Sternal Variation: Anatomical-Forensic Analysis

ORIGINAL

Viviane Moura Leite¹,
Caroline Freitas de Souza Plácido¹,
Carolina Lucena Veloso Gusmão¹,
Evelynne Pessoa Soriano², Adriana Conrado Almeida²,
Antonio Azoubel Antines²,
Gabriela Granja Porto Petraki²

¹ Master Forensic Ciencias, Faculty of Odontology, Sciences, PE, Brazil.
² Associate Professor Master Forensic Sciences, PE, Brazil.

Contact information:

Gabriela Granja Porto Petraki.

Address: Av. Governador Agamenon Magalhães s/n, Santo Amaro. Recife, Pernambuco, Brazil. CEP. 50100-010.
Tel: +55 81 992323241.

gabriela.porto@upe.br

Abstract

Background: The aim of this study was to analyze the extent and uniqueness of anatomical variations of the sternum bone, to assess its applicability for forensic analysis, especially for individual human identification.

Methods and Findings: Evaluations involved 501 computer tomography scans performed at the Medical Radiology Center, Manaus city, Amazonas, Brazil, and 427 skeletons belonging to the Collection of Identified Human Skeletons of the Center for Studies in Forensic Anthropology (CEAF), of the University of Pernambuco (UPE), Pernambuco, Brazil. Forms of morphological variations were evaluated, including the presence of foramina, fissures, and incomplete total or partial fusions, as well as forms of xiphoid process termination, and the presence of surgical sutures. Overall, summing computed tomographic images and skeletons, the sternal foramen was present in some 23% of samples, with a greater proportion in males (14%), while in females the frequency was 8.6%.

Conclusions: The qualitative analysis of the sternum bone is simple to apply and represents an important potential source of information in a human identification process.

Keywords

Sternum; Xiphoid Process; Congenital Anomaly; Computed Tomography; Human Identification.

Introduction

During investigations, materials that facilitate identification, such as of dental records, radiographs and medical-dental documents are frequently absent. However, the use of digital medical records is being increasingly adopted by institutions as, in addition to medical history, image examinations performed by the patient are archived. Since it is also common for patients to keep these exams at home throughout their lives, it becomes of paramount importance that such material is requested by experts in those cases involving human identification.

Principally due to the proximity to thoracic organs, such as the heart and lungs, medical records will generally indicate if the sternum of a living individual is fractured or has a foramen, due to the importance of recording such data. This is because in cases of cardiopulmonary resuscitation, fractures in the sternum may occur. These, or existing foramina, may cause or serious cardiac injuries and even death in situations of spinal cord biopsy or acupuncture, due to the proximity of the sternal foramen to the heart [1, 2].

It is not always possible, when identifying a body, to apply the primary methods of papilloscopy, dentistry and DNA analyzes, although medical-dental information can be successfully gained *ante mortem* [3]. However, digital record keeping has been increasingly adopted by medical institutions. In addition to the medical history, this frequently includes any image-based examination performed on the patient. As a result, the analysis of the sternum becomes an option.

Sternum bone formation occurs through the longitudinal fusion of the mesenchyme located on both sides of the chest wall. The mesenchymal bands have their origin in the of the latero-dorsal region of the body wall and merge in the central zone. These bands appear in the 6th week of intra-uterine life. Mesenchymal condensations (or sternal plaques) undergo chondrification and fuse in the

midline, in the craniocaudal direction, forming a cartilaginous sternum. Fusion progresses until the 10th week of intrauterine life. Ossification of the cartilaginous sternum then occurs via ossification centers, during the fifth and sixth months of intra-uterine life [5, 6, 7].

Anatomically, the sternum bone is divided into three parts, manubrium, mesosternum (or body) and the xiphoid process [8]. Calcification of the manubrium, usually begins before birth [9]. The process involves calcification centers termed sternebra. There are usually 4 sternebra. Their fusion begins during the third and fourth year of post-natal life, and is completed during adolescence, generally around 12 years old, although it may extend to 25 years [1, 10]. Sternum development may continue until the third or fourth decade of life [11]. Throughout this process, several anomalies may occur, for example, the bands of the mesenchyme may not join completely along the midline, leaving spaces, so creating sternal fissures [4, 1, 12].

Post-birth defects may occur during the calcification process between the ossification centers in the manubrium. Here, incomplete fusion of a pair of adjacent sternebra will give rise to the sternal foramina. These can be single or multiple, and are usually located in the lower portion of the mesosternum [4, 13, 6, 7], while incomplete fusion of the lower end of the sternum result in a biphid or perforated xiphoid process [14, 15]. As a result, the sternum is one of the parts of the skeleton with the highest frequency of anatomical variation [1, 16].

The types and frequency of sternum bone anatomical variation have been studied for a variety of locations and populations. These provide an idea of the frequency status of each sternal variation, that is, if the observed characteristic is, as classified by Verna et al (2014): very rare (<1%), rare (1 to 10%), infrequent (10 to 20%), frequent (20 to 50%) or very frequent (>50%). **Table 1** summarizes studies to show the types and frequencies of sternal foramina [17].

Table 1. Studies of types of sternal foramina and their frequencies in a variety of human populations.

Authors	Year	Population	Sample type	Sample size	Prevalence of sternal foramina
					%
Akin	2011	Turks	TCMD	500	9
Ashley	1956	East Africans	Skeletons	98	13.3
		Europeans		573	4
Bayaroğullari	2014	Turks	MDCT	250	6
El-Busaid	2012	Kenyans	Skeletons	80	13.8
Macaluso Lucena	2014	Spanish	Cadavers/ Radiography	122	3.3
McCormick	1981	USA	East Africans	324	7.7
			Europeans		
Paraskevas	2015	Greeks	Skeletons	60	18.3
Stark	1985	USA	TC	140	4.3
Yekeler	2006	Turks	MDCT	1000	4.5

MDCT: Multiple Detector Computerized Tomography.

As can be seen, sternal foramen frequency varied greatly between different studies and populations. This amplitude is the result of research with samples of radiological analysis such as radiographic or computed tomography (CT) or multiple detector computed tomography (MDCT), or examination of cadaveric or anatomical (skeletal) samples.

Accordingly, the current study aimed to analyze the nature and extent of anatomical variations of the sternum bone using computerized tomographic images of the chest as well as morphological analysis of identified human skeletons, to discover to what extent such variation characteristics can be used as a source of information for individualizing human identification.

Methods

The present study had two phases of data collection. The first involved the analysis of the osteological collection composed of 427 identified human skeletons, belonging to the Pernambuco University Center for Studies in Forensic Anthropology (CEAF), Pernambuco, Brazil. This collec-

tion contains individuals from northeastern Brazil, who were buried and exhumed between 2011 and 2018, in the city of Recife, Pernambuco. The individuals represent the current population of the northeast region of Brazil. The research was approved by the Research Ethics Committee of Oswaldo Cruz University Hospital of Pernambuco University (CEP/UPE), under permit no. 3.851.016, CAAE 29279120.6.0000.5192.

Skeletons of both sexes and of any age group, which had a sternum suitable for analysis, were included in the study. Of the 427 human skeletons documented in the collection, 195 had a sternum (45.67%).

In the second phase of the study, 501 chest CT scans of individuals of both sexes (228 men and 273 women), were analyzed at the Centre for Medical Radiology, in the city of Manaus, Amazonas, located in northern Brazil. The individuals represented the current population of the Northern region of Brazil. The research was approved by the Research Ethics Committee of Pernambuco University (CEP/UPE), under permit n. 2.284.094, CAAE 72907917.8.0000.5207.

For the tomographic images, individuals of both sexes and of all age groups were included. Presence of a congenital anomaly did not exclude the skeleton or tomographic image from the study, since such items can serve as individualizing characteristics. Tomographic sample participants were not exposed to unnecessary radiation and did not receive medication, because all selected patients had undergone a mandatory chest examination for other reasons and their records formed part of the clinic's digital archive.

Data were recorded on a spreadsheet detailing the presence or absence of any variable considered important for inclusion in the current study. Throughout the collection phase, data were reviewed for omissions and corrected.

The variables of discriminating interest considered in the current study were:

1. Manubrial fissure
2. Manubrial foramen
3. Mesosternal fissure
4. Mesosternal foramen
5. Xiphoid Process foramina, single or multiple.
6. Xiphoid Process Terminus, single, bifid or trifid.
7. Presence of Surgical Suture

Statistical tests were performed using the program Statistical Package for Social Science (SPSS® Professional Statistics, version 22.0).

To characterize the studied sample descriptive analysis was carried out to assess variable distribution frequencies. Data analysis calculated absolute and percentage distributions and mean, median and standard deviation (descriptive statistics techniques).

Results

501 computed tomography scans with multiple detectors (MDCT) were analyzed, 55.5% (n = 278) of which were female. Of the 195 CEAF skeletons that had the sternum, 58.5% (n = 114) were from males, and 41.5% from females. Mean sample age (MDCT and skeletons combined, n = 696) was 55 years, with a minimum age of 7 and a maximum of 109 years. Median (n = 696) was 55 years, the mode, 68 years and standard deviation, ± 17.80 .

In the total sample (MDCT and skeletons), the occurrence of the sternal foramen was 23%, with a greater predilection for males, 14%, while in females the frequency was 8.6% (**Table 2**).

In the MDCT sample, overall sternal foramen occurrence was 28.15%. However, as for mesosternal foramen presence, a percentage difference existed between the sexes, 16.97% among males vs 11% among females (**Table 2**).

A mesosternal foramen (that is the foramen located in the mid-part of the sternum), was present in 7.33% of the total sample (MDCT and skeletons). When the samples were separated, the frequency of the mesosternal foramen was higher in skeletons (8.72%), compared to the pure MDCT sample (**Table 3**).

Among the skeletons, there was single record of a sternal fissure accompanied by foramen in the final third of the mesosternum.

No manubrial fissures were found in either sample. Only one case of foramen was observed on a CT scan of a female patient.

In the MDCT sample, 52% of the individuals had a xiphoid process with single terminus. It was bifid

Table 2. Sternal Foramen Frequency.

Sample	MDCT + Skeleton	n=696	MDCT	n=501	Skeleton	n=195
	Frequency	%	Frequency	%	Frequency	%
Female	60	8.60	56	11.18	4	2.05
Male	101	14.53	85	16.97	16	8.20
Female + Male	161	23.13	141	28.15	20	10.20

MDCT: Multiple Detector Computerized Tomography.

Table 3. Sternal foramen variation frequencies.

Sample	MDCT + Skeleton	n=696	MDCT	n=501	Skeleton	n=195
	Frequency	%	Frequency	%	Frequency	%
Manubrial Foramen	1	0.14	1	0.20	0	0.00
Sternal fissure	2	0.29	1	0.20	1	0.51
Mesosternal Foramen	51	7.33	34	6.78	17	8.72
Xiphoid Foramen	115	16.52	111	22.16	4	2.05

MDCT: Multiple Detector Computerized Tomography.

Table 4. Frequency of variations of the xiphoid process in the MDCT sample.

Sample	(n = 501)		Fem. (n = 278)		Male (n = 223)	
	Frequency	&	Frequency	&	Frequency	&
Single Termination	261	52.09	146	52.52	115	51.57
Single Termination (elongated)	109	21.75	57	20.50	52	23.32
Bifid Termination	45	9.00	27	9.71	18	8.07
Trifid Termination	20	4.00	6	2.16	14	6.28
Undefined Termination	66	13.17	42	15.11	24	10.76
With Single Foramen	79	15.76	31	11.15	48	21.52
With Multiple Foramina	32	6.39	8	2.88	24	10.76

in 9%, trifid in 4% and undefined in 13%. A foramen was present in 27% of the xiphoid process examined, 15% being single and 6% multiple (**Table 4**). A surgical sternal suture was observed in 1.6% (n = 8) of tomographic images and in 2% (n = 4) of skeletons.

Discussion

The first written evidence for sternal foramina occurs in the XVI and XVII centuries, when anatomists of the period, among them Coiter in 1573 and Eustachius in 1714, noted their existence as an important variation [4, 19]. They were considered most common in the lower third of the mesosternum (**Figure 1**). In autopsies, sternal foramina were observed and described as a character of potential forensic value [15] as a characteristic allowing individual identification. Sternal foramina are asymptomatic and are occasionally encountered in

Figure 1: Illustrations of the Sternum and its anatomical divisions.

A: (Breathnach, 1958); B: Indications of the anatomical locations of sternal fissures and foramina.

radiographic examinations, such as CT, or *in post-mortem* analysis (**Figure 2**) [20, 21, 16]. In MDCT, in axial sections, they appear “bow-tie” formations [16]. Studies undertaken in a range of populations

Figure 2: Sternal foramen.

A: CT image, female, 35 years; presence of a foramen; B: skeleton, male, 64 years, foramen present.

Figure 3: Manubrial Foramen. Image, Female, 30 years, with a Manubrial Foramen.

Figure 4: Sternal Fissures. Foramen present in seta 1 and seta 2.

A: CT Image, 12 years, male. Foramen formation. B: skeletal material, male, 29 years, closure hole material.

have encountered occurrence frequencies ranging from 12.9% to 18.3% for skeletal material [4, 2, 22, 19, 23, 20] and 3.35% to 16.65% in radiological studies [14, 2, 9, 1, 24, 25, 26, 27, 15, 28, 16]. In the current study the sternal foramen frequency varied by sample (28.15% for MDCT; 10.2% in skeletons).

The manubrial ossification centres unite before birth. Although rare, it is possible for the centres not to fuse, causing a hole in the centre of the manubrium, either incomplete or incomplete [5]. Bayaroğulları et al (2014) recorded the occurrence of only one case of incomplete manubrial ossification, and one occurrence of a manubrial foramen. In the same study, the authors found no evidence for between-sex difference in the growth and differentiation of the manubrium, and concluded that manubrial growth was the same in both sexes [1]. In the current study, a MDCT image was recorded of a manubrial foramen (0.2% of the MDCT sample, see **Figure 3**). Therefore, the presence of fissured and foramina in the manubrium is an important finding for individual differentiation.

A MDCT image and a skeleton each had a sternal foramen with a slit in the final portion of the mesosterna in the form of a "key hole", similar to cases reported by other authors [16, 12, 20]. The sternal fissure may show complete or incomplete shapes, depending on the extent of fusion failure [6, 16]. Fusion failure is a rare birth defect. When incomplete forming a foramen, it often has the form of a "keyhole" (**Figure 4**: [20, 12, 16]). Bayaroğulları et al (2014) evaluated tomographic images of 200 patients between 0 and 20 years old and recorded 15 cases (7.5%) of foramina in the manubrium, and 10 cases (5%) of a sternal fissure [1]. Because this variation has low frequency, it has the potential to be a highly individual-specific character.

Table 5 shows the absolute and percentage values for sternal variations, from other studies in the literature.

Table 5. Studies of stern foramen frequency.

Authors	Year	Type of sample studied	Sample Size	Sternal foramen prevalence in sample	Proportion male: female	Sternal Fissure	Prevalence of Perforated Xiphoid Process	Presença of Manubrial Foramen
				%	%	%	%	
Akin	2011	MDCT	500	9	-	-	34.2-9	none
Ashley	1956	Skeleton	98	13.30	-	-	-	none
			573	4				
Babinski	2012	MDCT	180	16.60	-	-	-	none
		Skeleton						
Babinski	2015	MDCT	114	10.5	58: 42	-	-	none
Bayaroğullari	2014	MDCT	250	6	-	-	-	1 case
Boruah	2016	MDCT	1180	11.60	-	-	-	none
El-Busaid	2012	Skeleton	80	13.8	mes		2.50	none
Gkantsinikoudis	2017	Skeleton	35	14.20	mes		7	none
Gossner	2013	MDCT	352	4.50	3:2			none
Kirum	2017	Skeleton	100	12.90	-	8.20	9.50	none
Macuso Lucena	2014	Cadavers/ Radiography	122	3.3	Only mes	-	-	none
Mccormick	1981	Cadavers/ X-Rays	324	7.7	-	-	-	none
Mccormick	1981	Cadavers/	324	7.7	-	-	-	none
Moore	1988	Radiography	2016	6.7	2:1	-	-	none
					9.6: 4.3			
Paraskevas	2015	Skeleton	60	18.3	-	2 cases	-	none
Stark	1985	TC	140	4.30	-	-	-	none
Turkay	2017	MDCT	544	5.20	-	0.60	-	none
Yekeler	2006	MDCT	1000	4.5	-	1 case	27.40	none
Currentstudy		MDCT	501	23.13	1:1	1 case	11.93	1 case
		Skeleton	195		3:1			

MDCT: Multiple Detector Computorized Tomography.

In the literature consulted, the frequency of sternal foramina in the xiphoid process varied between 2.5% and 34% (**Table 6, Figure 8**). In the current study, the recorded prevalence (15.76%) lay within the range reported by these other authors. Akin et al. (2011) reported the presence of multiple xiphoid sternal foramina in 9% of the study population,

while in the current study, this situation occurred in 6% of the MDCT sample (**Figure 9**). The xiphoid process, from the Greek *xifhos* ("straight sword"), is a region with many morphological variations. At birth, it is cartilaginous. During adulthood, the xiphoid process is ossified, merging into the mesosternum in older individuals [19, 16]. The morphologi-

Table 6. Survey of literature to show variation in xiphoid terminus morphology.

Authors	Year	Type of sample studied	Sample Size	Prevalence of single xiphoid terminus	Prevalence of bifid xiphoid terminus	Prevalence of trifid xiphoid terminus	Prevalence of peeforated xiphoid terminus
				%	%	%	%
Akin	2011	MDCT	500	62.6	32.8	4.6%	34.2-9
Babinski	2015	MDCT	114	-	17.5	-	-
El-Busaid	2012	Skeleton	80	80	12.5		2.5
Gkantsinikoudis	2017	Skeleton	35	-	-	-	7
Kirum	2017	Skeleton	100	-	42.9	-	9.5
Macaluso Lucena	2014	Cadavers/ Radiography	122	54.9	41.6	-	-
Turkay	2017	MDCT	544	72	25	1%	-
Yekeler	2006	MDCT	1000	71	27.2	0.7	27.4
Currentestudy		MDCT	501	52.09	9	4%	15.76

Figure 5: Xiphoid Process-Single Terminus.

A: CT image, female, 63 years; B: skeletal material, female 25, both with a single terminus to the xiphoid process.

cal variations lack any known clinical significance. Yekeler et al. (2006) described the presence of a tri-partate xiphoid process with associated foramina [16]. In the current study, 52.9% of the MDCT had a uniform xiphoid process, while in 21% the terminus was single, but elongated. However, this

region allows individuals to be distinguished since it shows significant morphological variation within the various populations studied, as shown in **Table 6** and **Figure 5**.

Another qualitative individualizing aspect observed in the current study was the fusion of the sternal, manubriosternal and sternoxiphoidal joints. These fibrocartilaginous regions will continue to calcify throughout life, until complete fusion, forming a single bone piece (**Figure 10**) [7, 16]. Sternal articulation calcification can occur in an incompletely, in which case some small areas will remain open forming small unique foramina (**Figures 9C & 9E**), which are termed pseudofoamina or pseudofissures. These features have no known clinical significance, but can be important in identifying individuals. Unless the person is suffering osteodegeneration, manubriosternal articulation is usually complete by 25 years of age [5, 10, 16], with the sternoxiphoidal complete by 40 years. A study by Yekeler et al. (2006) shed that 20 year olds showed complete fusion of the two sternal articulations. Turkay et al. (2017) studied 544 MDCT

Figure 6: Xiphoid Process-Bifid Terminus.

A: CT image, female, 42 years; B: skeletal material, male, 31, both with a bifid terminus to the xiphoid process.

Figure 8: Xiphoid Process-Single. Foramen.

A: CT image, female, 56 years; B: skeletal material, male 49, both with a xiphoidal foramen.

Figure 7: Xiphoid Process-Trifid.

A: CT image, female, 62 years; B: skeletal material, male, 61, both with a trifid terminus to the xiphoid process.

images from individuals covering an 18 to 95 year age range. In their sample, the youngest patient with complete fusion in all sternal articulations was 32 years old. In the current study, where the sample ranged from 7 to 109 years, also found age-related differences (**Figures 10 & 11**).

Due to their importance in various pathological or preventive situations, once the presence of fissures and/or foramina is diagnosed it is essential

that such information be recorded in the medical record of a patient. Information on the presence of sternal fissures and foramina must be available to the health team in cases, for example, of cardiopulmonary resuscitation, sternal biopsy procedure, bone marrow aspiration, acupuncture practice, and also to avoid diagnostic errors in cases of patients with complaints of chest pain, victims of accidents or physical aggression, where they might be confused with fractures of the sternum [10, 1, 29, 30, 31]. Fatal cases of heart penetration have been documented in the literature, for example, Babinski et al. (2012) analyzed 16 bodies with sternal foramina, and all of them had damage to the right ventricle of the heart caused by transthoracic penetration of needles, due to the existence of a sternal foramen in a position that lay above the heart.

Likewise, the lack of knowledge of the morphological variations of the sternum bone can hinder investigations of the cause of death [32]. Erroneous interpretation of sternum bone anatomical variation may hinder forensic investigations if it is mistaken and classified as a firearm projectile injury or other type of traumatic penetration, especially in *post mortem* examinations of bodies in an advanced

Figure 9: Xiphoid Process Foramina. Small foramina: A, B and C, CT image; D and E, skeletal material.

Figure 10: Sternal Articulations.

A: CT, male, 20 years; in B, image of skeletal material, female, 23 years;
C: male, 25 years, showing the sternal articulations in different stages of calcification.

Figure 11: Sternal Articulations-Total. Fusion. Skeletal material, male, 78 years.

A/B: external and internal faces, showing complete fusion of the sternal articulations. C: CT image, male, 60.

state of decomposition, so causing error in investigations of *causa mortis* and, consequently, in the homicide investigations [26, 8]. In such cases it is important to check medical records for the existence of these forms of variation. Several authors have stressed the importance of such finding for forensic anthropology in cases that would contribute to individual identification of human skeletons [33, 10, 32, 28].

In the current study, the presence of surgical sutures in the sternum was observed, both in MDCT (8 cases) and skeletal (4 cases) samples (a total of 1.72% of the entire sample, $n = 696$ (**Figures 12**

Figure 12: Surgical Sutures.

A: skeletal material, male, 58 years; B: CT image, male 69 years, both showing the presence of surgical sutures.

& 13). There are no records in the consulted literature regarding the presence of sutures in the reviewed literature because, as noted by Babinski et al (2015), the presence of sutures, deformations and chest trauma are generally excluded from sample reporting. However, in a forensic investigation that aiming to identify human body, this can be important individualizing information.

Figure 13: Sternal Sutures.

A: skeletal material, female, 90 years; B: CT image, female 70 years, both showing the presence of surgical sutures.

Conclusion

Qualitative analysis of the sternum is simple to apply and can safely be used to obtain a positive human identification. The presence of surgical sutures, not yet referenced in the literature consulted as an individualizing datum, greatly enhances image comparison reliability since each suture is likely to have a unique form. The absence from medical records of information on a patient having a sternal fissure or foramen can result in a variety of fatalities. For this reason, it is recommended that such information be recorded in medical records as soon as it is discovered. This practice will certainly facilitate any eventual *post mortem* forensic investigation.

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