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Morphometric analysis of dog bitemarks. An experimental study

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ABSTRACT

Dog attacks on humans represent a global issue with significant health and medico-legal implications. A dog attack may cut or puncture a victim's skin resulting in distinctive lesions representing the morphology of the dentition that created it. Analysing the compatibility of dog bite marks is exceedingly intricate due to numerous variables involved in wound dynamics. The primary parameter under evaluation is the inter-canine distance, representing the space between two canine teeth within the same dental arch. However, a limitation arises when suspected dogs have similar skull sizes, particularly among adults of the same breed and no studies have been identified that experimentally analyze bite marks on human tissues. The aim of this experimental study is to conduct a morphometric comparison between the dental measurements of canine teeth from 20 different dogs and the skin lesions produced on human tissue. Two metric parameters were assessed: "inter-canine distance" and "interdental incisor-canine distance". The inter-canine measurements ranged between 21 and 52 mm, and 20–53 mm on skin. The incisor-to-canine measures ranged between 5 and 21 mm, and 4–21 mm on skin. The degree of agreement for all inter-canine measurements is high, regardless of the type of arch or skull (superior-inferior or mesocephalic-dolichocephalic-brachycephalic). Conversely, the agreement for incisor-to-canine measurements is high in measurements obtained from the lower arches and brachycephalic skulls. Considering the promising results shown by the morphological and morphometric analysis reported in the study, a multidisciplinary approach, fostering collaboration between forensic experts in pathology, dentistry, anthropology, DNA and veterinary medicine, is essential for a comprehensive evaluation of bite marks.

1. Introduction

Dog attacks on humans represent a global issue with significant health and medico-legal implications [1]. The majority of these aggressive incidents (70–80 %) occur against the animal's owners or family members within their own homes or gardens. Children are particularly vulnerable, with injuries predominantly affecting the head, neck, and facial regions. The second most affected demographic is individuals over 70 years old, who primarily sustain injuries to their extremities [2–13].

A dog attack may cut or puncture a victim's skin resulting in distinctive lesions mimicking the morphology of the dentition that created it [14–21]. A dog's deciduous dentition begins to erupt between 20 and 35 days and is replaced by the permanent teeth between 3 and 7 months of age, although the chronology of dental development shows a wide variability among dog breeds [22]. Permanent dentition consists of 42 permanent teeth: 20 in the upper arch (6 incisors, 2 canines, 8 premolars, and 4 molars) and 22 in the lower arch (6 incisors, 2 canines, 8 premolars, and 6 molars) [23–26].

Incisors, due to their reduced thickness and linear margin, produce typical linear and continuous ecchymotic-excoriative lesions. Canine teeth, with their conical shape and sharp, curved cusp, pierce and tear tissues through a mechanism known as 'hole and tear,' resulting in four puncture wounds corresponding to each tooth. Premolar and molar

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Table 1
Breed, Cephalic Index and size of the dogs involved in the study.

Dog number	Breed	Cephalic Index	Dog Size
1	English Spaniel	Dolichocephalic	Small
2	English Setter	Dolichocephalic	Medium
3	Breton Spaniel	Dolichocephalic	Medium
4	Golden retriever	Mesocephalic	Large
5	Border collie	Dolichocephalic	Medium
6	Siberian Husky	Dolichocephalic	Medium
7	Mixed breed	Mesocephalic	Small
8	Mixed breed	Mesocephalic	Medium
9	Pekingese	Brachycephalic	Small
10	Mixed breed	Mesocephalic	Medium
11	German shepherd	Dolichocephalic	Large
12	Maremma Sheepdog	Dolichocephalic	Large
13	Pekingese	Brachycephalic	Small
14	Poodle	Dolichocephalic	Small
15	Cavalier King Charles Spaniel	Mesocephalic	Small
16	Labrador retriever	Dolichocephalic	Large
17	French Bulldog	Brachycephalic	Small
18	Mixed breed	Mesocephalic	Large
19	Pekingese	Brachycephalic	Small
20	Mixed breed	Mesocephalic	Medium

teeth, characterized by their elongated and cuboid shape, respectively, and large surface area, contact the skin more extensively [14–16,21,27].

Another factor influencing canine dentition conformation is the Cephalic Index (CI) of the specific animal, calculated by multiplying the cranial width by 100 and dividing the result by the cranial length [11]. According to this classification, dolichocephalic dogs have a cranial length that exceeds the width; mesocephalic dogs have relatively similar cranial length and width measurements; and brachycephalic dogs have a cranial width that exceeds the length.

In cases of fatal or severe injuries caused by dogs, forensic pathologists may be asked to conduct a thorough investigation of the victim's injuries in order to compare them morphologically and morphometrically with the dentition of the suspected dogs. Analysing the compatibility of dog bite marks is exceedingly intricate due to numerous variables involved in wound dynamics. However, in instances where multiple points of concordance exist, dog identification can be provided [9–12,16,17,28,29]. The primary parameter under evaluation is the inter-canine distance, representing the space between two canine teeth within the same dental arch. Given that these teeth are the longest and conical, they are the most likely to inflict skin lesions [29]. This measurement varies based on the dog skull size and differs among breeds, typically ranging from 20 mm to 65 mm for the upper arch and 18 mm to 49 mm for the lower arch [20]. However, a limitation arises when suspected dogs have similar skull sizes, particularly among adults of the same breed [9,20,30]. Furthermore, no studies have been identified that experimentally analyze bite marks on human tissues, despite experimental data on human tissue bite marks could provide valuable insights into forensic investigations.

The aim of this experimental study is to conduct a morphometric comparison between the dental measurements of canine teeth from 20 different dogs and the skin lesions produced on human tissue.

2. Materials and methods

Bite lesions were experimentally produced on the skin of amputated human limbs by 20 dogs that differed in size and Cephalic Index (CI) (Table 1). The CI is calculated by multiplying the cranial width by 100 and dividing the product by the cranial length. The resulting classification is dolichocephalic ($CI < 50$), mesocephalic ($50 < CI < 60$), and brachycephalic ($CI > 60$) [31].

Dog skulls were obtained from veterinary necropsies conducted at the Department of Veterinary Medical Sciences of the University of Bologna and stored in a freezer at −20 °C. Amputated limbs were procured from the Orthopedic and Vascular Surgery Departments, then stored in cold storage at a temperature of + 4 °C. Dog skulls and limbs were unfrozen and brought to room temperature before implementing bite marks. Limbs devoid of cutaneous lesions in the targeted bite mark region were selected for inclusion in the study. Ethical approval was granted by the Bioethics Committee (protocol number 0366808). Bite lesions were produced applying pressure from the upper and lower jaws

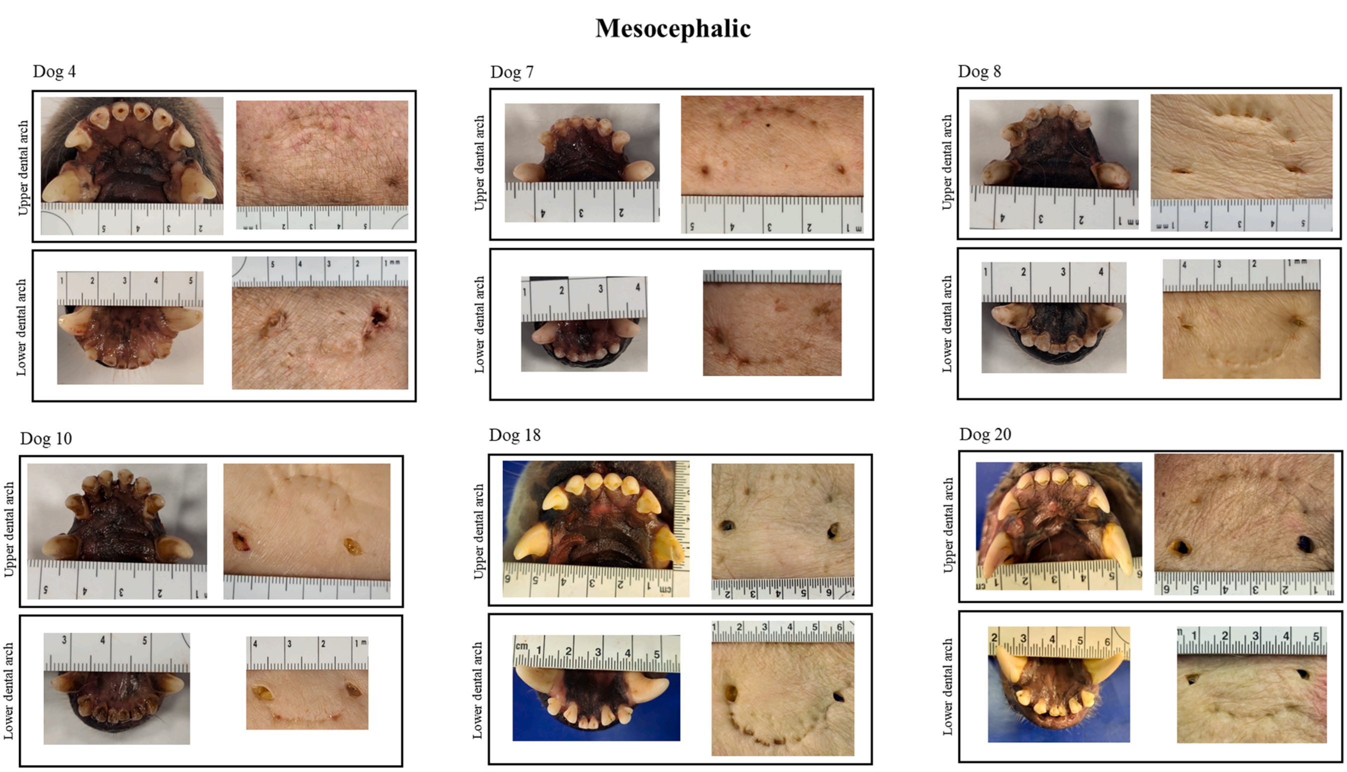

Fig. 1. Compared photographs in the study of mesocephalic dogs.

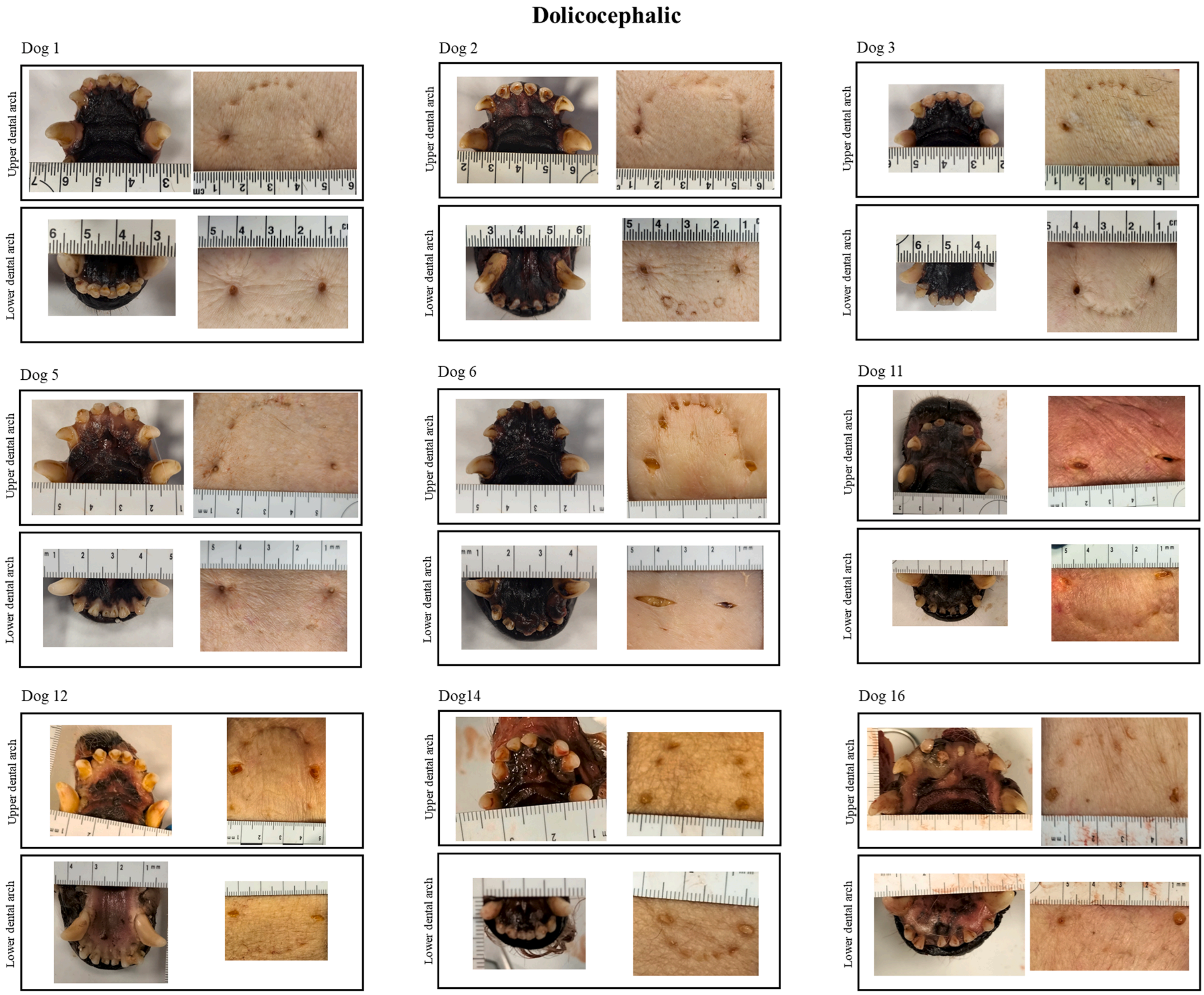

Fig. 2. Compared photographs in the study of dolicocephalic dogs.

of each specimen onto the skin, until full penetration of the canine teeth. The amount of pressure was not measured. Bites were imprinted perpendicularly on the posterior surface of the calf to avoid interaction with the tibial bone.

Subsequently, the morphological and metric attributes of the teeth and their respective bite lesions, generated by each of the twenty dog specimens, were examined and photographed in color and high definition. The study focused specifically on evaluating the bite marks of the anterior teeth (incisors and canines) because these are the ones that are reported in the literature to be easiest to identify, while the molar teeth result in more irregular lesions that are difficult to interpret. The assessed morphological parameters were: canine teeth and incisors number and characteristics (well-shaped or worn out), characteristics of the lesion produced (shape and type of lesion, namely circular, oval, rectangular). Two metric parameters were assessed: 1) "inter-canine distance", referring to the space between the two cusps of the canines on each jaw at the dental level, and the distance between the two lesions corresponding to the action of the two canines on each jaw at the skin level [9,30,32]. The average values for the upper arch range from a minimum of 13 mm to a maximum of 48 mm, and for the lower arch from 6 mm to 49 mm [20]; 2) "interdental incisor-canine distance", indicating the distance between the cusps of the canine and of the adjacent incisor at the dental level, and the distance between the two lesions corresponding to the action of the canine and the adjacent incisor at the skin level.

The mean difference between teeth and bite mark distances was evaluated with the paired *t*-test, while agreement between measurements was assessed with Lin's concordance correlation coefficient [33,34]. This coefficient combines measures of both precision and accuracy to evaluate the deviation of the observed data from the line of perfect concordance (i.e., the 45-degree line in a square scatter plot). The value of Lin's coefficient increases as a function of the proximity of the data's reduced major axis to the line of perfect concordance (accuracy) and the tightness of the data around its reduced major axis (precision). All analyses were stratified by dental arch (upper or lower), cephalic index (brachycephalic, dolichocephalic, or mesocephalic), and, where applicable, side (right or left). Parametric methods were applied despite the small sample size, as normality of the data was confirmed using the Shapiro-Wilk test and normal Q–Q plots. All data were analyzed using Stata 18 (StataCorp. 2023. Stata Statistical Software: Release 18. College Station, TX: StataCorp LLC.). The significance level was set at 0.05, and all tests were two-sided.

3. Results

For each dog, photographs of the dentition and bite mark were

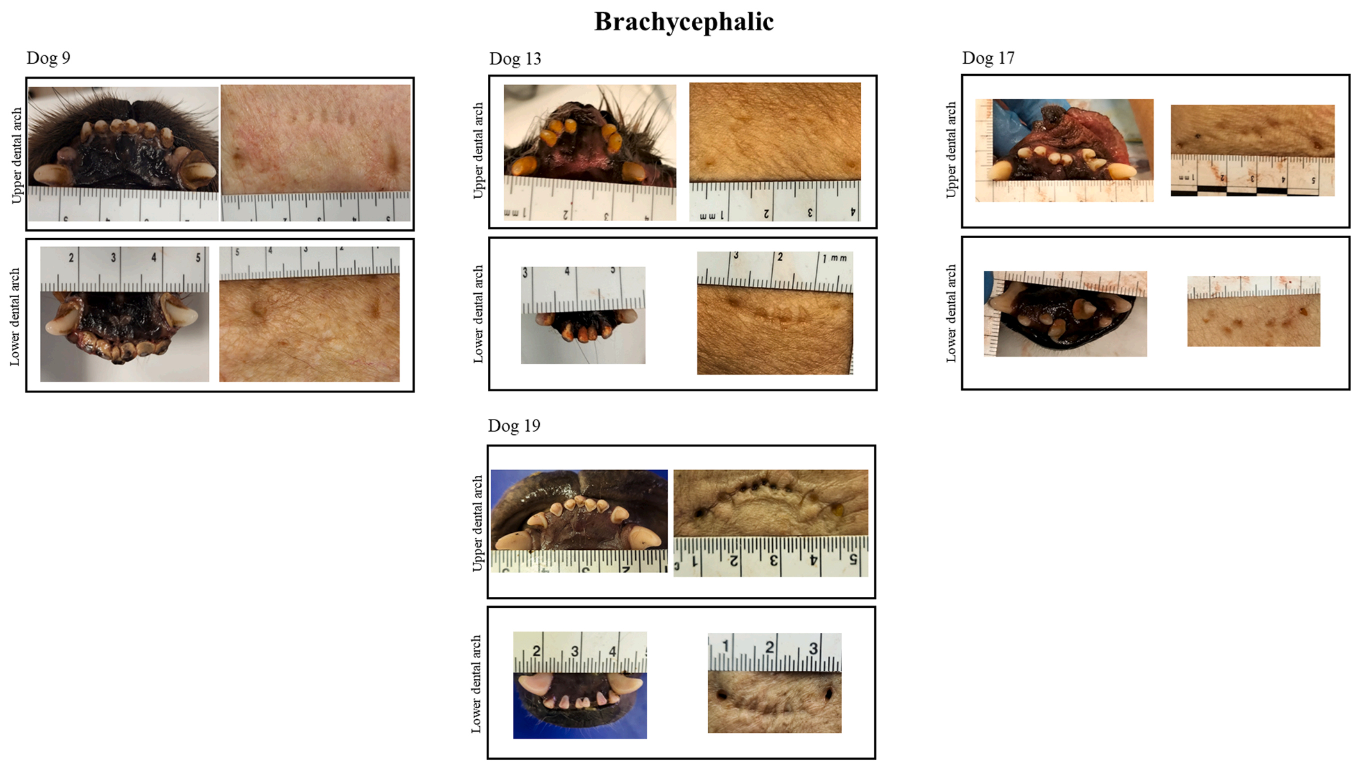

Fig. 3. Compared photographs in the study of brachycephalic dogs.

obtained and compared (Figs. 1–3). The results of the morphological analysis of the dogs' dentitions and corresponding skin lesions and are detailed in Table 2. It is emphasized that the morphology of lesions predominantly caused by incisors, characterized by skin depressions, differs from those observed in real-life cases involving living subjects. This discrepancy is attributed to the altered muscle configuration resulting from amputation, as well as the absence of an immune response and bleeding.

The inter-canine and interdental incisor-to-canine distance measurements of all specimens performed on the dentitions and skin lesions are summarized in Tables 3 and 4: inter-canine measures ranged between 21 and 52 mm on dentition and 20–53 mm on skin; incisor-to-canine measures ranged between 5 and 21 mm on dentition and 4–21 mm on skin. Each measurement at both dentition and skin level was performed three times to reduce the variance in measurement error. The measurements presented in the Tables 3 and 4 were consistently taken using the same measuring ruler. The values shown in the table represent the average of the three measurements taken.

The statistical results are presented in Tables 5 and 6, which respectively analyze the agreement between inter-canine and incisor-to-canine distance measurements obtained from the comparison of dentition and bite marks. The degree of agreement for all inter-canine measurements is high (p-value < 0.001 for all concordance correlation coefficients), regardless of the type of arch or skull (superior-inferior or mesocephalic-dolichocephalic-brachycephalic). Notably, the mean difference remains close to zero across all stratified analyses, while the concordance correlation coefficient approaches 1, indicating near-perfect agreement between measurements. Conversely, the agreement for incisor-to-canine measurements is less robust. Mean differences close to zero and concordance correlation coefficients near 1 are observed only in comparisons involving data from lower arches and brachycephalic skulls.

4. Discussion

The analysis of bite marks is a complex and delicate task, still the subject of ongoing research due to the numerous variables that influence the dynamics of wound production. These variables include the positions and movements of the dog and the victim, the anatomical location of the wound, tissue resilience, the pressure applied, and possible post-mortem changes [30,35–39]. There are also studies in the literature on the differential diagnosis of bite wounds caused by animals as opposed to humans, an evaluation which is crucial for the subsequent court implications [17,36]. For this reason, the morphological analysis of bite marks should be conducted jointly by forensic pathologists and veterinarians, using wound measurements, dental casts, or computational xerography-assisted techniques as reference data [30]. It is further recommended that the results of morphological odontological analysis be integrated, where possible, with genetic analysis. This is especially relevant for the examination of salivary biological material found on the victim's skin during the attack, as it allows for the identification of the specific specimen responsible for the bite [14,40].

In the present experimental study bite marks produced using dog skulls on human calves were investigated and compared to the related canine dentition. Bite marks were produced on calves by applying pressure from the upper and lower jaws of each specimen onto the skin until canine teeth penetrated, as described in detail in the Section 2. As the study aimed to investigate morphological features, the monitoring of the pressure applied by each jaw was not implemented, which represents a limitation of this research. The resulting lesion consisted of an impression of incisors on the skin associated to two holes produced by the penetration of the canines. A complete impression of all frontal teeth is considered an ideal circumstance for bite mark analysis although more often only a prominent canine impression [17] or multiple tear wounds with adjacent puncture wounds ("hole-and-tear" effect) can be seen.

In the experimental setting, potential confounding factors, such as lacerations and avulsion of skin and other soft tissues, which significantly compromise tissue integrity, were eliminated. This could be seen as a limitation of the study, as these features are commonly observed in real cases. However, it was considered the most reliable method for performing a morphometric analysis, which could be useful in forensic settings when the bite mark is not irreparably altered. Therefore, the

Table 2
Results of the morphological analysis of the dogs' dentitions and corresponding skin lesions. For each dog, the first row indicates the upper dental arch (U) and the second row the lower dental arch (L). The number and degree of wearing of the canine and incisor teeth are reported, together with the number, shape and characteristics of the corresponding skin lesions.

Dog number	Canine characteristics	Characteristics of the lesion produced by canine	Incisor characteristics	Characteristics of the lesion produced by incisors
1 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	5 rectangular depressions and 1 circular depression (third right incisor)
1 L	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	6 circular depressions
2 U	2 worn out teeth	2 circular puncture wounds	6 worn out teeth	6 circular depressions
2 L	2 worn out teeth	2 circular puncture wounds	5 worn out teeth (2 right, 2 left, 1 median)	5 circular depressions
3 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
3 L	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
4 U	2 worn out teeth	2 circular depressions	6 worn out teeth	6 rectangular depressions
4 L	2 worn out teeth	2 irregular puncture wounds	6 worn out teeth	6 rectangular depressions
5 U	2 worn out teeth	2 circular depressions	6 worn out teeth	6 rectangular depressions
5 L	2 worn out teeth	2 circular depressions	6 worn out teeth	6 rectangular depressions
6 U	2 worn out teeth	2 oval puncture wounds	6 sharp teeth	6 circular puncture wounds
6 L	2 worn out teeth	2 oval puncture wounds	6 non-worn out teeth	6 circular depressions
7 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 rectangular depressions
7 L	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
8 U	2 worn out teeth	2 oval puncture wounds	6 worn out teeth	6 rectangular depressions
8 L	2 worn out teeth	2 oval puncture wounds	6 worn out teeth	6 rectangular depressions
9 U	2 worn out teeth	2 circular depressions	8 worn out teeth	5 circular depressions
9 L	2 worn out teeth	2 circular depressions	6 worn out teeth	No bite mark
10 U	2 well-pointed teeth	2 oval puncture wounds	6 non-worn out teeth	6 rectangular depressions
10 L	2 well-pointed teeth	2 oval puncture wounds	6 worn out teeth	6 rectangular depressions
11 U	2 well-pointed teeth	2 oval puncture wounds	5 worn out teeth (3 right, 2 left)	5 rectangular depressions
11 L	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	6 rectangular depressions
12 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
12 L	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 rectangular depressions

Table 2 (*continued*)

Dog number	Canine characteristics	Characteristics of the lesion produced by canine	Incisor characteristics	Characteristics of the lesion produced by incisors
13 U	2 well-pointed teeth	2 circular puncture wounds	5 non-worn out teeth (3 right, 2 left)	5 circular depressions
13 L	2 well-pointed teeth	2 circular depressions	4 worn out teeth (2 right, 2 left)	4 rectangular depressions
14 U	2 well-pointed teeth	2 circular puncture wounds	5 non-worn out teeth (3 right, 2 left)	4 circular depressions
14 L	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 rectangular depressions
15 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 rectangular depressions
15 L	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
16 U	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	6 circular depressions
16 L	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	4 anterior rectangular depressions and 2 posterior circular depressions
17 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
17 L	2 well-pointed teeth	2 circular puncture wounds	5 non-worn out teeth (3 right, 2 left)	5 circular depressions
18 U	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	6 rectangular depressions
18 L	2 well-pointed teeth	2 circular puncture wounds	5 worn out teeth (2 right, 3 left)	5 circular depressions
19 U	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	6 rectangular depressions
19 L	2 well-pointed teeth	2 circular puncture wounds	6 worn out teeth	6 rectangular depressions
20 U	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 circular depressions
20 L	2 well-pointed teeth	2 circular puncture wounds	6 non-worn out teeth	6 rectangular depressions

morphometric criteria obtained in this experimental study are still expected to be valuable in forensic setting. These criteria could potentially be applied to incomplete skin impressions and in cases of dog pack attacks: usually dogs tend to drag their victims down, initially biting the lower limbs, and this setting can resemble our experimental conditions. In case of attacks involving more dogs, the identification of the dog initiating the aggression, actually biting the victim or provoking the fatal injury might become legally relevant. Indeed, it has been suggested that in a pack situation, once an aggressive act is initiated, dogs which singly taken are docile, may join in and the pack instinct escalates the attack until the victim's death [28]. A significant limitation of reproducing dog bites on non-vital tissue is the inability to observe bleeding and inflammatory reactions, such as ecchymosis and abrasions, at the skin level caused by the action of the teeth. Indeed, only depressions corresponding to the incisor marks were observed, with no evidence of vital skin reactions.

In our experimental setting, we chose to apply pressure to each dog's

Table 3
Intercanine distance measurements (mm) of teeth and bite marks.

Dog number and dental arch	Cephalic Index	Dental arch	Intercanine distance (dog)	Intercanine distance (bite mark)
1	Dolicho	Upper	35	35
		Lower	30	31
2	Dolicho	Upper	40	41
		Lower	35	34
3	Dolicho	Upper	30	31
		Lower	28	29
4	Meso	Upper	52	53
		Lower	40	40
5	Dolicho	Upper	45	45
		Lower	39	40
6	Dolicho	Upper	38	39
		Lower	35	35
7	Meso	Upper	35	36
		Lower	28	29
8	Meso	Upper	35	36
		Lower	32	33
9	Brachy	Upper	47	47
		Lower	33	34
10	Meso	Upper	35	34
		Lower	30	29
11	Dolicho	Upper	43	40
		Lower	46	41
12	Dolicho	Upper	41	39
		Lower	39	37
13	Brachy	Upper	32	33
		Lower	22	23
14	Dolicho	Upper	26	24
		Lower	21	20
15	Meso	Upper	38	39
		Lower	29	30
16	Dolicho	Upper	42	44
		Lower	47	46
17	Brachy	Upper	48	47
		Lower	34	33
18	Meso	Upper	52	53
		Lower	40	40
19	Brachy	Upper	32	33
		Lower	22	23
20	Meso	Upper	40	41
		Lower	35	34

jaws until their canines penetrated the skin, rather than using a uniform force for each experimental bite. This approach was chosen because the pressure applied to the jaws of a specific dog varies according to the size of the animal, breed, cephalic index and size of the upper to lower dentition. For instance, large breed dogs can generate forces exceeding 1394 N during an attack, while small breed dogs exert significantly weaker forces [39]. Consequently, it was decided not to apply a predetermined level of pressure. Instead, each bite was carried out until the canine teeth perforated the skin, thereby allowing the incisors to also leave impressions on the surface.

In fact, our sample included a wider range of breeds, not limited solely to those traditionally labeled as "dangerous". Indeed, while certain breeds, such as Pit Bulls, Rottweilers, German Shepherds, Siberian Huskies, Doberman Pinschers, and even Cocker Spaniels, have gained notoriety for attacks on humans, despite the so-called "dangerous breeds" are not necessarily the most common culprits in bite incidents. The research therefore included a variety of dog breeds, not only those commonly regarded as dangerous, but also other widely distributed breeds, in order to obtain the broadest and most diverse sample possible.

Morphological analysis revealed that canines consistently produced almost circular puncture wounds in all cases, whereas incisors produced skin depressions of circular or rectangular shape. These depressions were clearly visible when the incisors had a well-pointed surface, but were difficult to detect, particularly in photographic records, when the teeth were blunt or showed greater wearing. These findings are consistent with the literature, which suggests that canines typically produce four puncture wounds corresponding to each tooth element [15,16,21,27]. Conversely, incisors, due to their linear lower edge and minimal thickness, typically induce linear, continuous ecchymotic-abrasive lesions in living subjects [14–16]. In this study, however, the lesions produced by incisors consisted solely of skin depressions without ecchymoses or abrasions due to the use of post-mortem human tissue.

Dogs may exhibit peculiar dental features, which can include missing or fractured teeth, supernumerary teeth, misaligned teeth or abnormal teeth. While the variation in the number of dental elements might be due to various aetiologies, in our study sample such as anatomical variations were consistently observed in the bite mark. Specifically, six dogs had five incisors (instead of six), and similarly there were five depressions in the bite mark; one dog had only four incisors, and correspondingly the bite mark showed four depressions. Also in the present study, where teeth showed morphological features related to number and placement, it was possible to speculate on the dog involved from the analysis of the bite mark. This is consistent with previous reports in the literature [16,17,28].

Regarding metric analysis, the study investigated both inter-canine and incisor-to-canine distance. The degree of agreement for all inter-canine measurements is high, regardless of the type of arch or skull (superior-inferior or mesocephalic-dolichocephalic-brachycephalic). Conversely, the agreement for incisor-to-canine measurements is high in measurements obtained from the lower arches and brachycephalic skulls. It can be speculated that the promising results for inter-canine distance are attributable to its relatively greater length compared to other dental measurements, which facilitates more precise assessment using a millimeter ruler. Furthermore, the distinctive shape of the canine cusp and the well-defined morphology of the corresponding wound tip enhance the ease and accuracy of this measurement. Conversely, high agreement for incisor-to-canine measurements is observed only in data obtained from lower arches and brachycephalic skulls. Consequently, the study suggests that the use of this second measurement for dentition-bite mark compatibility analysis is advisable exclusively under these two conditions. This approach may be particularly relevant in cases of pack attacks, where inter-canine measurements could be identical among different specimens. In such scenarios, the comparison of incisor-to-canine measurements in suspected brachycephalic dogs could play a decisive role in identifying the responsible animal.

However, if both the inter-canine and incisor-to-canine measurements overlap in the dentition and correspond to the bite mark, bite mark analysis alone cannot distinguish between two or more dog specimens. Therefore, while the study offers valuable forensic insights into dentition and bite mark comparison, when the dental conformations of two or more dogs are identical, genetic analysis becomes the only reliable method for identifying the specific dog.

Moreover, the present study does not permit conclusions regarding which dog breed yields the most reliable dentition-bite mark comparisons. Such an analysis would require data from multiple specimens of the same breed. In this study, however, it was only possible to compare the different cranial index values characterizing the species involved.

Thus, in real-world scenarios, therefore, several steps are required to obtain the necessary information for the dentition-bite mark comparison. Initially, the assessment of dental formulas, focusing on distinctive features such as missing or fractured teeth, may facilitate inferences regarding potential suspect dogs. Subsequent analysis may involve measuring inter-canine distance and, if necessary, incisor-to-canine distance. Ultimately, a direct comparison of the entire dental arch is required for definitive identification. This process typically requires obtaining a cast of the dog's dental arches, a task requiring sedation and presenting challenges due to the incompatibility of standard odontological tools with canine dentition and the extreme morphological variability of dog breeds. Both direct comparison of dental casts with the bite mark and indirect methods, such as photographic analysis or xerography, are employed. To improve the precision and accuracy of morphometric evaluation of dental characteristics and bite mark

Table 4
Incisor-to-canine interdental distance measurements (mm) of teeth and bite marks.

Dog number and dental arch	Cephalic Index	Dental arch	Incisor-to-canine interdental distance Right hemiarch (dog)	Incisor-to-canine interdental distance Right hemiarch (bite mark)	Incisor-to-canine interdental distance Left hemiarch (dog)	Incisor-to-canine interdental distance Left hemiarch (bite mark)
1	Dolicho	Upper	15	15	15	12
		Lower	7	10	7	10
2	Dolicho	Upper	15	5	18	7
		Lower	10	13	10	13
3	Dolicho	Upper	13	13	13	12
		Lower	9	7	9	10
4	Meso	Upper	15	15	15	17
		Lower	10	10	10	9
5	Dolicho	Upper	12	13	12	13
		Lower	10	13	10	11
6	Dolicho	Upper	12	12	12	15
		Lower	10	8	10	8
7	Meso	Upper	10	13	10	13
		Lower	7	8	7	6
8	Meso	Upper	10	9	20	20
		Lower	10	11	10	12
9	Brachy	Upper	13	15	10	13
		Lower	15	13	15	12
10	Meso	Upper	15	15	15	17
		Lower	10	8	10	8
11	Dolicho	Upper	18	16	21	21
		Lower	15	11	15	15
12	Dolicho	Upper	11	15	11	13
		Lower	11	15	11	13
13	Brachy	Upper	10	10	10	11
		Lower	7	7	7	8
14	Dolicho	Upper	8	7	8	10
		Lower	5	6	7	5
15	Meso	Upper	12	11	10	12
		Lower	9	8	9	10
16	Dolicho	Upper	16	13	15	12
		Lower	13	13	13	13
17	Brachy	Upper	12	13	11	10
		Lower	10	7	8	4
18	Meso	Upper	15	15	15	17
		Lower	10	10	10	9
19	Brachy	Upper	10	10	10	11
		Lower	7	7	7	8
20	Meso	Upper	15	5	18	7
		Lower	10	13	10	13

Table 5
Agreement between inter-canine distance measurements (mm) obtained from teeth vs. bite marks.

	n	Mean Difference			CCC		
		Est.	95 % CI	*p*-value	Est.	95 % CI	*p*-value
All	40	0.00	−0.45, 0.45	1.000	0.983	0.968, 0.991	< 0.001
Dental Arch							
Upper	20	0.20	−0.42, 0.82	0.507	0.983	0.957, 0.993	< 0.001
Lower	20	−0.20	−0.91, 0.51	0.560	0.976	0.947, 0.989	< 0.001
Cephalic Index							
Brachycephalic	8	0.38	−0.39, 1.14	0.285	0.994	0.980, 0.998	< 0.001
Dolichocephalic	18	−0.50	−1.39, 0.39	0.252	0.966	0.914, 0.987	< 0.001
Mesocephalic	14	0.43	−0.06, 0.92	0.082	0.992	0.976, 0.997	< 0.001

CCC, Concordance Correlation Coefficient.

analysis, future studies should focus on adopting more sensitive and precise measurement techniques, such as three-dimensional scanning systems.

Given the promising results of the morphological and morphometric analysis reported in the study, a multidisciplinary approach is essential for a comprehensive bite mark assessment. This approach should promote collaboration among various forensic specialists, including pathologists, dentists, anthropologists, geneticists, and veterinarians. While this experimental study can assist in interpreting real-world bite mark cases, it's important to note that our findings may not directly translate to actual bite injuries. The process of producing bite marks in a controlled setting is fundamentally different from real-world scenarios, lacking factors such as inflammation, active bleeding, and the dynamic complexities of natural muscle attachments.

5. Conclusions

Morphometric analysis of the inter-canine distance is a valuable method for establishing correspondence between canine dentition and anterior bite injuries under these experimental conditions. Additionally, based on our experimental study, incisor-to-canine interdental distance show high agreement for incisor-to-canine measurements only in data

Table 6
Agreement between incisor-to-canine distance measurements (mm) obtained from teeth vs. bite marks.

	n	Mean Difference			CCC		
		Est.	95 % CI	*p*-value	Est.	95 % CI	*p*-value
All	80	−0.23	−0.90, 0.45	0.512	0.589	0.426, 0.715	< 0.001
Dental Arch							
Upper	40	−0.58	−1.78, 0.63	0.339	0.373	0.081, 0.606	0.013
Lower	40	0.13	−0.56, 0.81	0.712	0.670	0.461, 0.809	< 0.001
Cephalic Index							
Brachycephalic	16	−0.19	−1.22, 0.85	0.704	0.756	0.438, 0.905	< 0.001
Dolichocephalic	36	−0.25	−1.37, 0.87	0.655	0.535	0.257, 0.732	< 0.001
Mesocephalic	28	−0.21	−1.49, 1.06	0.733	0.556	0.244, 0.764	0.001
Side							
Right	40	−0.35	−1.29, 0.59	0.457	0.541	0.283, 0.726	< 0.001
Left	40	−0.10	−1.12, 0.92	0.844	0.621	0.388, 0.780	< 0.001

CCC, Concordance Correlation Coefficient.

obtained from lower arches and brachycephalic skulls. Therefore, it can be considered a valuable aid, particularly in cases involving multiple suspects with similar inter-canine distances. However, if both the inter-canine and incisor-to-canine measurements overlap in the dentition and correspond to the bite mark, bite mark analysis alone cannot distinguish between two or more dog specimens. In these cases genetic analysis becomes the only reliable method for identifying the specific dog.

CRediT authorship contribution statement

Mariana Roccaro: Writing – original draft, Formal analysis, Data curation. **Annamaria Grandis:** Formal analysis, Data curation. **Guido Pelletti:** Formal analysis, Data curation. **Jacopo Lenzi:** Writing – review & editing, Formal analysis. **Angelo Peli:** Writing – original draft, Supervision, Conceptualization. **Paolo Fais:** Writing – original draft, Supervision, Conceptualization. **Susi Pelotti:** Writing – original draft, Supervision, Conceptualization. **Simone Bianchini:** Writing – original draft, Investigation, Formal analysis, Data curation. **Elena Giovannini:** Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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