Fundamental characteristics of the vestibular coordinate system in human craniology

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Abstract The present study concerns with the methodological aspects of the vestibular method of orientating the cranium, which is mainly recommended for its physiological significance. Three dimensional coordinates of 36 landmarks were examined in the vestibular coordinate system which is defined by the plane of the lateral semicircular canals. This was determined utilizing a tomography apparatus. The coordinate data were obtained from 63 macerated modern Japanese crania by recording the landmarks with the cubic craniophore and then translocating the landmarks into the vestibular coordinate system.

Measurement errors were found to be small and variance as represented by bilateral asymmetry in the orientation of the lateral semicircular canals were estimated to be insignificant to the total variance. Thus, no apparent evidence exists indicating an instability of the vestibular orientation. Variability of the landmarks was investigated in the vestibular, Frankfort horizontal and *glabella-inion* line coordinate systems. This comparison revealed that the vestibular coordinate system characteristically shows a relatively high variability strongest in the facial landmarks.

INTRODUCTION

Craniologic studies are often undertaken utilizing reference planes. However, without adequate knowledge concerning the significance and characteristics of the reference plane, conclusions would be superfluous or even misleading. Thus, before a morphological analysis is made, an evaluation of the reference plane from both theoretical and technical viewpoints is desired.

The Frankfort horizontal conventionally

used in anthropology, is considered as a plane representing head posture. However, the Frankfort horizontal or any other reference plane defined by two or more arbitrary anatomical landmarks have no theoretical basis for any association with head posture. Furthermore, the problem of homology arises when various mammalian species are compared. From a study based on natural head position, the present author (1980) cautioned that the significance of the Frankfort horizontal was not necessarily the same between Japanese and European or American

whites. Technical problems also cannot be dismissed. Planes defined by two or more landmarks will fix the landmarks involved (FENART, 1966). For example, the use of the Frankfort horizontal will fix the landmarks *porion* and *orbitale*. MCHENRY and CORRUCINI (1978) also caution against the influence of fixing landmarks in coordinate data.

The vestibular method is a method of orientating the cranium according to the orientation of the lateral semicircular canals of the internal ear and has been of interest to some craniologists because of its direct association with the sense organs of equilibrium. It has been considered to actually represent the characteristic head posture of the particular species in question. Extensive craniological studies have been undertaken by DELATTRE, FENART and colleagues on various problems by orientating human, primate and other mammalian crania according to the anteroposterior orientation of the lateral semicircular canals. Most of their work take the method of orientating the sagittal diagram of a cranium, the horizontal axis being determined by the plane of the lateral semicircular canals. Other studies define a three dimensional space by the median sagittal plane and the plane of the lateral semicircular canals.

GIRARD was the first to believe in the vestibular method, proposing to orientate the skull by the lateral semicircular canals in 1910. In 1922, PEREZ published "Craniologie vestibienne, ethnique et zoologique", the first anthropological study applying the method. LEBEDKIN (1924)

also showed interest in the orientation of the lateral semicircular canals. More recently, PUCCIARELLI (1978 a ; b) utilized the vestibular method. However, by far the most extensive research applying the vestibular method has been undertaken by DELATTRE, FENART and colleagues. DELATTRE collectively published his initial results in "Du crâne animal au crâne humain" in 1951. Thereafter, an exhaustive literature has been accumulated. The topics they cover are vast, including topics in anthropology, primatology, hominization, growth studies, experimental craniology and orthodontics.

The basic philosophy underlying the use of the vestibular method is summarized below.

1) The physiological significance of the vestibular orientation. The notion of horizontality during locomotion is said to be furnished by the lateral semicircular canals (FENART, 1966). DEBEER (1947) states that the sense organs of a semicircular canal are in a condition of maximum receptivity when the motion to which they are subjected corresponds with the plane of the canal. It is also well known that if the head is rotated around a vertical axis while in a posture keeping the lateral semicircular canals horizontal, only the lateral canals will be stimulated without stimulating the anterior or posterior semicircular canals (GUEDRY, 1965; SUZUKI, 1967).

2) The relationship between the vestibular orientation and head posture. GIRARD (1929) explains that "l'attitude caractéristique" of animals and the vestibular

orientation coincide. This does seem to be true at first approximation. As can be seen in Fig. 1, the vestibular orientation does indeed agree with one's general impression of the animal's characteristic head posture. However, since an animal may take various head postures during different activities, a more precise definition is needed. PEREZ (1922) proposes "l'attitude normal du repos physiologique", the "rest" position. FENART (1966) argues that it is the position "d'alerte", the position of alertness, which coincides with the vestibular orientation. DEBEER (1947) presents some observations on living animals and a good discussion on the subject. From observations on a mouse, a rabbit, a horse and a dog, he confirmed that when in a state of alertness, the plane of the lateral semicircular canals roughly becomes horizontal. He also postulates that this state of alertness was probably a state of visual alertness. Re-

cently, LOREILLE (1975) developed a device which enabled him to record the head posture of humans during various activities. Although interesting, only examples of application have been reported.

3) The vestibular method is applicable to all vertebrates, Agnathes excluded (GIRARD, 1947; FENART, 1966). The agnathes do not possess lateral semicircular canals. Thus, the vestibular method seems to solve the problem of homology even in instances when other reference planes are inapplicable.

4) The independence of the vestibular orientation during phylogenesis. The whole cerebellar region is considered to have rotated around the vestibular axis (the axis made by uniting the center of the right and left lateral semicircular canals; the axis of PEREZ) 'en bloc' during phylogenesis of the human cranium (DELATTRE, 1951). Remarkably, this rotation of the posterior cranium includes

Fig. 1. Vestibular orientation of *Camelus*, *Bos* and *Bison* crania (from GIRARD, 1929).

not only landmarks on the cranial vault but also structures proximal to the vestibular axis, such as the ampulla of the posterior semicircular canal, the internal acoustic meatus and the fenestrae of the vestibule (DELATTRE and FENART 1960; 1961).

The above is the characteristics of the vestibular method from the theoretical viewpoint. In the present paper, fundamental problems arising with the actual usage of the vestibular coordinate system, heretofore never discussed, is investigated. After outlining its methodology, the stability of the vestibular orientation is examined in terms of measurement errors and excessive variance in the coordinates as represented by bilateral asymmetry of the lateral semicircular canals. Next, the variability of the landmarks is investigated in various coordinate systems. The vestibular orientation is compared with two conventional planes; the Frankfort horizontal and the *glabella-inion* line. The purpose of this comparison is to investigate the difference between conventional reference planes which fix the landmarks involved in their definition and the vestibular orientation which is independent from all landmarks. Such an analysis will enable an evaluation of the vestibular coordinate system from a technical viewpoint.

MATERIALS AND METHODS

The basic craniometric data are three dimensional cartesian coordinates obtained according to the vestibular method. The three dimensional space is defined follow-

ing PELLERIN (1970). The X-axis, the antero-posterior axis, is determined by the plane of the lateral semicircular canals and lies in the median sagittal plane. The Y-axis, the vertical axis, also lies in the median sagittal plane and is perpendicular to the X-axis. The Z-axis is perpendicular to the former two, thus being the transverse axis. The point *vestibion* (defined as the middle of the lateral semicircular canal projected onto the sagittal plane) is the origin. This basic data of cartesian coordinates were transformed into other coordinate systems. In the same vestibular coordinate system, X and Y coordinates were transformed into polar coordinates (R and T). Furthermore, in some instances, the antero-posterior (horizontal) axis was transferred to the Frankfort horizontal or *glabella-inion* line. Polar coordinates were defined as R, the distance from the origin and T, the amplitude. The coordinate T was defined to range from 0° to 360° with exception to landmarks ranging in both 1st and 4th quadrants in one or more of the three coordinate systems used in the present study. In these cases, the coordinate T was defined to range from -90° to 90°.

Materials

The specimens used in the present study were 63 crania, 40 male and 23 female. They were selected from the modern Japanese collection located at The University Museum, The University of Tokyo. This is a collection mostly collected from around 1880 to 1920. The crania were

Fig. 2. Median tomograph (above), lateral tomograph (below left) showing cross sections of the lateral semicircular canal, and the tomography apparatus (below right).

selected from the following criteria. 1) Known age and sex, age over 20 under 44 years. 9 female crania of unknown age were included. In these cases, they were chosen, on basis of dentition state, to be reasonably within the above age range. 2) State of dentition. All crania with one or more ante-mortem teeth loss in either side of the upper or lower jaw resulting in marked alveolar resorption were discarded. 3) No apparent pathological or traumas conditions. 4) Complete cranium and mandible available without damage. This criterion was almost completely satisfied owing to the characteristic of the collection.

Selection and definition of landmarks (see Fig. 3)

36 landmarks were chosen to cover all regions of the cranium. A list of the landmarks, their abbreviations used throughout the present study and the method fol-

lowed to locate them is presented in Table 1. Most of the landmarks were located by following closely the instructions of BUXTON and MORANT (1933), MARTIN and SALLER (1957), PELLERIN (1970) or HOWELLS (1973). However, as BUXTON and MORANT (1933) point out, MARTIN's definitions are written to apply to a perfectly symmetrical skull which is not the case in reality. For example, MARTIN uses the word "Mediansagittal-Ebene" in many of his definitions. He defines the "Mediansagittal-Ebene" as the plane passing through *nasion*, *basion* and *inion*. Surprisingly, *nasion*, *basion* and *inion* are in their turn defined by the "Mediansagittal-Ebene". Therefore, if one strictly follows MARTIN's instructions the median sagittal plane cannot be determined. Furthermore, if the "Median-sagittal-Ebene" is accepted as the plane defined by *nasion*, *basion* and *inion*, location of many landmarks cannot be realiz-

Fig. 3. Definition of landmarks.

Table 1. Procedure taken to locate landmarks.

nasion	NA	after Buxton and Morant.
basion	BA	after Howells, does not distinguish between hypobasion and endobasion.
inion	IN	in midline on common tangent of most superior border of right and left superior nuchal lines.
bregma	BR	after Buxton and Morant.
lambda	LB	after Buxton and Morant.
supraglabellare	SG	deepest point in supraglabellar fossa on NA-IN-BA plane.
glabella	GL	most prominent point between right and left browridges on NA-IN-BA plane.
frontotempolare	FT	after Martin.
superior orbital point	OS	most superior point on superior border of orbit defined by common tangent of superior border of right and left orbits, when supraorbital notch is present locate on imaginary border.
maxillofrontale	MF	after Buxton and Morant.
orbitale	OR	most inferior point on inferior border of orbit defined by common tangent of inferior border of right and left orbits.
ectoconchion	EK	after Howells.
rhinion	RH	after Martin.
nariale	NAR	most lateral point on lateral border of piriforme aperture from NA-IN-BA plane.
prosthion	PR	after Howells.
infradentale	ID	analogous to PR.
gnathion	GN	after Martin.
zygomaxillare	ZM	after Martin.
ectomolare	EM	most inferior point on lateral surface of alveolar process opposite middle of upper second molar, not necessarily most lateral point.
posterior nasal spine	PNS	posterior tip of posterior nasal spine; when prominent tip not present, on midline.
anterior nasal spine	ANS	tip of anterior nasal spine, if bifurcated project onto midline.
lingula point	LG	base of sphenoid lingula, when not discernable make best estimate. This corresponds to the opening of the auditory tube (DOYLE 1977) and was chosen as a landmark representing nasopharyngeal breadth.
hormion	HO	most postero-superior point on base of vomer.
pharyngeal tubercle point	PHT	most prominent point or middle of pharyngeal tubercle. This landmark was chosen to represent the posterior border of the pharynx.
anterior occipital condyle point	CA	on intersection of anterior border of articular facet with line roughly parallel to medial border of occipital condyles also roughly bisecting articular facet.
posterior occipital condyle point	CP	analogous to CA on posterior border of articular facet. CA and CP were chosen to represent position and orientation of the occipital condyles.
opisthion	OP	after Howells.
coronale	COR	most lateral point from NA-IN-BA plane on coronal suture located with diagraph.
asterion	AST	after Buxton and Morant.
eurion	EU	analogous to COR.
zygion	ZG	analogous to COR.
condylion laterale	CDL	most lateral point on lateral border of articular facet, not necessarily most lateral point of condylar process.
gonion	GO	point on mandibular angle farthest from GN-CDL line, analogous to definition of Pellerin.
porion	PO	after Buxton and Morant.
sella turcica	SE	middle of sella turcica, Z-coordinate defined as 0.0.
anterior crible point	CRA	anterior margin of cribriform plate, Z-coordinate defined as 0.0, (after Pellerin).
vestibion	VB	middle of lateral semicircular canal projected onto NA-IN-BA plane, Z-coordinate defined as 0.0.

with the right lateral tomograph except for in this case SE and CRA were not recorded.

Three dimensional cartesian coordinates of all landmarks except for SE, CRA and VB were recorded using the cubic craniophore and diagraph of MARTIN. Since asymmetry was not of concern in the present study, landmarks of only one side were recorded, the left being chosen conventionally. When minor damages of the cranium were present, best estimates were made in determining the location of the landmark in question. The cranium without the mandible is fixed to the craniophore so that NA, BA and IN lie on the same plane and parallel to the graph paper placed beneath the craniophore. X and Y coordinates were obtained by projecting the landmarks onto the graph paper with the diagraph. The Z coordinate was measured as the height of the landmark above the graph paper. After recording all landmarks with the exception of the mandibular landmarks, the mandible is placed in a position of maximal occlusion and firmly fixed to the cranium with scotch tape. Next, ID, GN, GO and CDL were recorded by the method explained above.

The X and Y coordinates were read from an arbitrary origin, all measurements being read to the nearest 0.5mm. This original random coordinate data were transformed into vestibular coordinates in three steps. First, the enlargement rate of the tomographs were calculated from the ratio of NA-BA length obtained from tomograph and craniophore

data respectively. The original coordinates of the tomographs (NA, BA, SE and CRA) were reduced to true size using this ratio. Next, the originally recorded X, Y coordinates from the craniophore were translocated into the vestibular orientation by superimposing NA and BA from the craniophore onto the enlargement corrected NA and BA of the left tomograph. Finally, difference in orientation of the right and left semicircular canals was calculated and the full set of 36 landmarks were rotated around VB of the left side to the ultimate vestibular coordinate system, of which the antero-posterior axis was determined by the mean direction of the right and left semicircular canals. The origin is the left VB.

Position of the lateral tomographs

FENART (1969) notes that allowing individual variation, the stylomastoid foramen gives a good estimate of the position of the labyrinth. PELLERIN (1970) states that for Northern French caucasoid crania, the position which gives the best tomograph of the lateral semicircular canals was situated medial to the medial border of the foramen by about its diameter. CANAL (1978) also reports this relationship for a Gallo-Romanian population. However, populational differences exist in this relationship. In Melanesian crania, it was found approximately 5mm medial to the stylomastoid foramen, as was also the case for Australian crania (PELLERIN, 1970). In the Japanese crania of the present study, it was situated

medial to the medial border of the stylomastoid foramen by approximately 1.0mm and 0.5mm in males and females respectively.

EXAMINATION OF ERRORS

Measurement errors resulting from positioning the cranium on the tomography apparatus so that the NA-IN-BA plane was parallel to the plane of the film was found to be insignificant to the total error involved in processing data from the tomographs. This was confirmed from the following procedure taken on both right and left sides of 6 crania. The magnitude of errors involved in the process of obtaining data from the tomographs was calculated by measuring the X and Y coordinates of NA twice from the same set of tomographs (s_A). The formula $s^2 = \sum d_i^2 / 2n$ was used where d_i is the difference of the duplicate measurements and n is the sample size (12 in this case). On the other hand, two sets of tomographs were obtained from the same cranium by replacing it on the apparatus for each set. From each set of tomographs X and Y coordinates of NA were measured and the errors involved were calculated as above (s_B). Results are given in Table 2. It can be seen from the s_B^2/s_A^2 values that s_B is far from being significantly

Table 2. Evaluation of errors resulting from placing the cranium on the tomography apparatus.

	s_A	s_B	s_B^2/s_A^2
NA X	0.409	0.393	0.93
NA Y	2.325	2.973	1.64
$\tan^{-1} \left \frac{Y}{X} \right $	1.295	1.584	1.49

different from s_A , the F value significant at the 5% level being 2.687.

Table 3. Measurement errors.

	VEST VB origin			FH PO origin	
	X	Y	Z	X	Y
NA	0.674	1.150		0.622	0.775
BA	0.501	0.428		0.593	0.806
IN	0.724	1.423		0.621	1.573
BR	1.232	1.054	1.387	0.972	0.994
LB	1.096	1.532	1.220	0.686	1.806
SG	0.612	1.176		0.604	0.907
GL	0.581	1.308		0.755	0.908
FT	0.716	1.476	0.559	1.027	0.936
OS	0.785	1.005	0.548	1.042	0.437
MF	0.688	0.942	0.487	0.658	0.690
OR	0.765	0.986	2.208	0.851	
EK	0.705	1.432	0.612	0.804	1.306
RH	0.786	1.094	0.000	0.729	0.818
NAR	1.105	1.219	0.742	0.805	0.825
ANS	1.120	0.826	0.851	1.015	0.708
PR	1.421	1.137	1.061	0.893	0.711
ID	1.286	0.922	1.487	1.008	0.760
GN	1.890	1.279	2.121	1.218	0.879
ZM	0.857	0.716	0.894	0.684	0.348
EM	1.390	1.041	0.894	0.970	0.799
PNS	0.918	0.512	0.837	0.669	0.702
LG	0.808	0.375	0.487	0.562	0.590
HO	0.612	0.614	0.570	0.561	0.788
PHT	0.741	0.496	0.766	0.541	0.845
CA	0.988	0.540	0.887	0.715	0.723
CP	0.692	0.677	0.371	0.630	0.684
OP	1.252	1.023	0.661	0.922	1.118
COR	1.417	2.620	0.922	1.871	2.543
AST	1.339	1.717	0.929	0.770	1.546
EU	1.749	3.193	1.055	1.939	3.561
ZG	1.176	0.763	0.335	1.174	0.750
CDL	0.979	1.451	0.512	0.665	1.372
GO	1.135	1.683	1.240	1.122	1.521
PO	0.748	0.499	0.387		
SE	0.398	0.670		0.777	0.890
CRA	1.042	1.600		1.340	1.245
VB				0.716	0.579

VEST—vestibular coordinate system
FH—Frankfort horizontal coordinate system

From the above consideration, measurement errors were calculated without taking account of errors resulting from positioning the cranium on the tomography apparatus. Two sets of vestibular coordinates were obtained from the same cranium for all landmarks by duplicating the whole measurement process twice, excepting the tomography process as mentioned above. This was carried out on a total of 10 crania to obtain a rough estimate of errors involved in the procedure of obtaining the coordinates. The measurement error values for all landmarks are given in Table 3. It can be seen that errors were small, few exceeding 1.5mm and over half being below 1.0mm. Exceptionally high values were found in the Y coordinates of EU and COR and in the Z coordinates of OR and GN. This was to be expected from anatomical grounds and from the definitions of the landmarks. The exact position of EU and COR were difficult to determine owing to minor positional errors not influencing the Z coordinate. A similar situation was found with OR where the Z coordinate could fluctuate without influencing X and Y coordinates greatly. The relatively large value for X and Z coordinates of GN and the Y coordinate of GO could be attributed to errors due to fitting the mandible to the cranium.

Table 3 also gives the corresponding measurement error values of the cartesian coordinates in the Frankfort horizontal coordinate system with PO origin. Theoretically, measurement errors are expected to be greater in the vestibular coordi-

nate system because of errors resulting from determining the plane of the lateral semicircular canals. This was confirmed from the results. There were 20/71 values greater than 1.0 mm in the Frankfort horizontal system compared with 36/72 for the vestibular system. However, the difference was not great and in many cases, values of the Frankfort horizontal system were greater than the corresponding values of the vestibular system.

ASYMMETRY OF THE LATERAL SEMICIRCULAR CANALS

Asymmetry in position, asymmetry in transverse (medial-lateral) inclination and asymmetry in antero-posterior inclination can be considered. ROBIN *et al* (1967), CAIX and OUTREQUIN (1979) report all three types. On the other hand, FENART and FENART (1975), LOUBAUD (1976) argue that the definition of the median sagittal plane would greatly alter the results, and therefore, without the use of a "plan median vrai" nothing can be said about asymmetry. They propose to define the median sagittal plane as the plane bisecting and perpendicular to the axis of PEREZ (the axis made uniting the middle of the right and left semicircular canals).

In the present study, the median sagittal plane was conventionally defined by NA, BA and IN merely for convenience. Therefore, no analysis was made concerning asymmetry in position and asymmetry in transverse inclination. Asymmetry in antero-posterior inclination has been reported by PEREZ (1922), ROBIN *et al* (1967), BONJEAN and VIDEAU (1975) and

CAIX and OUTREQUIN(1979), while FENART and colleagues report that as a rule the right and left orientations coincide well (FENART, 1975; LOUBAUD, 1976). They also caution that studies based on parasagittal tomographs or lateral profile radiographs which were not taken with the X-ray incidence coinciding with the axis of PEREZ could be misleading. This condition was not satisfied in the present study. However, as explained under examination of errors, it was found that minor changes in positioning the cranium on the tomography apparatus did not significantly alter the vestibular orientation, which implies that minor differences in the direction of the X-ray incidence would not alter results.

Measurement errors seem to be a greater problem either in studies by tomography, radiography or dissection. Therefore, data is not presented as how many cases the right and left orientations coincide and how many cases they don't, but the angle of difference, defined as positive when the left lateral semicircular canal is orientated more antero-superiorly than the right, is treated as a continuous variable. The result obtained in the present study is that the right and left orientations do not necessarily coincide. Statistical descriptions are given in Ta-

ble 4. Measurement error of the angle of difference was 1.464° , the 95% confidence limit being $\pm 2.869^{\circ}$. Therefore, one must be conservative in evaluating individual values. However, maximum values were 5.06° and 6.15° for males and females respectively, and minimum values were -9.13° and -7.19° for males and females respectively, by far exceeding values explicable from measurement errors alone.

From the evidence presented above, it is concluded that bilateral asymmetry in the antero-posterior inclination of the lateral semicircular canals does indeed exist, not as an exception but as a rule. This is the major reason for averaging the right and left orientations in the present study when determining the X-axis.

Asymmetry as representing instability of the vestibular orientation

Assuming that no genetical or functional background is involved in this asymmetry, it can be considered to be a result of fluctuating factors influencing the orientation of the semicircular canals during morphogenesis. If this random variation should be great, value of the vestibular orientation would diminish. An estimation of the magnitude of the resulting excessive variance can be made

Table 4. Statistical descriptions of the angle of difference.

Study	sex	no.	mean	max.	min.	st.dev.
Present study	M	40	-1.743	5.06	-9.13	4.171
	F	23	-1.946	6.15	-7.19	3.649
ROBIN <i>et al</i> (1967)	?	25	0.2	8	-9	4.39
BONJEAN <i>et al</i> (1975)	M	26	0.481	8.5	-7.5	6.49
	F	16	3.719	8.5	-23.0	4.96

as follows. Orientation of the lateral semicircular canals of both right and left sides of an individual are considered as samples of the "true" orientation of the individual; thus deviating randomly from the "true" orientation. Then, influence of fluctuating factors on one side is expressed by the formula $s^2 = \Sigma d_i^2 / 2n$, where d_i is the difference of the right and left sides of individual i and n is the number of individuals. In the present study, the right and left sides were averaged in calculating the vestibular coordinates, so variance originating from fluctuating factors would be $s^2/2$. Values thus obtained were 5.00 and 3.63 for males and females respectively. On the other hand, mean variance of the T coordinates (of the polar coordinates) calculated from 35 landmarks (PO which is extremely proximal to the origin has an exceptionally high value and was excluded in the calculation) is 39.92 in males and 29.21 in females. Thus, it can be concluded that variance resulting from fluctuating factors represented by bilateral asymmetry maintains only an insignificant portion of the total variance.

VARIABILITY OF LANDMARKS

In order to analyze the characteristics of the vestibular orientation, comparisons of the variability of the landmarks projected onto the sagittal plane were made with that in other orientations. The Frankfort horizontal and the *glabella-inion* line were chosen. The origin VB was not changed, thus, different results can strictly be attributed to difference of

the horizontal plane. Subsequently, the vestibular, Frankfort horizontal and *glabella-inion* line coordinate systems will be called VEST, FH and GLIN respectively. Only results of males are presented, females showing essentially the same pattern.

Illustrations of actual dispersions

From the X and Y coordinates, the actual two dimensional normal distribution of a landmark can be illustrated as an ellipse representing probability limits around the mean. This was calculated for each landmark at the 95% level and are illustrated in Fig. 4. Fig. 4a shows the dispersion of the landmarks in VEST. Generally speaking, facial and cranial vault landmarks are highly variable while landmarks of the cranial base are less variable. Now, turning to FH (Fig. 4b), the striking difference from VEST is the low variability of the facial landmarks, while the occipital and cranial vault landmarks are similar. GLIN (Fig. 4c) also differs from VEST in the low variability of the facial landmarks. However, in GLIN, the occipital landmarks also show low variability.

Analysis of polar coordinates

A metric comparison of differences among VEST, FH and GLIN can easily be made from polar coordinates. The origin VB being the same, R coordinates (distance from origin) are common to all three orientations. Therefore, only the coordinate T remains to be analyzed. In this section, the standard deviation of coordinate T is analyzed. However, for a

Fig. 4a. Variability of 36 landmarks in the vestibular coordinate system.

Fig. 4b. Variability of 36 landmarks in the Frankfort horizontal coordinate system.

Fig. 4c. Variability of 36 landmarks in the *glabella-inion* line coordinate system.

Fig 5. Comparison of the variability of coordinate T in the vestibular, *glabella-inion* line and Frankfort horizontal coordinate systems.

given dispersion of a landmark, the deviation of coordinate T will be greater when situated nearer to the origin. From this geometric relationship, the formula $\sigma_T = c/\bar{R}$ is derived, where σ_T is the standard deviation of coordinate T, $\bar{R}$ the mean of coordinate R and c a constant. Therefore, the value $\bar{R}\sigma_T$ was compared rather than σ_T itself. $\bar{R}\sigma_T$ represents the actual dispersion of a landmark in terms of an arc in a direction around the origin.

Results are given in Fig 5. Conclusions reached in the previous section were confirmed. Compared with VEST, 1) facial landmarks show a markedly lower variability in both FH and GLIN but more pronounced in FH, 2) variability of landmarks on the occipital do not change in FH while there is a marked decrease in GLIN, and 3) variability of the landmarks on the cranial base is lower in both FH and GLIN but difference with VEST is small.

Influence of "fixing" reference points

The use of certain landmarks in defining a reference plane is expected to influence the variance of the landmarks in question. For example, if the Frankfort horizontal coordinate system is used with *porion* origin, the variance of coordinate Y of *orbitale* will be 0.0. This can be considered as an artificial "fixing" of *orbitale*. Although this "fixing" process is not marked in the present study because *porion* is not used as origin, the same principle exists. Furthermore, landmarks correlating with the landmarks defining the reference plane are also expected to be influenced.

Difference between FH and GLIN can be interpreted from the above considerations. FH defined by PO and OR "fixes" the facial landmarks more intensively than GLIN which is defined by GL and IN. Conversely, GLIN "fixes" the occipital and cranial vault landmarks while FH does not.

Characteristics of the vestibular orientation

Although a somewhat higher variability is expected in VEST as explained above, difference between VEST and FH or GLIN cannot be attributed solely to a decrease of variability in the latter two. First, in GLIN compared with VEST, difference of variability of the facial landmarks clearly exceeds that of the occipital landmarks. Second, maximum differences between FH and GLIN (which occur in the facial or occipital regions) are considerably smaller than the maximum difference between either of the two and VEST. And third, in the landmarks on the cranial base where variability of FH and GLIN is of similar magnitude, VEST always has higher var-

iability. Taken together, a decrease of variability in FH and GLIN brought about by the "fixing" process cannot by itself explain the difference from VEST, and it is concluded that the difference between VEST and FH or GLIN is a combination of a low variability of the facial region in FH and of the facial and occipital regions in GLIN on one hand, and a characteristically high variability in VEST which is most conspicuous in the facial region on the other.

As discussed in the previous section, an instability of the vestibular orientation represented by bilateral asymmetry was found. Could this be the cause of the high variability in VEST? This question can be answered as follows. In males, the lowest standard deviation value of

Table 5. Comparisons of variability of the Frankfort horizontal in vestibular orientation and in natural head position.

	study	population	sex	n	var.	st.dev.	
vestibular orientation	present study	Japanese	M	40	26.60	5.16	
			F	23	18.53	4.31	
	CANAL 1977	Gallo-Romanian	?	56	21.16	4.60	
	FENART 1967	European white	?	51	26.63	5.16	
	PFULLERIN 1970	Melanesian	?	55	10.63	3.26	
	PRUDON 1975	Peruvian	?	35	17.22	4.15	
natural head position	SUWA 1980	Japanese	M	21	20.43	4.52	S I T M I R #
					25.00	5.00	STD M I R
					15.44	3.93	S I T
					21.81	4.67	STD
			F	21	13.54	4.02	S I T M I R
					15.37	3.92	STD M I R
					16.24	4.03	S I T
					14.67	3.83	STD
	BJERIN 1957	European white	M+F	35	18.15	4.26	S I T M I R
					20.70	4.55	STD M I R
	MOORREES and KEAN 1958	European white	F	61	13.54	3.68	S I T M I R
					16.16	4.02	STD M I R

mode of natural head positioning, see SUWA 1980

coordinate T was 5.14 (deg) for BR. Subtracting the value of 5.00 obtained in the previous section as excessive variance would only alter 5.14 to 4.63 ($\sqrt{5.14^2 - 5.00}$). The $\bar{R}\sigma_T$ value of BR would be altered from 10.41 to 9.38. Landmarks with higher σ_T values will be influenced less. Therefore, it is concluded that the high variability found in VEST is not the result of an instability of the vestibular orientation of random nature as represented by bilateral asymmetry.

In natural head position orientation also, craniofacial reference lines are reported to vary relatively highly (SOLOW and TALLGREN, 1971). Table 5 compares the variances of the angle the Frankfort horizontal makes with the vestibular horizontal with the variances of the angle it makes with the true vertical in natural head position orientations. Natural head position is defined as the head position one feels most natural while looking straight forward. A vertically placed mirror is often used to help the subject attain horizontal gaze. It can be seen that the magnitude of variability in the vestibular orientation and natural head positioning is about the same. This is interesting because natural head position has the characteristic in common with the vestibular orientation of not fixing cranial landmarks.

The relatively great variability of craniofacial reference lines in natural head position may be considered as the result of multiple factors involved in head positioning. Physiological factors such as respiration, swallowing and speech are

reported to have relationship with head posture (SOLOW and TALLGREN, 1976). Extent of the visual field may also have influence. Similarly, in VEST, multiple factors are expected to be the cause of the relatively augmented variability of the facial landmarks. However, what factors actually influence vestibular orientation and with what aspects of head positioning it has strongest association remains to be examined.

SUMMARY

The vestibular method of orientating the cranium was applied to 63 Japanese crania. The present paper examined the methodological aspects of its characteristics, and the following results were obtained.

- 1) An examination of errors revealed that measurement errors were small.
- 2) Bilateral asymmetry in the antero-posterior inclination of the lateral semicircular canals was found. However, variance resulting from factors causing asymmetry was estimated to be insignificant to the total variance.
- 3) A comparison of the variability of 36 landmarks in the vestibular coordinate system (VEST), Frankfort horizontal coordinate system (FH) and *glabella-inion* line coordinate system (GLIN) revealed that in FH and GLIN an artificial decrease of variability was found in landmarks correlating with the landmarks involved in the definition of the reference planes.
- 4) The vestibular orientation characteristically showed a relatively high variability which was most conspicuous in the

facial landmarks.

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REFERENCES

- BJERIN, R., 1957: A comparison between the Frankfort horizontal and the sella-turcica-nasion as reference planes in cephalometric analysis. *Acta Odont. Scand.*, 15: 1-12.
- BONJEAN, P. and J. VIDEAU, 1975: Quelques problèmes posés par l'orientation de la tête. *C.R. Assoc. Anat.*, 164: 63-81.
- BUXTON, L. H. D. and G. M. MORANT, 1933: The essential craniological technique. *J. Roy. Anthropol. Inst.*, 63: 19-47.
- CAIX, M. and G. OUTREQUIN, 1979: Variability of the bony semicircular canals. *Anat. Clinica*, 1: 259-265.
- CANAL, P., 1978: Analyse cranio-faciale d'une population de Gallo-Romains en orientation vestibulaire. Th. Dr. en Sc. Odont.
- DEBEER, G. R., 1947: How animal hold their heads. *Proc. Linnean Soc. London*, 158: 125-139.
- DELATTRE, A., 1951: Du crâne animal au crâne humain. Masson, Paris.
- DFLATTRE, A. and R. FENART, 1960: Relations angulaires entre le vestibule osseux et l'arrière-crâne des mammifères. *C.R. Ac. des Sc.*, 250: 3722-3724.
- _____, 1961: Evolution des fenêtres du vestibule de mammifères à l'homme. *Bull. Mém. Soc. d'Anthrop. de Paris*, 11-2: 273-289.
- DOYLE, W. J., 1977: A functiono-anatomic description of Eustachian tube vector relations in four ethnic populations: An osteologic study. Ph. D. Dissertation, University of Pittsburgh.
- FENART, R., 1966: Influence des modifications expérimentales et tératologiques de la station et de la locomotion, sur la morphologie céphalique des mammifères quadrupèdes. Etude par la méthode vestibulaire. *Arch. d'Anat., d'Histol. et d'Embryol. normales et expérimentales*, XLIX.
- _____, 1967: Situation vestibulaire moyen des principaux éléments des neuro-crâne humain adulte, et étude de leur variabilité. *Bull. Mém. Soc. d'Anthrop. de Paris*, 12-1: 335-357.
- _____, 1969: Le vestibulographe. *Bull. Mém. Soc. d'Anthrop. de Paris*, 12-4: 363-370.
- _____, 1975: Point actuel et perspectives sur l'orientation radiologique vestibulaire de la tête. *Orthopedie Dentofaciale*, 9: 469-478.
- FENART, R. and G. FENART, 1975: Détermination du plan sagittal médian par tomographies bilatérales des labyrinthes, corrigées par ordinateur. *Bull. Ass. Anat.*, 165: 551-552.
- GIRARD, L., 1929: L'attitude normale de la tête déterminée par le labyrinthe de l'oreille. *Bull. Mém. Soc. d'Anthrop. de Paris*, 7-10: 77-99.
- _____, 1947: Port habituel de la tête et fonction vestibulaire. *Mammalia*, 10: 1-17.
- GUEDRY, F. E., 1965: Psychophysiological studies of vestibular function. in: *Contributions to sensory physiology* (W. D. NEFF ed.), Academic, New York.
- HOWELLS, W. W., 1973: Cranial variation in man. *Papers of the Peabody Museum of Ar-*

- chaeology and Ethnology, Harvard University, vol. 67.
- LEBEDKIN, S., 1924: Über die Lage des canalis semicircularis lateralis bei Säuger. *Anat. Anz.*, 58: 448-460.
- LOREILLE, J. P., 1975: Déterminations de la position "habituelle" de la tête, par clinomètre enregistreur. Th. Dr. Sc. Odontol., Paris.
- LOUBAUD, J. P., 1976: Détermination, par calcul électronique, de la situation du plan médian de la tête. basée sur la méthode d'orientation vestibulaire. Th. Dr. Sc. Odontol., Paris.
- MARTIN, R. and K. SALLER, 1957: *Lehrbuch der Anthropologie*, Bd. 1. Gustav Fischer, Stuttgart.
- McHENRY, H. M. and R. S. CORRUCINI, 1978: Analysis of the hominoid os coxae by cartesian coordinate. *Am. J. Phys. Anthropol.*, 48: 215-226.
- MOORREES, C. F. A. and R. KEAN, 1958: Natural head position, a basic consideration in the interpretation of cephalometric radiographs. *Am. J. Phys. Anthropol.*, 16: 213-234.
- PELLERIN, C., 1970: Analyse tridimensionnelle des éléments cranio-faciaux d'une population de Mélanésians en orientation vestibulaire; comparaison avec le crâne européen. Th. Dr. Sc. Odontol., Paris n°93.
- PEREZ, F., 1922: Craniologie vestibienne, ethnique et zoologique. *Bull. Mém. Soc. d'Anthrop. de Paris*, 7-3: 16-32.
- PRUDON, R. G., 1975: Crânes péruviens précolombiens "non-déformés", Tome 2: Interprétations statistique des données vestibulaires et comparaisons. Th. Dr. en Sc. Odontol., Paris n°130.
- PUCCIARELLI, H. M., 1978a: Craniofacial development of the rat with respect to the vestibular orientation. *Acta Anat.*, 100: 101-110.
- _____, 1978b: The influence of experimental deformations on craniofacial development in rats. *Am. J. Phys. Anthropol.*, 48: 455-461.
- ROBIN, M., M. CAIX and G. OUTREQUIN, 1967: Contributions a l'étude de l'orientation des canaux semi-circulaires sur le crâne sec par radiographie. *C. R. Assoc. Anat.*, 136: 906-924.
- SOLOW, B. and A. TALLGREN, 1971: Natural head position in standing subjects. *Acta Odont. Scand.*, 29: 591-607.
- _____, 1976: Head posture and craniofacial morphology. *Am. J. Phys. Anthropol.*, 44: 417-436.
- SUWA, G., 1980: The somatological significance of the Frankfort horizontal. *J. Anthrop. Soc. Nippon*, 88: 83-95.
- SUZUKI, J., 1967: The vestibulum and nystagmus. In: KATSUKI, Y. ed.: *Japanese handbook of physiology*, Vol. VI, Physiology of sensation. Igakushoin, Tokyo, 854-896.

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S G	X	-101.38	3.598	A N S	X	-87.26	7.242	P H T	X	-9.52	2.603	G O	X	-4.62	7.573
	Y	22.06	10.107		Y	-50.75	8.351		Y	-19.81	2.621		Y	-68.49	6.155
	R	104.23	3.604		R	101.45	4.240		R	22.17	2.236		R	69.07	5.896
	T	167.78	5.580		T	210.25	5.836		T	244.18	7.646		T	266.10	6.603
	Z				Z	-0.25	2.051		Z	-0.20	0.876		Z	47.46	3.710
G L	X	-100.26	3.380	P R	X	-84.73	8.623	C A	X	1.02	3.366	P O	X	-4.06	1.525
	Y	9.46	9.650		Y	-68.11	8.273		Y	-27.13	3.128		Y	-2.61	2.772
	R	101.15	3.541		R	109.29	3.642		R	27.35	3.125		R	5.38	2.045
	T	174.68	5.459		T	218.85	6.021		T	271.94	7.195		T	208.32	26.323
	Z				Z	0.09	2.597		Z	11.88	1.471		Z	58.39	2.623
F T	X	-85.03	4.036	I D	X	-74.77	9.089	C P	X	20.03	3.031	S E	X	-30.16	2.666
	Y	22.51	8.720		Y	-85.18	8.185		Y	-20.56	3.249		Y	6.06	3.427
	R	88.39	3.751		R	113.91	4.138		R	28.90	2.866		R	30.95	2.742
	T	165.22	5.791		T	228.72	5.844		T	314.29	6.929		T	168.70	6.217
	Z	45.55	2.846		Z	-0.76	3.719		Z	20.71	1.829				
O S	X	-93.49	2.989	G N	X	-54.83	11.740	O P	X	38.63	3.655	C R A	X	-77.47	3.269
	Y	9.44	8.469		Y	-112.09	7.925		Y	-15.89	4.854		Y	0.93	7.112
	R	94.34	2.987		R	125.47	4.945		R	42.04	3.698		R	77.79	3.195
	T	174.27	5.170		T	243.89	6.105		T	-22.28	6.656		T	179.39	5.306
	Z	23.23	2.549		Z	-0.36	4.934		Z	-0.33	0.866				

S G	X	-96.54	3.419	A N S	X	-81.04	4.904	P H T	X	-8.69	2.326	G O	X	-4.80	4.512
	Y	18.59	7.575		Y	-48.23	6.820		Y	-18.49	2.428		Y	-61.26	4.841
	R	98.60	3.326		R	94.95	3.438		R	20.58	2.210		R	61.60	4.872
	T	169.13	4.479		T	210.63	4.632		T	244.71	7.275		T	265.56	4.197
					Z	0.57	1.885		Z	-0.39	0.543		Z	43.63	3.231
G L	X	-94.64	3.303	P R	X	-79.35	6.669	C A	X	1.00	2.765	P O	X	-4.33	1.660
	Y	9.01	6.799		Y	-66.20	5.825		Y	-24.79	2.941		Y	-1.64	2.303
	R	95.30	3.224		R	103.63	3.921		R	24.96	2.890		R	5.11	1.785
	T	174.58	4.151		T	219.89	4.376		T	272.46	6.558		T	201.24	24.066
					Z	0.30	2.439		Z	10.87	1.576		Z	55.04	2.078
F T	X	-80.41	3.287	I D	X	-69.73	6.883	C P	X	18.79	2.847	S E	X	-28.27	2.034
	Y	20.28	6.440		Y	-82.72	6.405		Y	-18.35	3.146		Y	4.65	2.927
	R	83.18	3.000		R	108.51	3.902		R	26.46	2.712		R	28.79	2.108
	T	165.86	4.572		T	229.86	4.505		T	315.80	7.216		T	170.81	5.823
	Z	43.89	2.105		Z	0.11	3.500		Z	19.11	1.602				
O S	X	-88.76	2.858	G N	X	-50.05	8.610	O P	X	36.48	2.818	C R A	X	-75.02	3.256
	Y	8.06	6.781		Y	-105.04	6.468		Y	-14.92	4.130		Y	-0.53	5.621
	R	89.37	2.745		R	116.73	4.775		R	39.61	3.051		R	75.22	3.201
	T	174.82	4.407		T	244.49	4.719		T	-22.09	5.804		T	180.42	4.330
	Z	22.80	1.970		Z	0.70	4.369		Z	-0.17	1.062				

人類頭蓋学における半規管座標系の基本的性質

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頭蓋の形態を解析する場合しばしば基準面を使用するが、その基準面の意義、特徴、および実践上の問題点を十分に吟味したうえで研究を進めることが望ましい。本研究では頭蓋の水平面として三半規管の外側半規管のなす面（以上、半規管面とする）を用いた。この方法は古くから主としてフランスで活用されてきたもので（PEREZ, 1922; GIRARD, 1929; DELATTRE, 1951）以下の理論的性質を備えている。1) 半規管面は実際に生理学的意義をもつ（GUEDRY, 1965; FENART, 1966; SUZUKI, 1967）。2) 哺乳動物を全般的に見渡すと半規管面と頭位（head posture）との間に密接な関係が存在する（DEBEER, 1947; GIRARD, 1947), Fig. 1 参照。3) この方法は無顎類を除くすべての脊椎動物に適用できる。4) 系統発生をたどると半規管面はあらゆる形態変化とは独立に水平に保たれていることが分かる（DELATTRE, 1951; DELATTRE and FENART, 1960; 1961）。以上の性質は通常人類学で用いられている耳眼水平面には見られない注目すべきものである。

本研究では原点を vestibion（外側半規管の中心を正中矢状面に投影した点）、水平面を半規管面と定め、これらと正中矢状面とで三次元直交座標系（半規管座標系）を定義した。この座標系の中に 36 個の計測点（Table 1, Fig. 3）を組み込み、得られる座標値を原データとした。このように頭蓋を各計測点の三次元座標値として解析する場合、半規管面に十分な安定性が存在するか否かを計測誤差、半規管面における左右の非対称性という二観点から調べた。また、各計測点の半規管座標系（VEST）における変異を調べ、他の水平面によって定義される座標系、耳眼水平座標系（FH）および *glabella-inion* 線座標系（GLIN）における変異といかなる相違点が存在するかを調べた。これらの考察は半規管座標系を頭蓋学で実際に応用する場合、前段階として不可欠なものである。

使用標本は東京大学総合研究資料館医学部内所蔵の現代日本人頭蓋骨標本63個（男40, 女23）である。年令は20~44才に制限した。また、半規管面の決定は断層撮影によった（Fig. 2）。

1) 誤差の考察 同一頭蓋を2回計測することによって(n=10)計測に伴う誤差のめやすを得た(Table 3)。測定誤差は十分に小さいと結論できる。また、半規管座標系（VEST）における誤差は耳眼水平座標系（FH）における誤差より大きいという傾向が認められたがその差はわずかであった。これは半規管面の決定に固有の誤差が存在するがその大きさはわずかであることを示している。

2) 左右半規管面の不一致 左右の半規管面は必ずしも一致しないことが確認された（Table 4）。この左右の不一致は半規管面自身の不安定性を意味し各計測点の座標値における過剰な分散の原因となり得る。これが無視できる程度のものでない限り、半規管面を基準面として用いるのは好ましくない。実際にこの過剰な分散の程度を推定したところ全分散に対する割合は十分に小さく、従って左右半規管面の不一致は問題にならない程度のものであることが確認された。

3) 計測点の変異 各計測点を矢状面に投影した時の変異は等確率楕円として実際に図示できる（Fig 4a, b, c）。半規管座標系（VEST）を用いると顔面の計測点の変異が大きくなることが分かる。また、矢状面における極座標を用いて三つの座標系の相違点をより厳密に調べた（Fig 5）この場合、各座標系の原点は同一であるため原点からの距離は不変であり、偏角だけを比較すればよい。結果をまとめると、1) GLIN と FHにおいては水平面の定義にそれぞれ *glabella* と *inion* および *porion* と *orbitale* を使用しているため、その影響としてこれらの計測点と関連の高い計測点の偏角の分散は人為的に減少されている、2) VESTにおいては各計測点の偏角の分散は相対的に大きく、この傾向は顔面部で最も著しい。

以上より、半規管座標系における顔面部の計測点の相対的に大きい変異は半規管面自身の不安定性に起因するものではなく、半規管座標系に特有の性質であると結論できる。これがいかなる原因に基づくかは然るべき研究を待たねばならないが、自然頭位（natural head position）に対してもやはり顔面部は変異が大きい（SOLOW and TALLGREN, 1971）ことは興味深い。