent of error(CE) of less than 1%. Decreasing the number of slices by systematic sampling increased the CE but this was still only 5% when just 5-6 slices were analysed. A set of 14 other brains were physically sliced to assess sampling error. It was found that 5-6 slices per brain is enough to yield efficient estimate of mean brain volume. According to these authors these findings demonstrate the potential for non-invasive longitudinal studies on in-vivo brains (see fig-6).

(ii) SIENA (Structural Image Evaluation , using Normalisation of Atrophy) method :

At present a completely automated longitudinal and cross-sectional measurement method named respectively SIENA (Structural Image Evaluation , using Normalisation of Atrophy) and SIENAX (an adaptation of SIENA for cross-sectional measurement) are available.

SIENA performs segmentation of brain from non-brain tissue in the head and estimates the outer skull surface (for both time-points) , and uses these results to register the two images, while correcting (normalising) for imaging geometry changes. Then the registered segmented brain images are used to find local atrophy, measured on the basis of the movement of image edges.

SIENA also performs segmentation of brain from non-brain tissue in the head and estimates the outer skull surface , with data from a single time-point. The brain and skull images are then registered to a standard space brain and skull image pair. This step normalises for skull size, and means that it is not necessary to measure CSF volume (otherwise a problem in T1- weighted images as it is hard to accurately separate CSF and skull). Next a probabilistic brain mask derived in standard space is applied to make sure that certain structures such as eyes/optic nerve have not been included in the brain segmentation. Finally tissue-type segmentation is carried out (inculding partial volume estimation) and a (normalised) brain volume estimate is produced .

SIENA is useful for example , for longitudinal studies where maximal sensitivity to change over time is required. SIENA is useful for example , for differentiating two groups of subjects on the basis of single time point brain size measurement.

The methods are fully automated , robust and accurate: 0.15% brain volume change error (longitudinal) and 0.5-1% brain volume accuracy for single time point(cross sectional).

The SIENA and SIENAX software are freely available on as part of the FMIRB soft ware library(FSL) from the website:

http:// www.fmrib.ox.ac. Uk/analysis/research/ siena/siena2/www.fmrib.ox.ac.uk/fsl (stephen Smith 2001-12-09)

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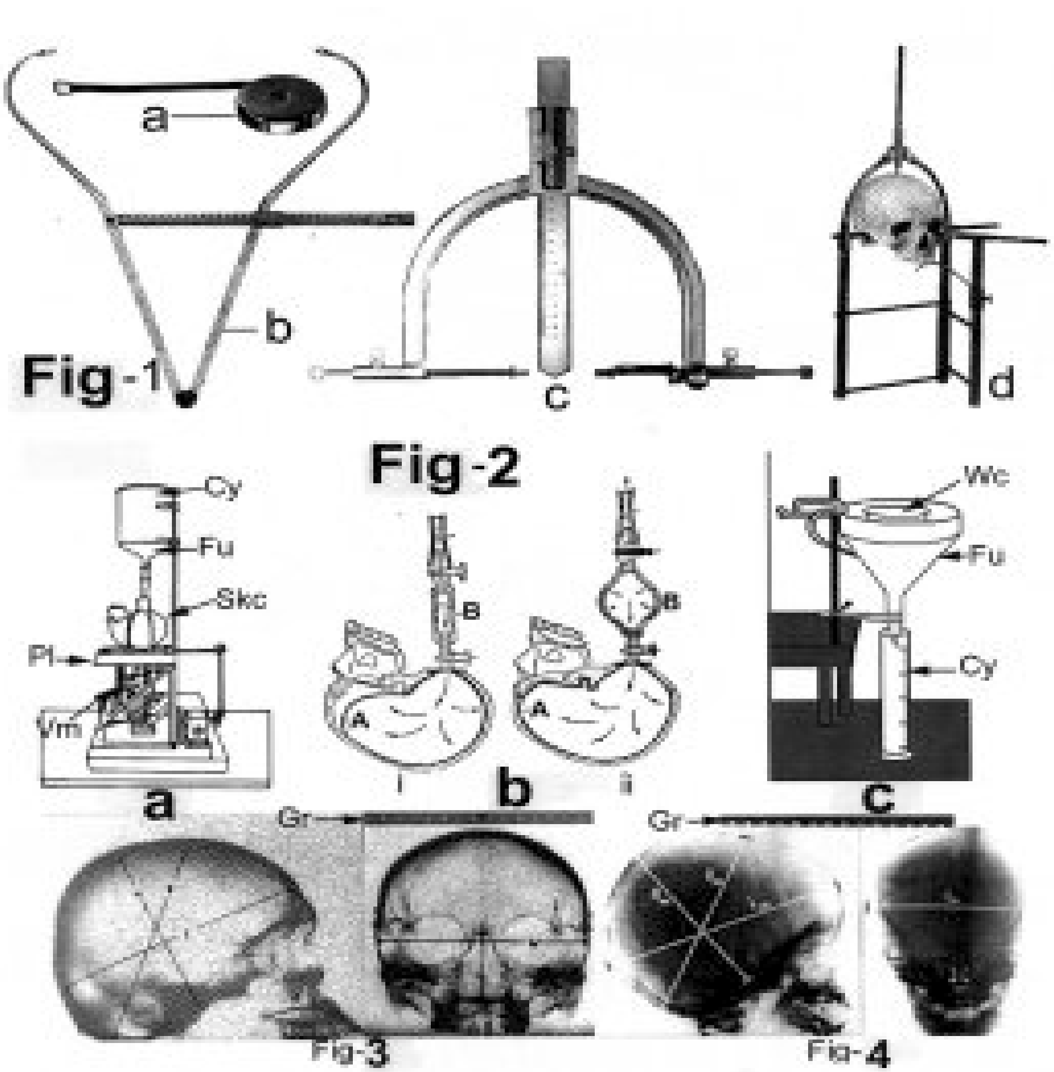

Fig-1: Shows the anthropological instruments used in measuring linear dimensions of skull/ head .a) steel measuring tape; b) spreading caliper; c) Todd's head spanner ; d) craniophore with skull for orienting the skull in Frankfurt plane.

Fig-2 : Figs a,b,c show the apparatus for filling/packing methods : a) -Cranial capacity machine (redrawn from Stewart-1934) . Cy-cylinder containing seeds; Fu-funnel; Sk-skull fixed to the cradle; Pl-platform ; Vm-vibrating mechanism .b)-balloon method figs i-ii demonstrate the distension of balloon B acting as pressure guage following complete filling of balloon A (recopied from Uspenskii-1954);c) shows the apparatus for water displacement method (redrawn from. Jorgensen, Paridon, Quaade-1959) Wc-water container ;Fu-funnel ; Cy-graduated cylinder .

Fig-3 and 4 show the radiological cranial silhouettes marked with the diameters to be measured . (copied from Mackinnon, Kennedy, Davis-1956 and Buda,Reed,Rabe-1975) Gr-graduated metal grid.

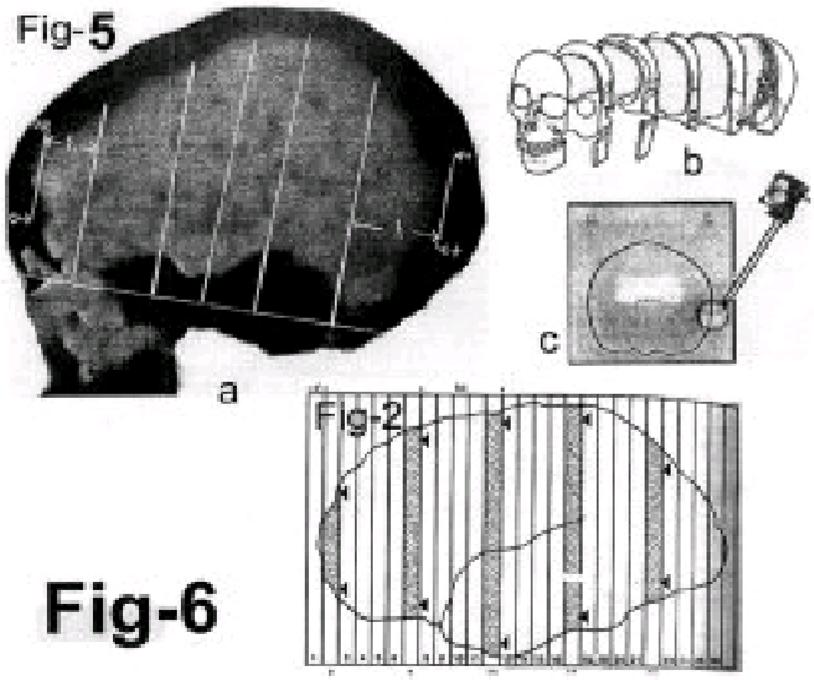

Fig-5: -a,b,c show the radiological method of calculation of cranial volume according to Kaufman and David (1972) . a) radiological cranial silhoutte showing planes at which the skull diameters were measured ;h-thickness of the sections. b) blown up view of the skull as shown in the fig-1; c) tracing the inner contour of the skull section using planimeter (recopied from Kaufman and David, 1972).

Fig-6-shows method of calculating brain volume by Cavalieri principle (recopied from Mayhew and Olsen -1991)