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COMPARING CONVENTIONAL RADIOGRAPHY AND COMPUTED TOMOGRAPHY IN FELINE HEAD TRAUMA: IMPACT OF VISUAL TRAINING ON FRACTURE DETECTION

RADIOLOGIA CONVENZIONALE E TOMOGRAFIA
COMPUTERIZZATA A CONFRONTO NEL TRAUMA CRANICO
DEL GATTO: IMPATTO DI UN TRAINING VISIVO
SULL'IDENTIFICAZIONE DELLE FRATTURE

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ABSTRACT

Head trauma is a frequent cause of morbidity and mortality in domestic cats. The gold standard for evaluating craniomaxillofacial injuries is represented by computed tomography (CT). Conventional radiography (RX), although limited by anatomical superimposition, remains the most accessible first-line imaging modality in emergency triage.

This retrospective study compared the diagnostic performance of RX and CT in identifying feline skull fractures. It also assessed whether a targeted CT-guided visual training protocol (“educated eye”) could improve radiographic fracture detection.

A cohort of 18 feline polytrauma cases with paired RX and CT examinations was evaluated to quantify the discrepancy between the two modalities. After a wash-out period of more than three weeks, a side-by-side training protocol using CT reconstructions from five cases was completed. To minimize recall bias and assess learning generalizability, the radiographic re-evaluation of the neurocranium and temporomandibular joint (TMJ) was structured as a primary analysis on 13 independent non-training cases, a separate descriptive analysis on the 5 cases used for training, and a secondary full-cohort analysis including all 18 cases. The 18-case analysis was interpreted descriptively in comparison with the independent 13-case test set, because the two samples are overlapping rather than independent.

At baseline, RX identified only 36.1% of all CT-confirmed fractures (43/119), and sphenoid fractures were completely missed. In the primary analysis of 13 independent test cases, visual training significantly improved global fracture detection (exact Wilcoxon signed-rank test:

$Z = -2.392$, two-tailed $P = 0.016$), with 53.8% of cats (7/13) showing an increased number of correctly identified structures. In the secondary full-cohort analysis, 66.7% of cats (12/18) improved and none worsened ($Z = -3.109$, exact two-tailed $P < 0.001$). Descriptively, across the five structures included in the training analysis, 14 of 48 CT-positive patient-structure observations were recognized before training (29.2%) and 34 of 48 after training (70.8%). Most notably, sphenoid sensitivity increased from 0.0% to 66.7% in the full cohort (exact two-tailed McNemar $P = 0.008$).

In conclusion, radiographic limitations in feline skull trauma are heavily influenced by examiner perception. When interpreted by an educated eye, RX becomes a valuable diagnostic tool when advanced imaging is unavailable or delayed. However, conventional radiography cannot replace CT for comprehensive surgical planning or soft-tissue evaluation.

INTRODUCTION

Anatomy of the Feline Skull

Normal Anatomy of the Feline Skull

The skull is a specialized structure mainly composed of flat bones that protect the brain. It houses the sensory organs and supports the respiratory and digestive systems. Topographically, the skull is divided in the *neurocranium*, which forms the cranial vault and base to protect the central nervous system, and the *splanchnocranium* (or facial skeleton), which includes the jaws and nasal structures.

Compared to other domestic animals like dogs, a characteristic feature of the feline skull is its rounded shape combined with a relatively shortened facial region (Tundo *et al.*, 2019).

Neurocranium:

- The frontal bones are paired; they form the rostral region of the skull roof and extends over approximately half of the cranium length. Each bone includes a squamous part, a zygomatic process and an orbital plate that contributes to the medial wall of the orbit.
- The temporal bone is paired; it forms the lateral wall of the skull and is divided into a squamous part, thin and flat, and a petrous part. The latter holds the structures of the inner ear, such as the cochlea and vestibular apparatus. It also contains the tympanic bulla, housing the middle ear.
- The parietal bones are paired; these bones form the dorso-caudal and lateral walls of the cranium, located between the frontal and occipital bones.
- The inter-parietal bone is single. It is located between the parietal and occipital bones; only in cats a suture remains visible after physiological fusion.
- The ethmoid bone is single; it is positioned deeply between the orbits. This bone forms the cranial, nasal, and paranasal cavities. Its cribriform plate allows the passage of the olfactory nerves.
- The sphenoid bone is single and located at the base of the cranium. It is divided into basi-sphenoid and pre-sphenoid, which is pneumatized and contains sinuses.

- The occipital bone is single and forms the caudal wall of the skull. This bone "contains the *foramen magnum*, through which the spinal cord passes to connect with the brainstem" (Bhamburkar & Banubakode, 2021, p. 68). It also has large condyles for the articulation with the atlas.

(König and Liebich, 2020; Bhamburkar and Banubakode, 2021)

Splanchnocranium:

- The maxilla is paired and it is the largest bone of the upper jaw. It forms the lateral walls of the face and most of the hard palate. These bones house the canine, premolar, and molar teeth.
- The incisive bone is paired, and it forms the upper jaw in its rostral portion. It houses the incisors in the incisive part of the dental arch.
- The palatine bones are paired. These bones extend on either side of the caudal nostrils, forming the caudal part of the hard palate and the lateral walls of the nasopharynx.
- The nasal bones are paired and form the dorsal base of the nose. These bones possess a convex external surface and a concave internal surface.
- The lacrimal bones are paired, and they are a small bone located on the rostral part of the orbit floor. These bones include the lacrimal fossa, which houses the lacrimal sac.
- The zygomatic bones are paired triangular bones forming the lateral boundary and floor of the orbit. The zygomatic arch is formed by the temporal process of the zygomatic bone articulating with the zygomatic process of the temporal bone.
- The vomer is a single thin plate-like bone that forms the caudal nasal septum, which divides the nasal cavities into two channels.
- The pterygoid bones are paired and small. These flat bones are located at the caudal part of the nasal cavity that contribute to the walls of the nasopharynx.
- "The mandible consists of two halves joined by a fibrocartilaginous symphysis" (Woodbridge & Owen, 2013, p. 212). In cats, this symphysis is a synchondrosis that does not typically undergo complete bony fusion. Each mandible consists of a vertical ramus and a horizontal body, which houses the lower teeth (Woodbridge and Owen, 2013). The ramus features three distinct processes: the angular, the coronoid for muscle insertion and

the condylar for the articulation with the temporal bone to form the temporomandibular joint (TMJ). (Constantaras and Charlier, 2014) (König and Liebich, 2020; Bhamburkar and Banubakode, 2021)

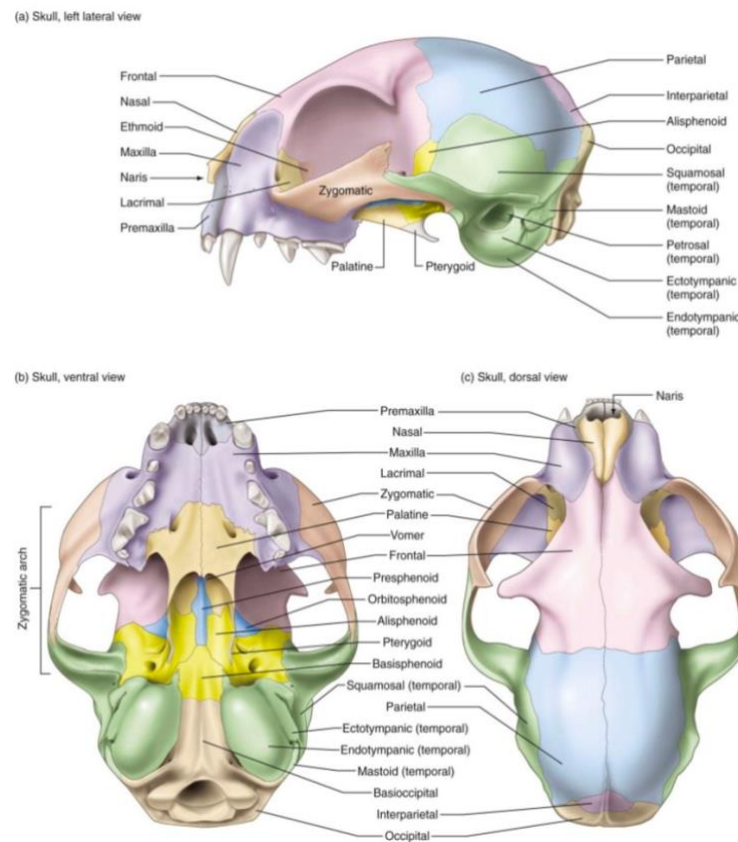


Figure 1: colour-coded cranial bones of the cat in left lateral (a), ventral (b) and dorsal (c) views (De Iuliis; Pulerà, 2011)

Cranial Bones of Traumatological Interest

Head trauma is a primary cause of morbidity and mortality in feline patients, studies indicate that approximately “27% of all trauma-related fractures involve the skull” (Knight & Meeson, 2019, p. 1120). The feline skull has a unique and specialized morphology that acts as a sophisticated mechanical defence system. This system is designed to preserve the integrity of the central nervous system during impacts (Zanotti, 2024). The high degree of structural resilience is also achieved thanks to the rounded conformation of the cat’s skull combined with thicker facial bones and more tightly spaced structures (Tundo *et al.*, 2019; Zanotti, 2024).

The fundamental principle of cranial protection in cats is the "sacrificial" role of the facial skeleton (Tundo *et al.*, 2018). A retrospective study conducted by Zanotti (2024) on patients from the University Veterinary Teaching Hospital (OVUD) of the University of Parma, shows that fractures predominantly involve the *splanchnocranium*. Indeed, facial injuries affect approximately 90.5% of cats with head trauma. Biomechanically, the energy of the impact is absorbing and dispersing

by the protective barrier formed by the greater rigidity of the facial bones (Tundo et al., 2018). This results into a decreased risk of serious brain damage, as “traumatic forces are more likely to cause fractures in the facial bones rather than directly impacting the brain” (Zanotti, 2024, p. 59). This high prevalence is consistent with published feline head-trauma series reporting frequent facial and mandibular injury patterns (Tundo et al., 2019; Knight & Meeson, 2019).

This protective function is supported by comparative studies showing that cats are more inclined to facial and skull base fractures than dogs. Moreover, cats with fractures isolated strictly to the facial region are significantly less likely to develop neurological signs (Amengual-Batle et al., 2020).

The mid-face region, specifically the nasal cavity and paranasal sinuses, works as an integrated crumple zone. By fracturing, these pneumatized structures physically prolong the time duration over which the kinetic energy of the impact is transferred. They are acting as an energy-absorbing buffer that reduces the transmission of mechanical force to the posterior cranial fossa and the brain parenchyma (Lee, Kellman and Darling, 2014). Several bones composing this complex structure are of high traumatological interest. Fractures in these mid-face regions are correlated to one another and often occur bilaterally, highlighting their collective role in impact absorption (Tundo et al., 2019).

The mandible is the most frequently injured structure, with fractures reported in 81.6% to 86.7% of cases; indeed, mandibular symphyseal separation is a hallmark of feline trauma (Knight and Meeson, 2019; Tundo *et al.*, 2019).

For the mid-face complex, Zanotti’s study (2024) shows that exist high correlations between fractures of the nasal bone (68.4%), lacrimal bone (63.2%), palate (57.9%), and zygomatic arch (50.0%).

The temporomandibular joint injuries, such as condylar process fractures and luxations, occur in 56.0% (Knight & Meeson, 2019) to 60.0% (Tundo *et al.*, 2019) of maxillofacial trauma cases. Although the cranial base is generally robust, the sphenoid is highly susceptible, representing 92.3% (Zanotti, 2024) of fractures at the skull base. The high frequency of TMJ involvement is also supported by CT-based clinical series (Knight & Meeson, 2019; Tundo et al., 2019; Mestrinho et al., 2022).

Some structures appear to have a specialized protective role; in this regard the pterygoid bone is of significant interest. Findings suggest that "the pterygoid bone appears to act as a protective structure, as cats with pterygoid fractures did not exhibit brain lesions" (Zanotti, 2024, p. 59). So, pterygoid fracture dissipates enough mechanical energy to prevent severe concussion (Zanotti, 2024).

Besides, fractures of the cranial vault (neurocranium), such as the parietal and occipital bones, are rarely observed in clinical survivors (Zanotti, 2024). This suggests that the *splanchnocranium* successfully absorbs the majority of traumatic energy, or that injuries reaching the neurocranium are often associated with immediate mortality (Amengual-Batle *et al.*, 2020; Zanotti, 2024).

Pathophysiology of Feline Head Trauma

Aetiology and Mechanical Forces

Feline head trauma is a critical emergency, as “the head is the second most frequently injured body region in cats” (Adamantos & Garosi, 2011, p. 806), after the extremities. The aetiology and the magnitude of the mechanical forces involved determine the nature and the severity of the resulting injuries (Lefman & Prittie, 2022).

“Road traffic accidents (RTAs) were the most common cause of skull fractures, occurring in 89% of cats, and caused fractures of multiple regions of the skull” (Knight & Meeson, 2019, p. 1120). RTAs are typically high-energy events that result in fractures across multiple regions of the skull and are frequently associated with concurrent thoracic, neurological, and ophthalmic injuries (Knight & Meeson, 2019). Specific factors predispose domestic cats to these accidents: research indicates that young age is a primary risk factor, with cats between 7 months and 2 years old being significantly more susceptible (Knight & Meeson, 2019; Rochlitz, 2003). Additionally, male cats are over-represented in RTAs, a trend attributed to the increased tendency to go outside observed in entire animals (Rochlitz, 2003; Vnuk et al., 2004). Environmental factors, such as high traffic density and the time of day, also contribute to the likelihood of vehicular trauma, particularly for cats with limited road experience (Rochlitz, 2003a, 2003b).

Another frequent cause of head trauma in cats is the High-Rise Syndrome (HRS), which refers to injuries sustained from falls from at least the second storey. From the study conducted by Vnuk and colleagues (2004) on 119 cases of feline HRS, it emerged that the injury pattern is highly dependent on the height of the fall and the "righting reflex", that is the cat's innate ability to right themselves. In falls below seven stories, cats typically land on their limbs, which are extended to slow the fall, leading to a higher incidence of limb fractures and mandibular symphyseal separations. These falls result in a specific triad of injuries: epistaxis, hard palate fractures, and pneumothorax.

However, once terminal velocity is reached, typically around the fifth or sixth storey, the vestibular system is no longer stimulated, and the cat adopts a more horizontal posture. Above seven stories, truncal injuries are more common, and the incidence of limb fractures may decrease as the impact is distributed more evenly across the body.

(Lefman & Prittie, 2022; Vnuk et al., 2004)

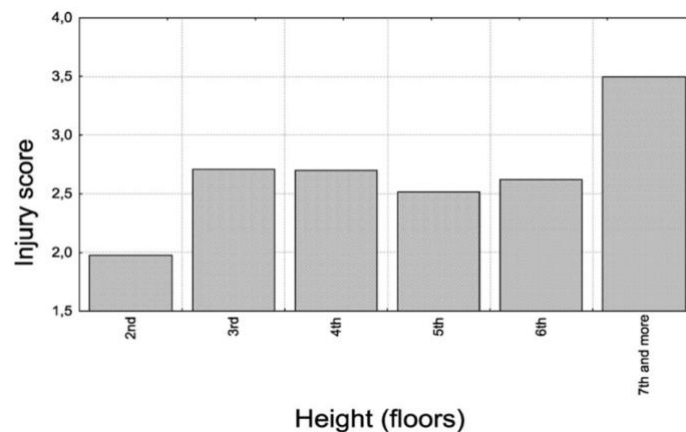


Figure 2: Graph showing the relationship between injury score and height of fall (Vnuk *et al.*, 2004)

According to Klainbart *et al.* (2022) animal bite wounds, particularly from dogs, account for 10% to 20% of feline head trauma cases. Canine bites exert a combination of crushing, laceration, and avulsion forces that result in perforating wounds. These injuries often present significant deep tissue damage that may be masked by superficial wounds (Klainbart *et al.*, 2022).

Regarding the impact dynamics, it is important to highlight the hydraulic protection and the *coup-contrecoup* phenomenon. Beyond the external defence provided by bone, the skull offers a system of internal hydraulic protection. The brain is suspended in the superior portion of the intracranial cavity, due to its lower density than the surrounding cerebrospinal fluid (CSF). Under normal conditions, the brain does not contact the bone surfaces and remains safely cushioned (Drew & Drew, 2004).

However, during abrupt impacts, the brain undergoes distortion due to forces of acceleration, linear translation and rotational or angular acceleration (Bešenski, 2002). According to the principle of conservation of movement: when the head is suddenly stopped, brain is displaced in the opposite direction of the impact. This results in the *coup-contrecoup* phenomenon, in which can be distinguished a coup injury and a contrecoup injury. The first one is a primary damage occurring at the side of the initial impact. The second one occurs when the brain is displaced and strikes the opposite internal surface of the cranium (Drew & Drew, 2004). In these dynamics, “the contrecoup or opposite injury is commonly of a greater severity than the coup injury” (Drew & Drew, 2004, p. 386). This severity is exacerbated when the impact energy of the contrecoup forces is more heavily concentrated at the frontal and temporal poles, due to their limited surface area (Drew & Drew, 2004).

Force direction dictates lesion patterns: linear acceleration acting along the latero-lateral diameter of the skull often causes extra-axial lesions such as subdural hematoma, epidural hematoma, or

subarachnoid haemorrhage. Contrariwise, fronto-occipital hit tends to produce lesions in deep structures and may lead to diffuse axonal injury (DAI) or brainstem damage (Bešenski, 2002).

Primary and Secondary Brain Injury

Traumatic brain injury (TBI) is traditionally categorized into two distinct phases: primary and secondary injury. This distinction is essential for understanding how initial mechanical trauma translates into a progressive clinical condition (Dos Santos *et al.*, 2018; Kuo, Bacek and Taylor, 2018).

Primary injury is an immediate damage, it is the direct result of mechanical forces at the moment of impact and is considered unavoidable once it has occurred (Garosi and Adamantos, 2011; Dos Santos *et al.*, 2018). This phase involves the physical disruption of intracranial and cranial structures. Examples include skull fractures, parenchymal lesions, primary haemorrhages and diffuse axonal injury (Kuo, Bacek and Taylor, 2018).

Secondary injury is a delayed damage, it develops minutes to days after the initial insult and consists of a complex cascade of biochemical, cellular, and systemic alterations (Dos Santos *et al.*, 2018; Kuo, Bacek and Taylor, 2018). Examples include excitotoxicity, cerebral edema and increased intracranial pressure (ICP) (Kuo *et al.*, 2018).

The fundamental "goal of managing head trauma is the prevention and treatment of secondary injury" (Kuo *et al.*, 2018, p.111).

Initial Assessment and Stabilization

Following the head trauma, the priority is to address the patient's life-threatening abnormalities (Garosi & Adamantos, 2011). Initially, the focus must be on the Airway, Breathing, and Cardiovascular status (ABCs), which the aim is to correct hypovolemia and ensure adequate oxygenation (Platt, 2005; Garosi and Adamantos, 2011).

Until the patient is physiologically stable, all surgeries should be postponed. As stated by Woodbridge and Owen (2013), "A period of stabilisation and appropriate treatment may be required prior to consideration being given to fracture repair" (p. 211).

Once normal blood volume and oxygenation are established, a complete neurological examination is performed to evaluate the brain damage.

The Modified Glasgow Coma Score and Animal Trauma Triage Score is another test that can be executed. The Modified Glasgow Coma Scale (MGCS) evaluates motor activity, brainstem reflexes, and the level of consciousness. This scale helps to grade the initial neurological status, monitor the patient serially and "may serve as guidelines for predicting outcome" (Kuo *et al.*, 2018, p. 111). (Platt, 2005; Kuo, Bacek and Taylor, 2018)

Diagnostic Imaging: Conventional Radiography (RX)

Physical Principles and Acquisition

In 1920s, radiography began to gain ground in veterinary medicine due to the introduction of high-tension transformers, the Bucky-Potter system and the Coolidge tube (Meomartino *et al.*, 2021). Radiographs are produced via the absorption of X-rays by tissues of different densities. Low-density tissues appear dark (*eg.* lungs), while high-density tissues (*eg.* bone) appear white. A major challenge in veterinary medicine is the scarce or absent patient collaboration. Therefore, manual or pharmacological constraint is necessary and patients with painful lesions must be sedated or anesthetized (Meomartino *et al.*, 2021). Furthermore, radiographs of the skull are best taken under general anaesthesia, which will ensure that the head is straight (Garosi and Adamantos, 2011).

General rules for radiographic exams include the use of at least two orthogonal views. To properly evaluate bone structures, a high contrast technique is traditionally recommended by setting higher milliamperere-seconds (mAs) and lower kilovoltage (kV). A lower kV decreases the penetrability of the X-rays beam, thereby increasing the visual contrast between the dense bone and the surrounding soft tissues. A higher mAs increases the total quantity of X-rays produced, compensating for the reduced penetration and ensuring adequate image exposure. (Meomartino *et al.*, 2021)

Under a radiography point of view, the feline skull is a difficult area to study, therefore "A complete skull study typically includes ventrodorsal (VD) or dorsoventral (DV), laterolateral (LL) and left and right lateral-oblique (OBL) projections" (Bar-Am *et al.*, 2008, p. 294). For evaluating the dental arches, a vastly used support is brought by the intraoral radiography because it is superior to traditional skull radiographs (Constantaras and Charlier, 2014).

Advantages and Diagnostic Limits in Head Trauma

The role of radiography in head trauma is just for initial screening; radiography is useful because a single image of the entire skull allows lesions to be visualized with spatial orientation (Bar-Am *et al.*, 2008). Regarding what can be seen, Bar-Am *et al.* (2008) report that the "Skull radiography is superior for visualizing the mandibular body (LL and OBL views) and dental occlusion (DV view)" (p. 299).

Proper interpretation of these images requires the knowledge of specific radiographic direct and indirect fracture signs. "Direct fracture signs refer to disruptions of cortical bone, abnormal linear densities (especially in plain films), cortical duplication, absent bone structures, abnormal

angulation of anatomic structures, and displaced bone segments" (Buitrago-Téllez et al., 2014, p. S122). While, indirect signs consist of fluid or gas accumulation within the paranasal sinuses, along with swelling or emphysema in the adjacent soft tissues (Buitrago-Téllez *et al.*, 2014).

Evaluating dental occlusion is a fundamental step in the head trauma assessment. The inability to close the mouth can be caused by TMJ fractures, mandibular fractures, or other maxillofacial trauma (Constantaras and Charlier, 2014). Radiography is a valuable tool to identify obvious jaw displacements and occlusal discrepancies (Bar-Am *et al.*, 2008).

However, the radiographic examination of the skull in head trauma patients presents significant diagnostic limits due to the very complex bone structure (Bar-Am *et al.*, 2008). Standard radiographs occasionally show evidence of fractures of the cranial vault with depression, but do not always reveal skull fractures (Platt, 2005). For instance, fractures of the tympanic bulla and subtle intracapsular condylar fractures are often undiagnosed. This highlights its lower sensitivity compared to advanced imaging (Schwarz *et al.*, 2002). Conventional radiographs compress a three-dimensional structure into a two-dimensional image through the sum of attenuations across the patient's entire thickness. This procedure creates superimposition and overlapping shadows (Soukup and Snyder, 2014). Superimposition makes the detailed examination and interpretation of skull radiographs difficult, while overlapping shadows obscure fine details, making the exact identification of mid-face fractures or TMJ lesions highly challenging (Schwarz *et al.*, 2002; Bar-Am *et al.*, 2008).

To overcome these visual limits, multiple radiographic projections can be acquired. Nevertheless, the continuous repositioning of the patient can severely compromise an already unstable head trauma animal. Due to these technical limits, standard radiography often underestimates the severity of the trauma (Bar-Am *et al.*, 2008).

Diagnostic Imaging: Computed Tomography (CT)

Physical Principles and Image Acquisition Standards

Computed Tomography (CT) is an advanced cross-sectional imaging technique based on x-ray technology. "In CT, a narrow, fan-shaped x-ray beam is emitted from a tube as it moves around the patient, and x-rays that pass through the patient are counted by a series of small electronic detectors" (Whatmough & Lamb, 2005, p. 789). These detectors transform the radiation into electrical signals, then a computer reconstructs these signals into two-dimensional images representing cross-sections of the patient's anatomy.

The Hounsfield Scale (HU) is used to measure the x-ray attenuation by different tissues, where water has a value of 0 HU and air is -1000 HU, while compact cortical bone can reach the value of +3000 HU. Because of this high density, bones are described as hyperattenuating tissue and they appear bright, light grey, or white on the monitor. (Whatmough & Lamb, 2005). For an accurate diagnosis, it is important to choose the thickness of the slice correctly. For example, slices of 1 mm or less are recommended to achieve maximal resolution of complex anatomical areas for small, high-contrast osseous structures. These narrow slices are mostly used to evaluate the temporomandibular joint (TMJ) as well as the bones of the middle and inner ear (Arzi et al., 2013; Whatmough & Lamb, 2005). Moreover, thicker slices can be used and reconstructed when evaluating soft tissues with similar attenuation, such as brain parenchyma injuries (Buitrago-Téllez et al., 2014; Whatmough & Lamb, 2005).

Regardless of the specific area, acquiring thin transverse slices is fundamental for the 3D CT reconstruction that is widely used in traumatology. These modern post-processing algorithms can generate high-quality multiplanar and three-dimensional images. 3D CT is "helpful to identify relevant displacement of fractures and evaluate condylar head displacement" (Buitrago-Téllez et al., 2014, p. S124).

Image acquisition requires patients to be perfectly still, so general anaesthesia or deep sedation is mandatory to avoid motion artifacts (Mann *et al.*, 2022; Greco *et al.*, 2023).

Advantages and Diagnostic Sensitivity in Head Trauma

Computed tomography is considered the gold standard imaging modality for head trauma patients and to assess maxillofacial injuries (Soukup and Snyder, 2014). Due to its superior resolution and the complete elimination of structural superimposition, CT has an exceptionally high diagnostic sensitivity. Indeed, it is very useful for detecting fractures even within the complex feline skull (Knight and Meeson, 2019).

As a rapid imaging modality, CT is considered the most appropriate choice for unstable feline patients with head trauma and polytrauma. As a matter of fact, the short image acquisition time often necessitates only deep sedation or a brief general anaesthesia.

It is important to acknowledge that CT involves exposure to ionizing radiation and has poorer soft tissue detail compared to Magnetic Resonance Imaging (MRI), making it less sensitive for the visualisation of subtle, non-haemorrhagic parenchymal lesions (Dos Santos *et al.*, 2018). However, CT offers a cost-effective solution compared to MRI (Greco *et al.*, 2023).

In acute scenarios, computed tomography excels in evaluating occult bone fractures, fine osseous details, intracranial haemorrhages, brain edema and soft tissue damage. Regarding osseous structures, CT clearly identifies cranial vault fractures, skull base fractures and complex mid-face injuries.

The resulting cross-sectional data, especially when enhanced by three-dimensional (3D) surface reconstructions, provide highly accurate anatomical information. These findings directly facilitate surgical planning, particularly in cases of multiple fragments or severe dislocation, thereby guiding immediate and life-saving interventions. (Mann *et al.*, 2022)

RX and CT Comparison

Radiography is best suited for initial screening as it allows the feline's entire skull to be visualized rapidly in a single image (Bar-Am *et al.*, 2008). It remains one of the most widely used diagnostic imaging techniques due to its affordability, speed of execution, and ease of interpretation (Greco *et al.*, 2023).

Diagnostic-wise, the study conducted by Bar-Am *et al.* (2008) highlights that conventional radiography is superior to CT in characterizing maxillofacial trauma in specific areas: body and ramus of the mandible, and dental occlusion. Furthermore, conventional radiographs can be as effective as CT in diagnosing mandibular symphyseal separations and TMJ luxations. (Bar-Am *et al.*, 2008)

Even though radiography has a limited ability to identify direct brain trauma, it can occasionally identify fractures of the cranial vault (Platt, 2005; Garosi and Adamantos, 2011). Nevertheless, as described in the previous chapter, given the complex anatomy of the feline skull, conventional radiography is limited by superimposition and overlapping shadows. In this regard, computed tomography appears to be the most suitable imaging technique for the overall evaluation of head trauma as it overcomes these visual limits. Indeed, CT eliminates the issue of structural superimposition, and it allows for a much more precise diagnosis than conventional radiography (Knight & Meeson, 2019). When directly comparing the two modalities, the superiority of CT over

standard radiography is remarkable. Studies have demonstrated that CT scans can identify 2.0 times more maxillofacial injuries in cats compared to conventional radiographs (Bar-Am et al., 2008), and "4.7 x more injuries when compared with skull radiographs" (Soukup & Snyder, 2014, p. 1).

As previously stated, CT allows for the creation of three-dimensional (3D) reconstructions that provide an exceptional spatial orientation of the fractures, facilitating surgical planning. (Greco *et al.*, 2023)

Moreover, achieving a complete radiographic study requires obtaining multiple projections, which necessitates the continuous and potentially dangerous repositioning of an unstable trauma patient. Also, the short image acquisition time of modern CT scanners reduces the required anaesthesia time compared to obtaining multiple skull radiographs (Bar-Am *et al.*, 2008). Furthermore, a rapid head CT has sufficient resolution to provide an effective evaluation of the intracranial compartment and identifies acute primary brain injuries (Mann et al., 2022).

In the end, the diagnostic gap between RX and CT is evident, confirming CT as the gold standard for head trauma.

The Skull Base in Head Trauma

Incidence and Distribution of Basilar Fractures

The feline skull base is composed of the sphenoid, pterygoid, and basioccipital bones. To fully comprehend the dynamics of skull base injuries, it is essential to consider the biomechanical concept of impact absorption (Amengual-Batle *et al.*, 2020). As demonstrated in comparative anatomy studies by Lee *et al.* (2014), "the presence of nasal cavity and paranasal sinuses behaves as a crumple zone to protect the cranial structures, preferentially posterior cranial fossa" (p. 2242). Although originally investigated in human models, this fundamental principle is highly applicable to feline head trauma, explaining how the rostral *splanchnocranium* acts as a physical shield to the deeper and vital structures of the cranial base.

Despite the protective effect of the facial crumple zone, severe traumatic events can transmit sufficient energy to damage the basicranium. Within this region, fracture distribution and configurations are depending on the specific bone involved.

The sphenoid bone is extremely susceptible to mechanical stress, representing 92.3% of all fractures at the skull base (Zanotti, 2024). These fractures often occur following severe perpendicular impacts, such as High-Rise Syndrome (HRS), where the kinetic energy is transmitted upward through the hard palate to the rostral skull base (Bonner, 2012). Fractures of the pterygoid bone often occur indirectly. Biomechanically, these specific fractures often present as avulsions of the hamular process caused by the excessive stress exerted by inserting muscles, such as the pterygoid and tensor *veli palatini*, during the traumatic event (Weichert, Kiefer and Theyse, 2025).

Fractures of the basioccipital bone are very rare or absent in surviving cats (Amengual-Batle *et al.*, 2020; Zanotti, 2024). Indeed, severe trauma reaching this deep region causes immediately fatal brainstem injuries.

Also, the origin of the mechanical forces causes adjacent fracture patterns. For instance, the highly variable and oblique force vectors in Road Traffic Accidents (RTAs) predispose cats to unilateral temporal bone fractures (Mestrinho *et al.*, 2022).

Imaging in Skull Base Evaluation

Evaluating the skull base in a trauma patient presents a major diagnostic challenge. Conventional radiography (RX) almost fails to detect fractures in this specific area due to the severe superimposition of complex anatomical structures. These overlapping shadows obscure fine

osseous details, leading standard radiographs to underestimate the presence and severity of basilar skull fractures (Bar-Am *et al.*, 2008).

In this context, computed tomography (CT) represents the definitive gold standard. CT eliminates structural superimposition, allowing for the precise identification of complex, fragmented, or undisplaced fractures (Bar-Am *et al.*, 2008). Given that the skull base directly protects the brainstem and major cranial nerves, achieving an accurate diagnosis is of fundamental importance. Missing a fracture or a secondary lesion in this deep region can have catastrophic consequences for the patient. So, precise CT imaging is crucial to rule out brainstem compression or caudal transtentorial herniation, which define the neurological outcome. Therefore, by enabling the rapid identification of secondary intracranial complications, CT imaging allows clinicians to establish a reliable short- and long-term prognosis using specific grading systems like the Koret CT Score (KCTS). The KCTS is a 7-point index that assigns scores based on the presence of specific CT abnormalities. A higher score is associated with a decreased probability of survival, thus aiding critical clinical decisions (Mann *et al.*, 2022).

Regarding the therapeutic approach, surgical intervention is on rare occasions indicated for fractures of the skull base itself. Surgery is reserved only for cases involving severe compression of the brain parenchyma or lead to progressive and life-threatening neurological deficits. In clinical practice, these fractures are typically managed using a conservative approach. Medical management and supportive care remain the treatment of choice for caudal skull injuries (Knight and Meeson, 2019).

The Temporomandibular Joint in Feline Head Trauma

Anatomy of the Feline TMJ

The feline TMJ is a complex and highly specialized transversely elongated condylar synovial joint that facilitates the essential functions of mastication (Schwarz et al., 2002). Anatomically, it is formed by the articulation of the *caput mandibulae*, which is the head of the condylar process, and the mandibular fossa located at the squamous portion of the temporal bone (Schwarz et al., 2002). Each mandible consists of a horizontal body and a vertical ramus, the latter of which features three distinct prominences: the condylar process, the coronoid process, and the angular process (Constantaras & Charlier, 2014). Furthermore, running through the horizontal body, the mandibular canal houses the neurovascular bundle made up of the inferior alveolar artery, vein, and nerve (Arzi et al., 2020).

A defining characteristic of the feline TMJ is its articular surface composition: "the articular cartilage of the temporomandibular joint (TMJ) is not made of hyaline cartilage but a fundamentally different fibrocartilaginous tissue" (Arzi et al., 2020, p. 453). Furthermore, a fibrocartilaginous articular disk completely separates the joint cavity into non-communicating dorsal and ventral compartments. This disc attaches circumferentially to the joint capsule, acting as a shock absorber and reducing friction through a double synovial film (Arzi et al., 2020; Schwarz et al., 2002).

In cats, the morphology of the TMJ is highly restrictive and limits mandibular movement compared to other species (Constantaras & Charlier, 2014). The deep mandibular fossa is strictly bordered by the articular eminence rostrally and the retroarticular process (*processus retroarticularis*) caudally. "The *processus retroarticularis* is a caudoventral extension of the *fossa mandibularis*, which cups and prevents caudal luxation of the *caput mandibulae*" (Schwarz et al., 2002, p. 85). Due to these prominent bony structures and a thickened lateral joint capsule, independent movements of the mandible are prevented. The feline TMJ functions as a strict hinge joint, and lateral grinding motion is minimal (Arzi et al., 2020; Constantaras & Charlier, 2014). Joint stability is further maintained by the masticatory muscle system, which is all innervated by the mandibular branch of the trigeminal nerve and function to close the mouth, whereas the *digastricus* muscle acts as the primary opener (Constantaras & Charlier, 2014).

Causes of Trauma and Injury Classification

TMJ injuries are common in cats suffering from high-energy head trauma, as in RTAs or HRS (Knight & Meeson, 2019; Mestrinho et al., 2022). In such cases, the impact forces can often result

in complex and multiple fractures and severe displacement of the condylar process from the mandibular fossa (Constantaras & Charlier, 2014; Knight & Meeson, 2019).

Less common causes include animal interactions, as dog bites or fights with other cats, being kicked, or domestic accidents (Mestrinho et al., 2022).

Traumatic injuries to the TMJ are categorized into luxations, subluxations, and intra-articular fractures (Çetinkaya, 2012).

The most frequent luxation is the displacement of the condylar process in rostradorsal direction (Çetinkaya, 2012; Mestrinho et al., 2022). These luxations can easily occur as isolated injuries, without concurrent mandibular fractures or symphyseal separations (Constantaras & Charlier, 2014). On the other hand, caudal luxations are rare and occur with a concurrent fracture of the retroarticular process (Çetinkaya, 2012; Constantaras & Charlier, 2014).

Fractures can involve the condylar process itself, involving the mandibular head or neck, or the temporal bone's mandibular fossa (Çetinkaya, 2012; Mestrinho et al., 2022). As reported in the study conducted by Mestrinho et al. (2022), "TMJ injuries were most commonly unilateral, representing 70.9% of cases. The mandibular condyle was fractured in 88 cases (55.7%) of the 158 TMJs observed. Of those, 84.0% were intra-articular condyle fractures, with the medial half of the mandibular condyle over-represented" (p. 1181). These fractures of the medial half of the mandibular condyle often appear as sagittal or comminuted lesions (Mestrinho et al., 2022).

Secondary structural alterations often follow the initial trauma. Osteoarthritis can develop, characterized by the formation of osteophytes, joint space narrowing, and subchondral bone sclerosis, particularly at the medial aspect of the joint (Arzi et al., 2013).

Another specific alteration is the "locking jaw" syndrome, where the coronoid process impinges on the zygomatic arch, preventing the cat from closing its mouth passively or actively (Constantaras & Charlier, 2014; Nutt et al., 2018). Additionally, trauma to the trigeminal nerve can result in bilateral mandibular neuropathy, leading to a "dropped jaw" that mimics TMJ instability but is often painless during clinical manipulation (Constantaras & Charlier, 2014).

Imaging Methods Comparison

When evaluating the TMJ, conventional radiography relies on laterolateral (LL), dorsoventral (DV), and lateral-oblique projections (Schwarz *et al.*, 2002). The DV view is often the most informative, depicting the normal TMJ space as a thin, radiolucent band (Schwarz *et al.*, 2002). As with the caudal skull, structural superimposition often obscures subtle fissures within the *caput mandibulae* or the mandibular fossa. Avoiding such shadows necessitates complex oblique views

requiring perfect alignment. However, achieving this is technically demanding in traumatized cats (Bar-Am et al., 2008; Nutt et al., 2018; Schwarz et al., 2002).

Given these limitations, computed tomography (CT) is essential for maxillofacial trauma quantification and recognition of the true extent of bone displacement (Bar-Am et al., 2008). To accurately evaluate the relationship between the condylar process and the mandibular fossa, three-dimensional reconstructions and thin-slice datasets (slice 1mm) are required; these tools are indeed essential for surgical planning (Bar-Am et al., 2008; Knight & Meeson, 2019).

Advanced imaging is also crucial when a patient presents with an inability to close the mouth. Indeed, in such cases, it is essential to differentiate between a true intra-articular TMJ luxation and the locking jaw syndrome. While standard radiographs often fail, a precise 3D CT assessment allows clinicians to identify coronoid displacement, evaluate the exact degree of overlap with the zygomatic arch, and rule out concurrent condylar fractures. (Nutt *et al.*, 2018)

Post-traumatic complications: TMJ Ankylosis

Ankylosis is defined as an abnormal immobility and consolidation of a joint (Schwarz *et al.*, 2002). In cats, it is a serious post-traumatic complication that typically manifests weeks after a head injury (Meomartino *et al.*, 1999; Çetinkaya, 2012). The literature distinguishes between intracapsular (true) and extracapsular (false) ankylosis (Zavodovskaya et al., 2020).

True ankylosis involves the direct destruction of the articular surfaces and the formation of bony or fibrous fusion within the joint capsule itself (Zavodovskaya *et al.*, 2020). It usually follows untreated intra-articular fractures, particularly those involving combinations of the condylar process and the mandibular fossa (Çetinkaya, 2012). Hemarthrosis formation, which is critical in the development of TMJ ankylosis in man, has been suspected as an initiating factor in cats falling from great heights. The primary radiographic signs are the loss of a regular TMJ space and *caput mandibulae* contour with associated irregular new bone formation (Schwarz et al., 2002). False ankylosis is caused by lesions situated outside the joint capsule that mechanically restrict movement, despite the TMJ itself being unaffected. It can result from fractures of the zygomatic arch or coronoid process where an exuberant callus forms between the bones and the masticatory muscles. Additional causes of progressive jaw immobility include extensive new bone formation resulting from surrounding infections, such as chronic *otitis media* or retro-orbital abscesses. (Schwarz *et al.*, 2002)

Clinical presentation involves a progressive inability to open the mouth, leading to severe malnutrition (Meomartino *et al.*, 1999). Regarding management and outcome, the primary

objective when treating any TMJ or maxillofacial injury is to restore a functional dental occlusion (Soukup & Snyder, 2014). As stated by Woodbridge and Owen (2013) "The overall goals of fixation are the re-establishment of dental occlusion, rapid return to masticatory function and uncomplicated fracture healing." (p. 212). Conservative management, including manual stretching under anaesthesia, is generally unsuccessful and leads to recurrence (Meomartino *et al.*, 1999). Therefore, a surgical intervention such as a condylectomy becomes necessary (Çetinkaya, 2012). "Excision arthroplasty represents the technique of choice for treatment of TMJ ankylosis in cats" (Meomartino *et al.*, 1999, p. 10), this surgical approach allows patients to regain excellent functional jaw movement without significant malocclusion (Meomartino *et al.*, 1999).

AIMS AND HYPOTHESIS OF THE STUDY

As previously described, evaluating skull fractures in cats presents significant diagnostic challenges. To address these challenges, the present study is divided into two distinct but complementary parts. Both are a retrospective statistical comparison of imaging modalities and a targeted visual training experiment.

The aim of the first part of the study is to retrospectively collect and compare the diagnostic yield of conventional radiography (RX) and computed tomography (CT) in detecting craniomaxillofacial fractures.

The hypothesis is that conventional radiography significantly underestimates the number and severity of skull fractures compared to CT.

Building upon these considerations, the aim of the second part of the study was to investigate whether the diagnostic performance of conventional radiography could be improved by targeted CT-guided visual training in an inexperienced observer, represented by a fifth-year veterinary student without specific experience in the radiographic interpretation of feline head trauma. The objective was to determine whether the acquired visual patterns could improve identification of fractures of the neurocranium and temporomandibular joint (TMJ) on conventional radiographs, particularly when CT is unavailable or delayed.

The hypothesis is that an “educated eye” can partially overcome the visual limits of superimposition and overlapping shadows.

MATERIALS AND METHODS

Case Selection and Inclusion and Exclusion Criteria

The cases were retrospectively recruited by searching the digital clinical records system "Fenice" of the University Veterinary Teaching Hospital (OVUD) of the University of Parma. The observation period for the case selection spanned from 2017 to 2026.

Moreover, the same cohort of feline patients was utilized for both parts of this study.

To be included, patients had to be cats that experience a head trauma and underwent both a conventional radiographic examination and a computed tomography scan. Furthermore, the presence of at least one craniomaxillofacial bone fracture is required for inclusion. The present study focuses exclusively on the observable fractures with diagnostic imaging at the moment of the traumatic event. For this reason, the clinical outcome of the patients and the medical or surgical treatments performed were not considered as either inclusion or exclusion criteria.

Bone Fractures Study

The RX and CT scans of the selected cases were evaluated using the open-source medical imaging software Horos (Version 3, LGPL-3.0) to identify and categorize the skull lesions. To ensure a standardized and objective approach, it was used the craniomaxillofacial fracture classification system. This system topographically divides the skull into three main anatomical areas: the face, the cranial vault and the base of the cranium (Amengual-Batle et al., 2020; Audigé et al., 2014). Using this classification system, every single skull fracture identified in the RX and CT scans was collected into a Microsoft Excel (Version 16.111.2) spreadsheet. The resulting database served as the foundation for the statistical comparison between the diagnostic findings of the two imaging modalities.

In the first part of the study, statistical analyses were performed using Microsoft Excel.

A CT-to-RX Detection Ratio (Yield Ratio) was calculated for each anatomical areas. This ratio indicates how many times more effective CT was in identifying fractures compared to RX. McNemar's test was performed to determine the statistical significance of the differences between the two imaging modalities. It analyses the proportion of discordant pairs to establish whether the diagnostic superiority of one technique over the other is statistically significant ($P < 0.05$) or merely due to chance.

By establishing computed tomography as the "gold standard", the sensitivity and accuracy of conventional radiography were calculated. Sensitivity was defined as the ability of RX to correctly

identify fractures confirmed by CT. Accuracy expresses the overall proportion of correct radiographic assessments relative to the total number of evaluated anatomical structures. Furthermore, Cohen's kappa coefficient was calculated to quantify the strength of agreement between RX and CT. This statistical index allows for the quantification of radiographic reliability compared to the tomographic gold standard. The strength of agreement was interpreted according to the benchmarks proposed by Altman (1991): poor/no agreement ($\kappa < 0.40$), moderate agreement ($0.41 - 0.60$), good agreement ($0.61 - 0.80$) and excellent agreement ($\kappa > 0.80$).

Visual Training

The second part of the study used the same cohort of 18 feline patients as the first part. For this analysis, evaluation was restricted to the temporomandibular joint (TMJ) and the selected neurocranial bones (frontal, parietal, temporal, occipital, ethmoidal and sphenoid bones). The radiographic assessments were performed by a fifth-year veterinary student without specific experience in the radiographic interpretation of feline head trauma.

To distinguish learning generalizability from possible familiarity with cases directly used during training, the post-training evaluation was structured as follows:

- Primary Analysis (13 non-training cases): this independent test set comprised cases not used during training and represented the primary analysis for evaluating transfer of the acquired visual skills to novel radiographs.
- Descriptive Analysis (5 training cases): the cases directly used during training were analysed separately and descriptively to characterize performance on previously taught images.
- Secondary Full-Cohort Analysis (18 total cases): all 18 patients were analysed as a secondary full-cohort analysis. Its results were compared descriptively with those of the 13-case independent test set to assess how inclusion of the training cases influenced the overall estimates. No formal statistical comparison between the 13- and 18-case analyses was performed because the samples overlap.

The visual training was conducted utilizing Horos (Version 3) and the protocol was performed in three successive methodological phases:

1. Pre-Training: Baseline radiographic scoring was obtained from a dedicated pre-training structure-level dataset derived from the same radiographic examinations. This dataset was analysed separately from the broader fracture inventory used in the first part of the study; therefore, structure-specific counts from the two analyses are not necessarily interchangeable.
To minimize recall bias, a wash-out period of two weeks was maintained before the post-training reassessment. For reassessment, cases were anonymized, assigned new case identifiers and presented in a new order.
2. Training: Five cases were selected from the cohort of 18 exclusively for the instructional phase and were anonymized. Simulated radiographic images were generated from these patients' CT scans.

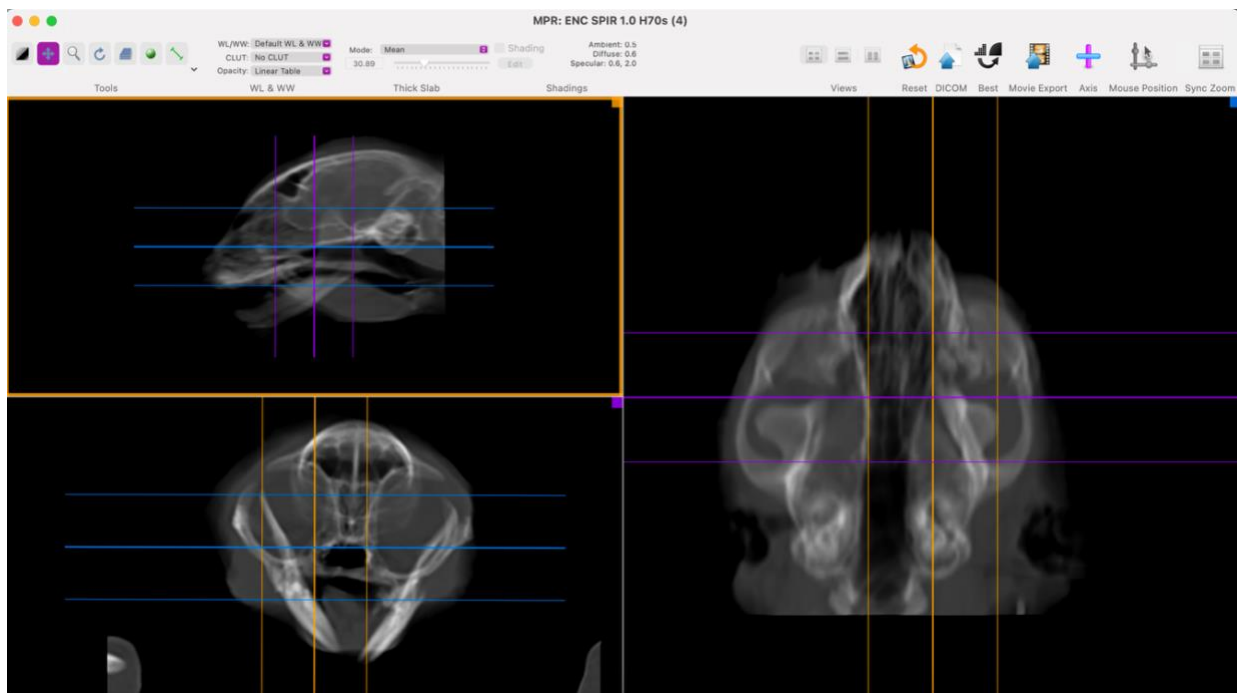


Figure 3: Methodological setup for generating simulated skull radiographs from CT scans during the training phase: 3D Multiplanar Reconstruction (MPR) window showing the "Mean" projection mode, manual slab thickness expansion, and window width/level (WW/WL) adjustment used to replicate conventional radiographic density and contrast

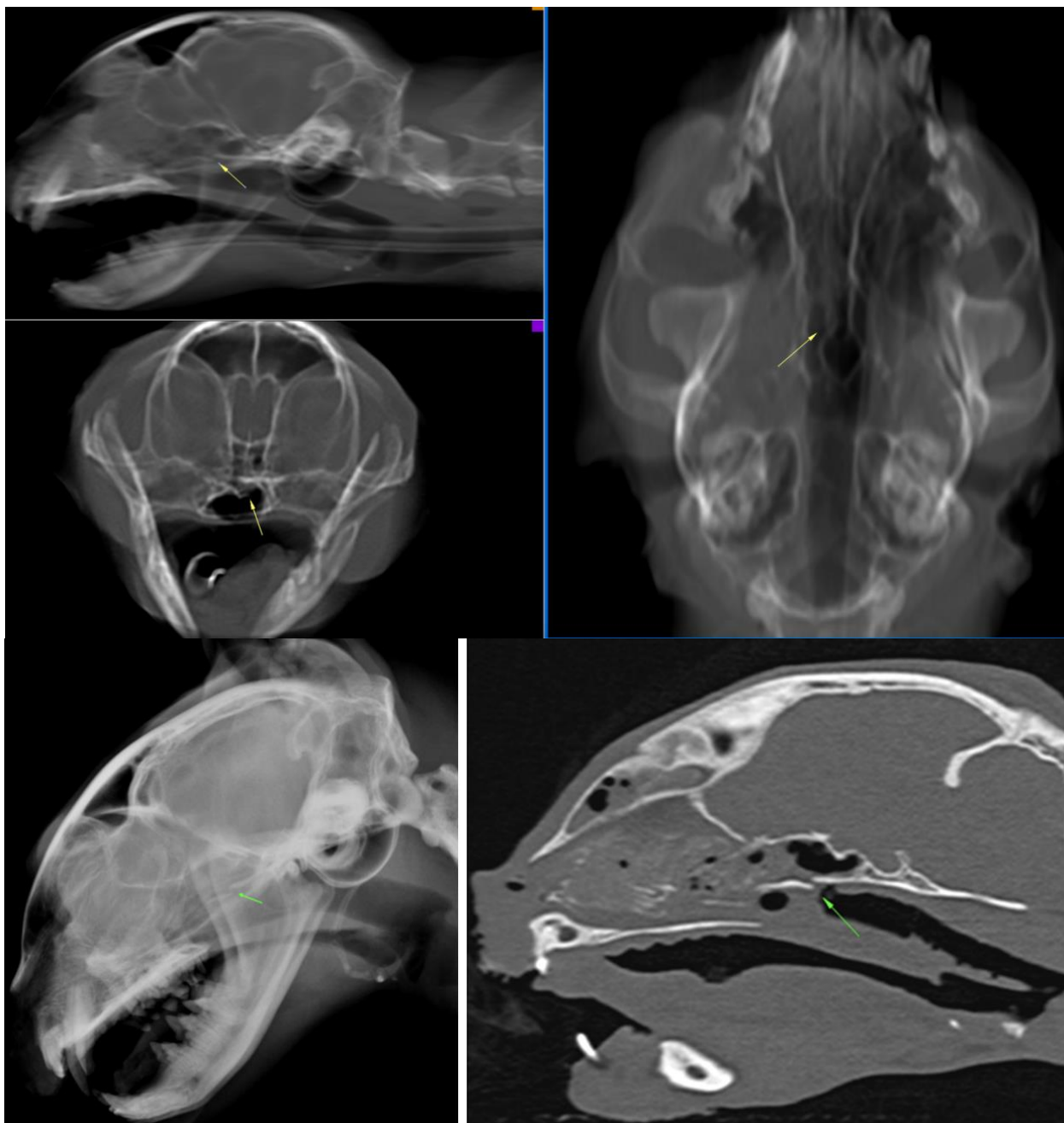


Figure 4 3D Multiplanar Reconstruction (MPR) window showing the "Mean" projection mode, corresponding RX and native CT slice of a cat with sphenoid bone fracture. (OVUD, Faculty of Veterinary Medicine, University of Parma)

On these simulated radiographs, the examiner localized the fractures, which had already been identified via CT analysis in the first part of the study. Then, each simulated radiograph was compared side-by-side with the patient's corresponding conventional radiograph. Through this comparison, the examiner learned exactly where and how the fracture lines manifested on actual plain radiographs.

This process was repeated systematically for all 5 training cases.

3. Post-Training: The examiner re-evaluated the real radiographs from the full cohort of 18 cases. For the primary inferential analysis, only the 13 cases not used during training were considered. The 5 training cases were analysed separately, and the full 18-case cohort was subsequently examined as a secondary analysis.

Finally, the diagnostic results from pre- and post-training were catalogued in a dedicated comparative Microsoft Excel spreadsheet.

Statistical analyses were conducted using Microsoft Excel and IBM SPSS Statistics (version 30.0, IBM Corp., Armonk, NY, USA). Computed tomography served as the gold standard reference modality for fracture presence or absence.

No statistical analyses were performed for the parietal and occipital bones, as no fractures were identified in these bones on radiography either before or after visual training. This complete absence of lesions was confirmed by CT reference standard.

For each anatomical structure, diagnostic sensitivity, specificity, and overall accuracy of conventional radiography were calculated relative to CT both pre- and post-training.

For the five selected structures, pooled pre- and post-training detection proportions were reported descriptively only. Because multiple patient-structure observations originated from the same cat, no inferential test treating these pooled observations as independent was performed.

Pre- and post-training paired binary outcomes were compared using the exact two-tailed McNemar test. For comparisons involving a constant variable (zero dataset variance), the exact two-tailed significance was derived from the number of discordant pairs.

Cohen's kappa coefficient (κ) was calculated to assess agreement between conventional radiography and CT before and after training. Agreement strength was categorized according to the criteria adopted in the first part of the study. When a diagnostic variable was constant (zero dataset variance), κ was considered non-estimable or non-interpretable.

The global effect of visual training on overall lesion detection per patient was evaluated using a two-tailed exact Wilcoxon signed-rank test for paired samples. Specifically, this test compared the per-subject counts of correctly identified structures before and after training.

To minimize recall bias and assess learning generalisability, the statistical evaluation was structured into the independent 13-case test set, the 5-case training subset, and the secondary 18-case full-cohort analysis. The 13-case analysis was considered primary. All statistical tests were two-tailed, with $P < 0.05$ considered statistically significant.

RESULTS

RX and CT Appearance of Skull Fractures

The study population includes 18 cats; imaging analysis was blinded to the patients' signalment, clinical history, clinical presentation and therapeutic outcomes.

All 18 patients presented at least one CT-confirmed skull fractures (100% trauma prevalence), totalling 119 distinct fractures across all evaluated bone. In stark contrast, conventional radiography identifies only 43 fractures, highlighting a diagnostic gap.

Facial fractures were the most common injuries, detected by CT in all 18 cats (100%), with 77 fractures. In contrast, radiography detected facial fractures in 14 cats (77.8%) with 36 fractures. Mandibular fractures occurred in 15 cats (83.3%) on CT and were identified in 11 cats (61.1%) on RX.

Nasal fractures were identified on CT in 16 cats (88.9%), but radiography detected 9 (50.0%). Maxillary fractures were present on CT in 10 cats (55.6%) compared to 6 (33.3%) on RX. Lacrimal fractures were recorded in 13 cats (72.2%) on CT and in 2 cats (11.1%) on RX. Zygomatic arch fractures were found in 11 cats (61.1%) on CT and 6 cats (33.3%) on RX. Palatine fractures were confirmed on CT in 10 cats (55.6%), but RX missed all of them (0%). For the incisive bone, fractures were present in 2 cats (11.1%) and were identified by both modalities.

Cranial vault fractures were detected on CT in 11 cats (61.1%, 21 fractures) and on RX in 3 cats (16.7%, 3 fractures).

Frontal fractures were found in 6 cats (33.3%) on CT but were visible on RX in 1 cat (5.6%). Temporal fractures were present in 7 cats (38.9%) on CT but were identified on RX in 1 cat (5.6%). Ethmoidal fractures occurred in 8 cats (44.4%) on CT, with only 1 cat (5.6%) showing radiographic signs on RX. This corresponds to a radiographic sensitivity of 12.5% (1/8) for the ethmoidal bone.

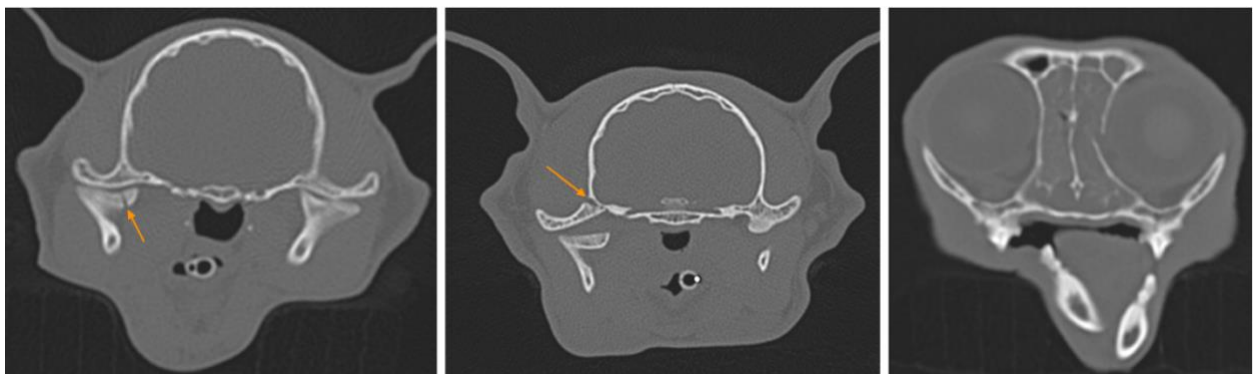
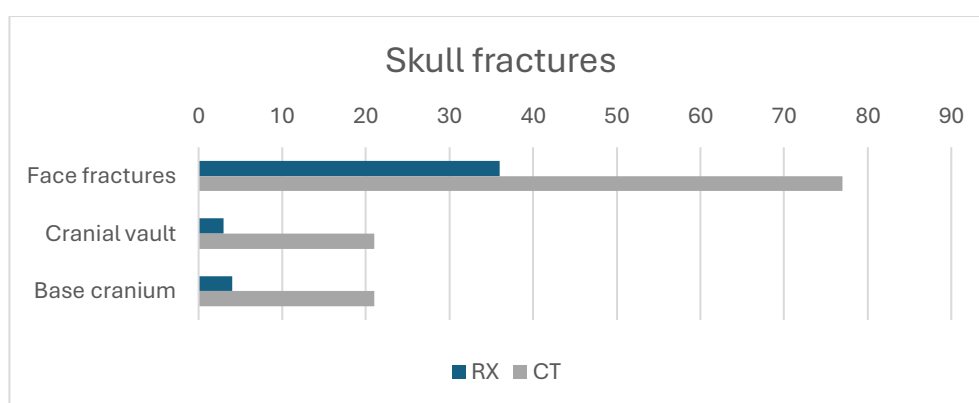


Figure 5: CT of feline skull, fractures of the mandible, temporal and frontal bones in three different patients (OVUD, Faculty of Veterinary Medicine, University of Parma)

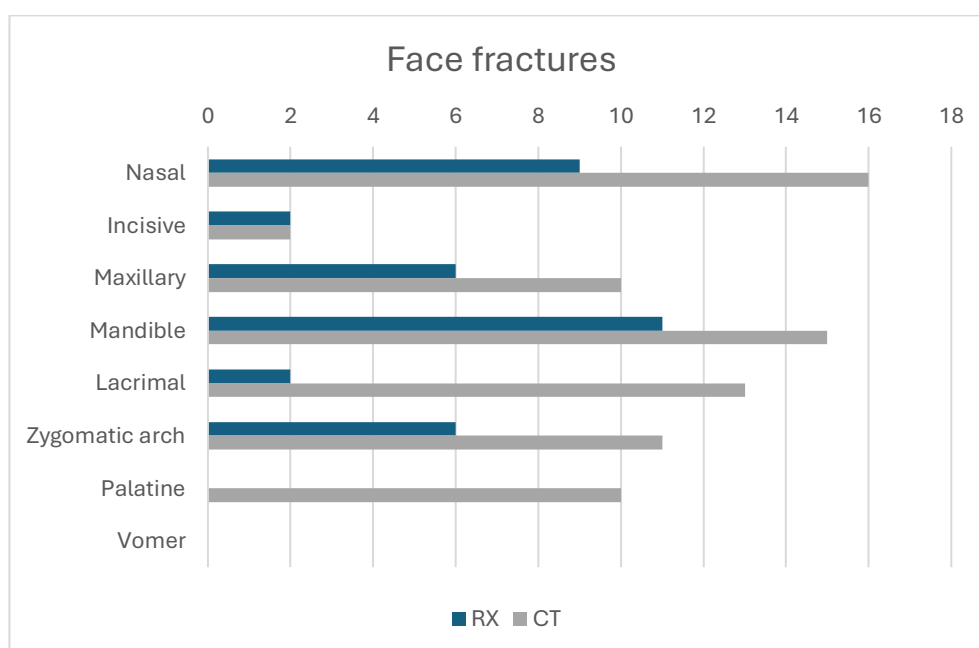
Fractures of the skull base were identified on CT in 15 cats (83.3%), resulting in 21 fractures. However, radiography detected them in 4 cats (22.2%), for a total of 4 fractures. Sphenoid fractures were confirmed on CT in 12 cats (66.7%), but RX completely missed these lesions (0%).

Pterygoid fractures were present on CT in 9 cats (50.0%) and were identified on RX in 4 cats (22.2%).

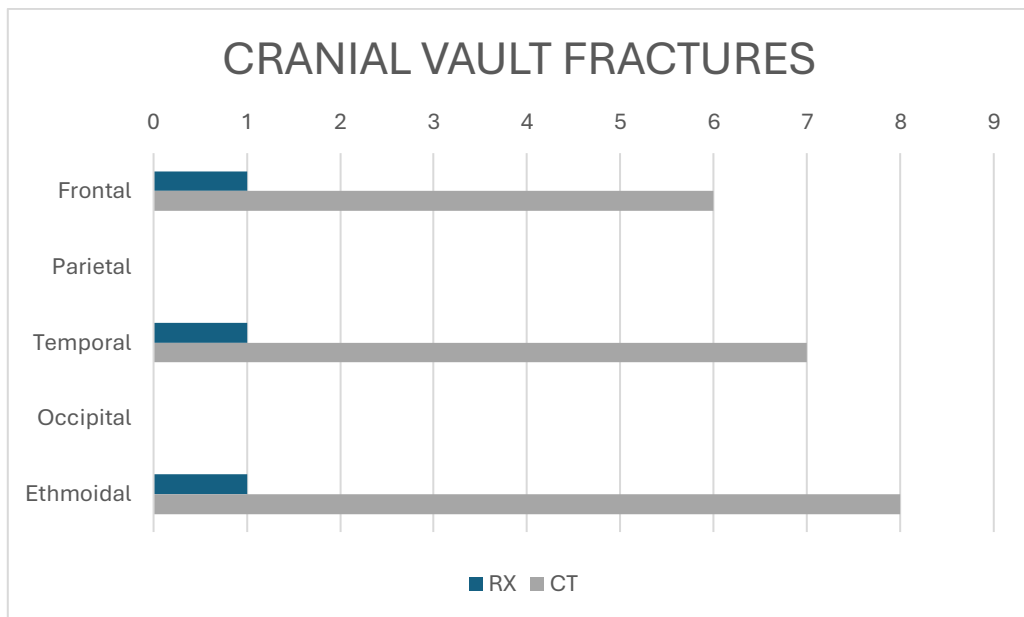
No fractures of the vomer, parietal, occipital or basioccipital bones were identified in any patient (0%) on both modalities.



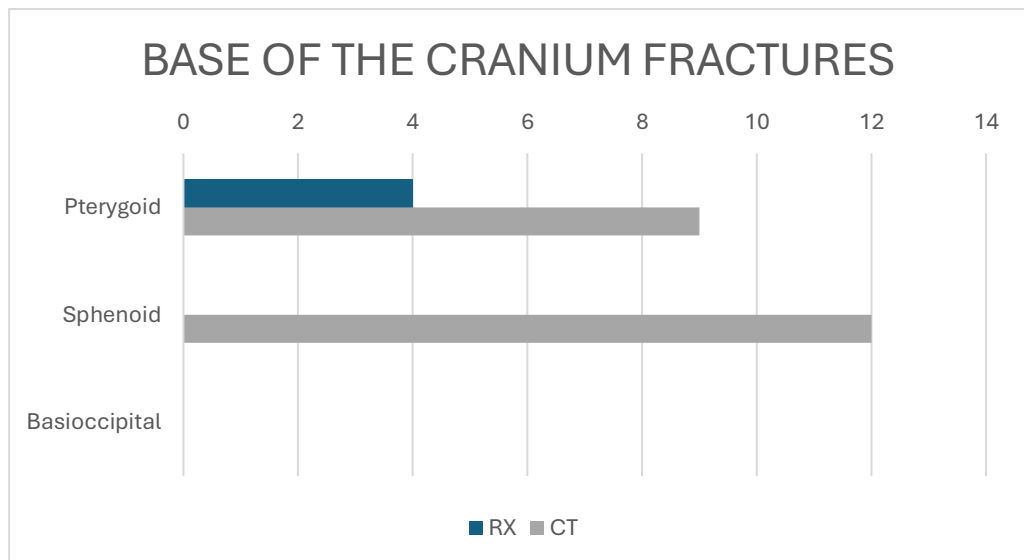
Graphic 1: Comparison of craniomaxillofacial fractures detected by RX and CT in the three categories of the craniomaxillofacial fracture system



Graphic 2: Comparison of face bones fractures detected by RX and CT



Graphic 3: Comparison of cranial vault bones fractures detected by RX and CT

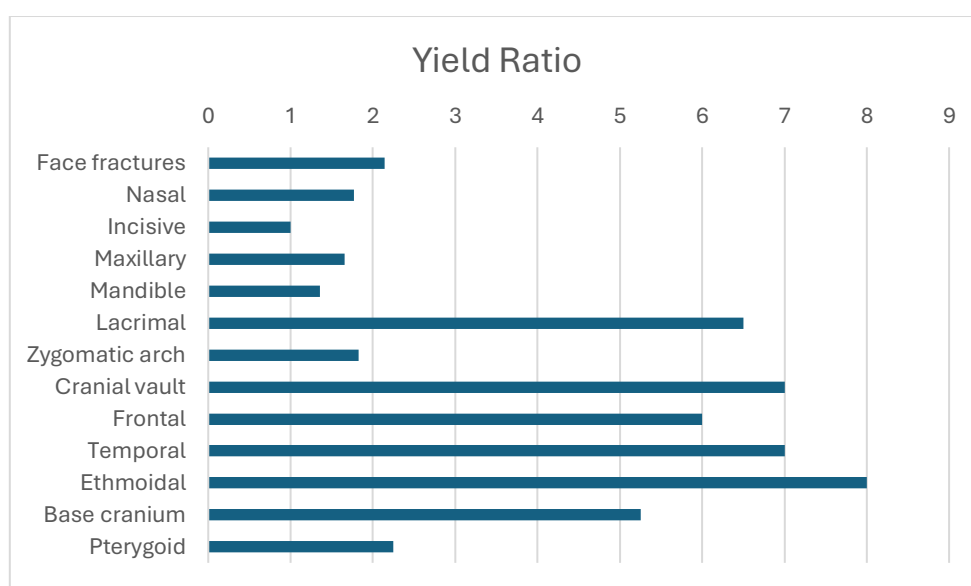


Graphic 4: Comparison of fractures of the bones of the base of the cranium detected by RX and CT.

Statistically, a Yield Ratio of 1.00 was observed for the incisive bone, indicating equal fracture detection. The lowest ratio above 1.00 was recorded for the mandible (1.36), followed by the maxillary bone (1.66), nasal bone (1.77), and zygomatic arch (1.83).

Higher ratios were observed for the pterygoid bone (2.25), cranial vault overall (7.00), base of the cranium overall (5.25), ethmoidal bone (8.00), frontal bone (6.00), lacrimal bone (6.50), and temporal bone (7.00).

For the palatine and sphenoid bones, the computed Yield Ratio was not calculable as radiography did not detect any fracture.



Graphic 5: CT-to-RX Yield Ratio (fracture detection multiplier) across feline skull structures.

McNemar's Test identified highly significant diagnostic differences ($X^2 > 3.84$, $P < 0.05$) in the sphenoid bone ($X^2 = 10.08$), lacrimal bone ($X^2 = 9.09$), base of the cranium ($X^2 = 9.09$), palatine bone ($X^2 = 8.10$), nasal bone ($X^2 = 5.14$), cranial vault ($X^2 = 6.13$), temporal bone ($X^2 = 4.17$), and ethmoidal bone ($X^2 = 5.14$).

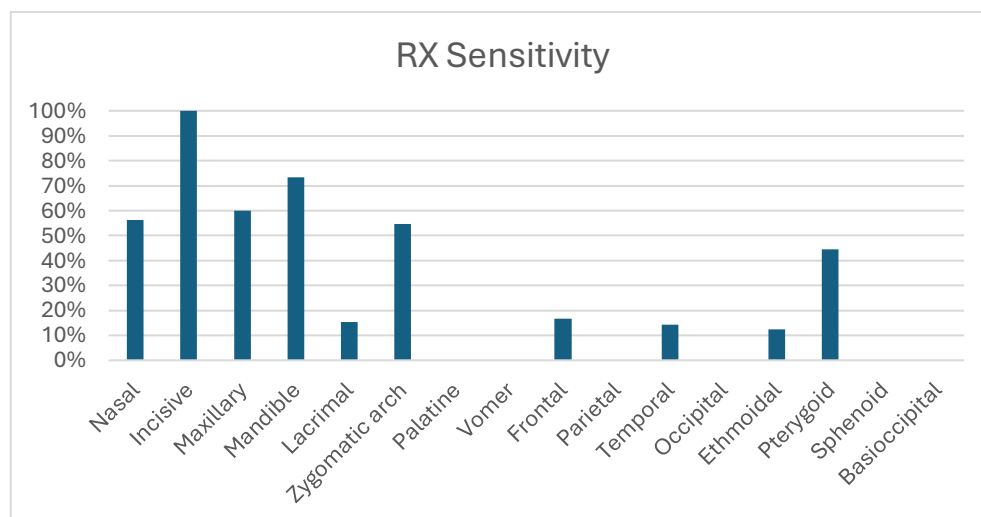
However, no statistically significant differences in diagnostic distribution were found for the zygomatic arch ($X^2 = 3.20$), frontal bone ($X^2 = 3.20$), pterygoid bone ($X^2 = 3.20$), maxillary bone ($X^2 = 2.25$), overall face fractures ($X^2 = 2.25$), and mandible ($X^2 = 2.25$).

For the incisor, vomer, parietal, occipital, and basioccipital bones, the McNemar test was mathematically uncalculated. This is due to the 100% concordance between the RX and CT findings; the lack of discordant pairs, in fact, annulled the denominator of the McNemar formula. Overall, conventional radiography identified 36.1% of all CT-confirmed fractures (43 out of 119).

The sensitivity and accuracy of RX varied across the specific bones. The highest sensitivity was calculated for the incisive bone (100%) and the mandible (73%), followed by the maxillary bone (60%), nasal bone (56%), and zygomatic arch (55%). Sensitivity was lower for the pterygoid bone (44%), cranial vault overall (27%), base of the cranium overall (27%), ethmoidal bone (13%), frontal bone (17%), lacrimal bone (15%), and temporal bone (14%). Sensitivity was 0% for both the palatine and sphenoid bones.

The highest accuracy was recorded in the mandible (78%) and the maxillary bone (78%). The lowest accuracy values were found in the temporal bone (67%), ethmoidal bone (61%), nasal bone (61%), cranial vault overall (56%), palatine bone (44%), lacrimal bone (39%), base of the cranium overall (39%), and sphenoid bone (33%).

For bones where no fractures were detected by either CT or RX (vomer, parietal, occipital, and basioccipital), the sensitivity could not be calculated.



Graphic 6: Diagnostic sensitivity of conventional radiography (RX) for the detection of skull fractures across different anatomical regions in 18 cats.

For Cohen's kappa, agreement was interpreted as follows:

- Excellent Agreement was observed only in the incisive bone ($\kappa = 1.00$).
- Moderate Agreement was recorded for the mandible ($\kappa = 0.48$), the maxillary bone ($\kappa = 0.57$), zygomatic arch ($\kappa = 0.48$), and pterygoid bone ($\kappa = 0.44$).
- Poor Agreement was observed for the cranial vault ($\kappa = 0.23$), ethmoidal bone ($\kappa = 0.14$), nasal bone ($\kappa = 0.22$), frontal bone ($\kappa = 0.21$), temporal bone ($\kappa = 0.17$), base of the cranium ($\kappa = 0.11$), and lacrimal bone ($\kappa = 0.09$).

For the palatine bone, sphenoid bone and overall face category, κ values at or near 0 were not interpreted as evidence of meaningful agreement, because one of the marginal distributions was constant or extremely unbalanced. For these categories, the diagnostic counts and sensitivity were considered more informative than κ .

For the vomer, parietal, occipital, and basioccipital bones, the kappa coefficient was not computable. This occurs because both modalities registered 100% negative cases (zero variance in the dataset), which results in a division by zero in the formula of Cohen's kappa.

Educated Eye Study

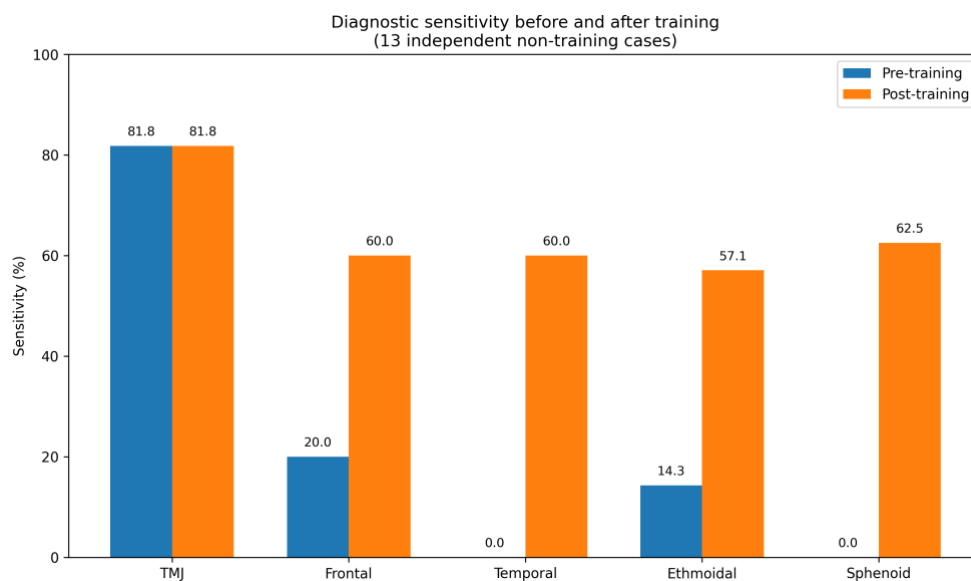
Primary Analysis: Independent Test Set

The primary analysis was conducted on 13 cases not utilized during the training protocol. It served as an independent test set to evaluate true learning generalizability to novel radiographs.

On an individual patient basis, 7 of 13 cats (53.8%) showed an increase in the total number of radiographically identified fractures. The remaining 6 cats (46.2%) showed no change, and no patients had a decrease in detected lesions. An exact Wilcoxon signed-rank test for paired samples confirmed a statistically significant increase in overall lesion detection per patient ($Z = -2.392$, exact two-tailed $P = 0.016$), supporting a learning effect that generalized to cases not used during training.

When analysing bones individually, diagnostic sensitivity varied between the pre-training and post-training assessments.

For the temporomandibular joint, sensitivity was 81.8% at baseline and remained at 81.8% post-training. For the frontal bone, sensitivity increased from 20.0% (1/5) at baseline to 60.0% (3/5) post-training. For the temporal bone, sensitivity increased from 0.0% (0/5) at baseline to 60.0% (3/5) post-training. For the ethmoidal bone, sensitivity increased from 14.3% (1/7) at baseline to 57.1% (4/7) post-training. For the sphenoid bone, sensitivity increased from 0.0% (0/8) at baseline to 62.5% (5/8) post-training.



Graphic 7: Diagnostic sensitivity of conventional radiography before and after training across the five evaluated structures in the 13 independent non-training cases

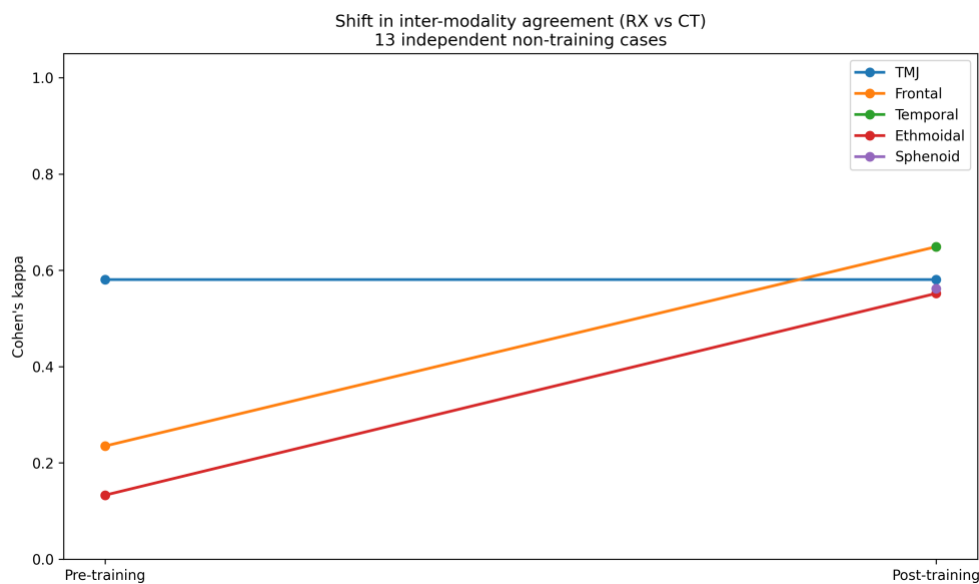
McNemar's test for paired binary data computed the following two-tailed exact P-values:

- Frontal bone: $P = 0.500$
- Temporal bone: $P = 0.250$
- Ethmoidal bone: $P = 0.250$
- Sphenoid bone: $P = 0.063$

For the TMJ the test was not applicable, due to the absence of discordant pairs.

Agreement between conventional radiography and computed tomography shifted across the study phases:

- TMJ: κ remained at 0.581 (moderate agreement).
- Frontal bone: κ increased from 0.235 (poor agreement) to 0.649 (good agreement).
- Temporal bone: κ was not estimable pre-training due to zero positive detections, reaching 0.649 (good agreement) after training.
- Ethmoidal bone: κ increased from 0.133 (poor agreement) to 0.552 (moderate agreement).
- Sphenoid bone: κ was not estimable pre-training due to zero positive detections, reaching 0.562 (moderate agreement) after training.



Graphic 8: Shift in inter-modality agreement (RX vs CT) expressed by Cohen's kappa in the 13 independent non-training cases.

Note: pre-training Cohen's kappa was not estimable for the temporal and sphenoid bones because the corresponding radiographic variables were constant (no positive detections). Therefore, the respective lines are shown only from the post-training assessment.

Descriptive Analysis: Training Subset

The 5 cases directly employed during the visual training protocol were analysed separately as a descriptive subset.

On an individual patient basis, all 5 cats (100%) showed an increase in the total number of radiographically identified fractures, with no unchanged or worsened cases. An exact Wilcoxon signed-rank test for paired samples yielded $Z = -2.070$ ($P = 0.063$), which did not reach statistical significance due to the limited sample size of five subjects.

When analysing bones individually, diagnostic sensitivity shifted as follows:

- For the temporomandibular joint, sensitivity increased from 50.0% (2/4) at baseline to 100% (4/4) post-training.
- For the frontal bone, sensitivity was 0.0% (0/1) pre-training and remained 0.0% (0/1) post-training.
- For the temporal bone, sensitivity increased from 50.0% (1/2) at baseline to 100% (2/2) post-training.
- For the ethmoidal bone, sensitivity increased from 0.0% (0/1) at baseline to 100% (1/1) post-training.
- For the sphenoid bone, sensitivity increased from 0.0% (0/4) at baseline to 75.0% (3/4) post-training.

McNemar's test for paired binary data computed the following two-tailed exact P-values:

- TMJ: $P = 0.500$
- Frontal bone: $P = 1.000$
- Temporal bone: $P = 1.000$
- Ethmoidal bone: $P = 1.000$
- Sphenoid bone: $P = 0.250$

Agreement between conventional radiography and computed tomography shifted across the study phases:

- TMJ: κ increased from 0.286 (poor agreement) to 1.000 (excellent agreement).
- Frontal bone: κ was not estimable pre-training, reaching -0.250 post-training.
- Temporal bone: κ increased from 0.545 (moderate agreement) to 1.000 (excellent agreement).
- Ethmoidal bone: κ was not estimable pre-training, reaching 1.000 (excellent agreement) after training.
- Sphenoid bone: κ was not estimable pre-training, reaching 0.545 (moderate agreement) after training.

Secondary Full-Cohort Analysis and Comparison with the Independent Test Set

Across the five structures included in the training analysis, CT identified 48 positive patient-structure observations in the full cohort. Radiography correctly identified 14/48 before training (29.2%) and 34/48 after training (70.8%). These pooled proportions are descriptive because multiple observations came from the same patient; the inferential assessment of overall training effect was therefore based on the paired per-patient Wilcoxon analysis.

When analysing bones individually, diagnostic sensitivity varied between pre-training and post-training assessments.

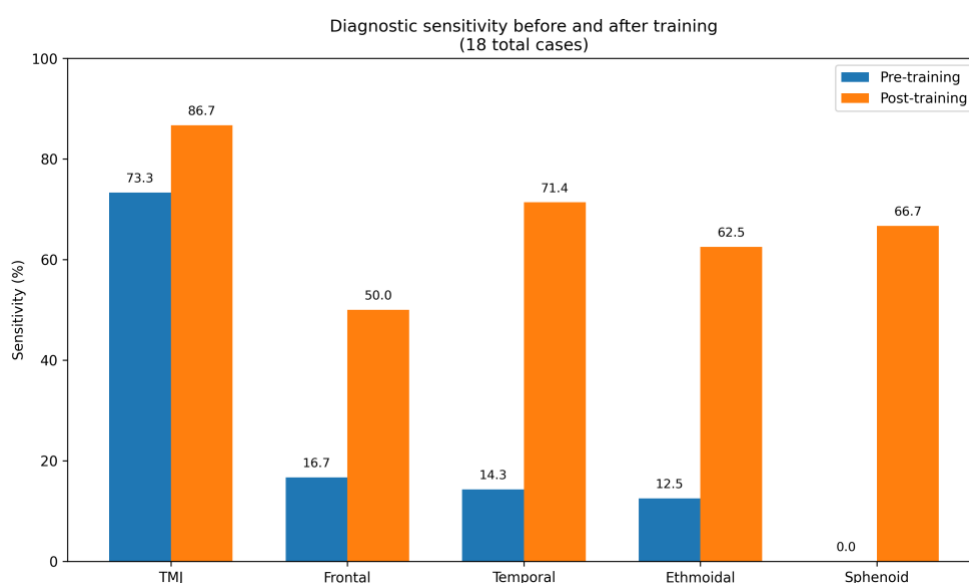
For the temporomandibular joint, sensitivity increased from 73.3% (11/15) at baseline to 86.7% (13/15) post-training.

For the frontal bone, sensitivity increased from 16.7% (1/6) at baseline to 50.0% (3/6) post-training.

For the temporal bone, sensitivity increased from 14.3% (1/7) at baseline to 71.4% (5/7) post-training.

For the ethmoidal bone, sensitivity increased from 12.5% (1/8) at baseline to 62.5% (5/8) post-training.

For the sphenoid bone the sensitivity increased from 0.00% (0/12) at baseline to 66.7% (8/12) post-training.



Graphic 9: Diagnostic sensitivity of conventional radiography before and after training across the five evaluated structures in the full cohort of 18 cases.

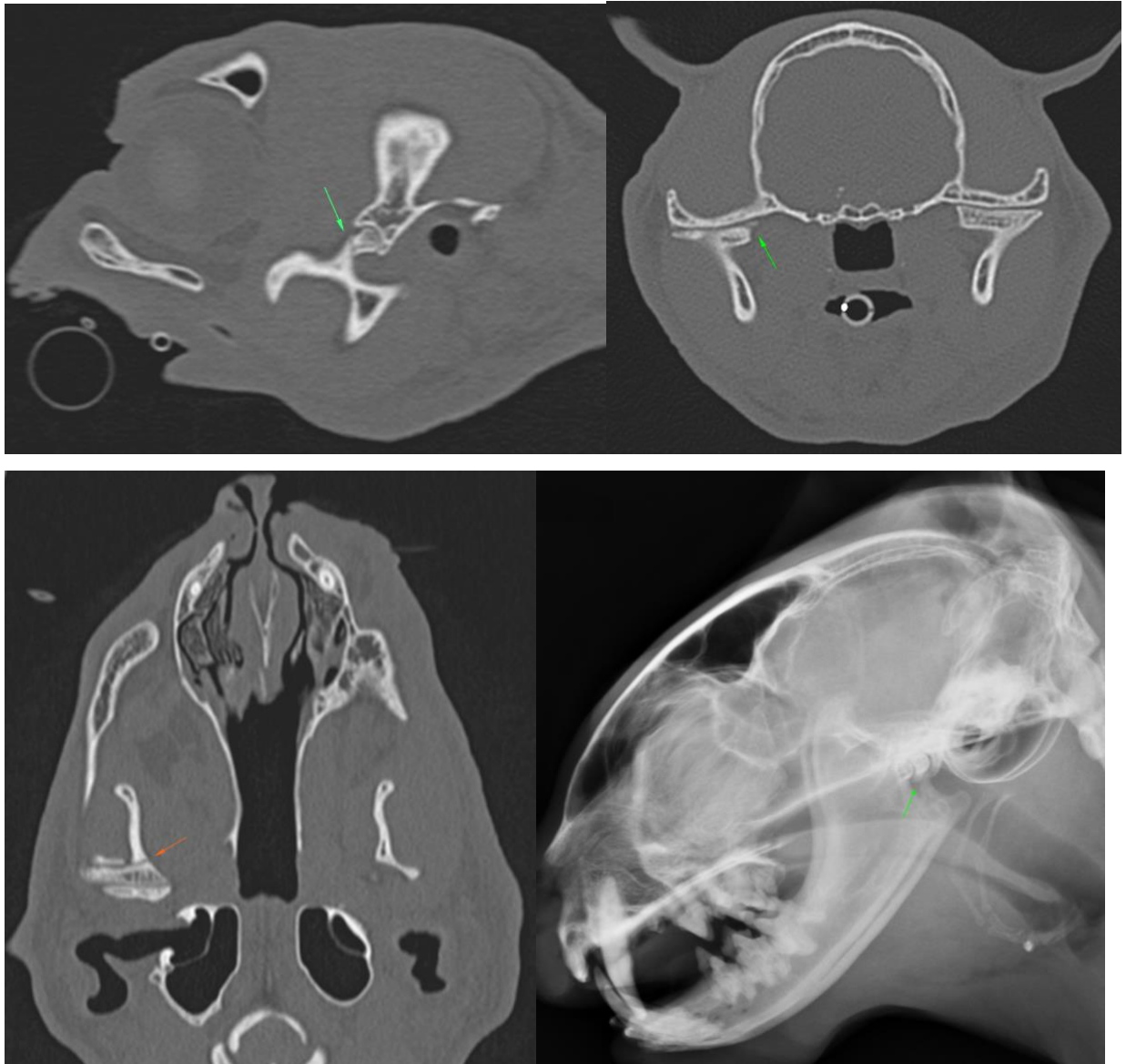


Figure 6: TMJ fracture detected on RX evaluated post-training and corresponding native CT slice (OVUD, Faculty of Veterinary Medicine, University of Parma)

On an individual patient basis, 12 of 18 cats (66.7%) showed an increase in the total number of correctly identified structures. The remaining 6 cats (33.3%) showed no change, and no patient worsened. The exact Wilcoxon signed-rank test confirmed a significant increase in the per-patient detection score ($Z = -3.109$, exact two-tailed $P < 0.001$).

The overall CT-to-RX Yield Ratio decreased from 3.43 before training to 1.41 after training, corresponding to a 58.8% relative reduction in the CT-to-RX detection ratio.

For the TMJ, the Yield Ratio decreased from 1.36 to 1.15.

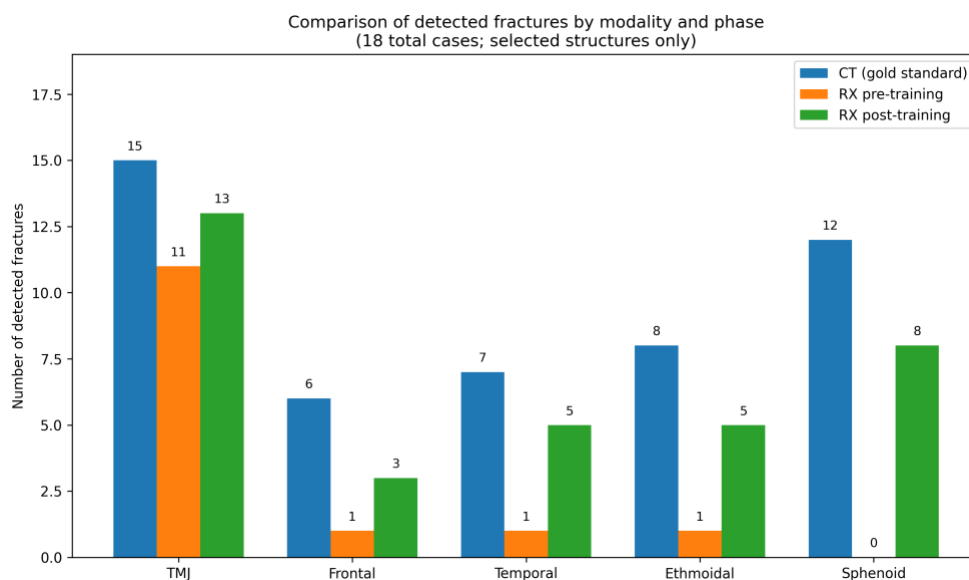
For the frontal bone, the Yield Ratio decreased from 6.00 to 2.00.

For the temporal bone, the Yield Ratio decreased from 7.00 to 1.40.

For the ethmoidal bone, the Yield Ratio decreased from 8.00 to 1.60.

For the sphenoid bone, the pre-training Yield Ratio was not calculable because no fractures were detected radiographically; after training, the Yield Ratio was 1.50.

These ratios are presented as descriptive measures of the reduction in the diagnostic detection gap between CT and radiography. The 18-case full-cohort results were interpreted as a secondary analysis because this cohort includes the 5 cases used during training, whereas the 13-case non-training set represents the independent test set.



Graphic 10: Comparison of fracture counts identified on CT, pre-training radiography, and post-training radiography in the 18 total cases (selected structures only).

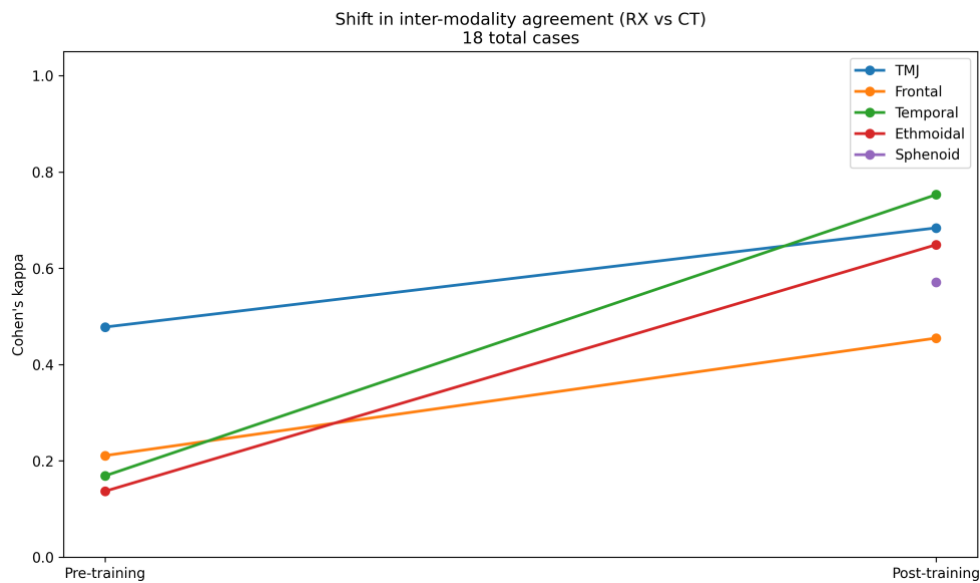
McNemar's test for paired binary data computed the following exact two-tailed P -values:

- TMJ: $P = 0.500$
- Frontal bone: $P = 0.250$

- Temporal bone: $P = 0.125$
- Ethmoidal bone: $P = 0.125$
- Sphenoid bone: $P = 0.008^*$

Agreement between conventional radiography and computed tomography shifted across the study phases:

- TMJ: κ increased from 0.478 (moderate agreement) to 0.684 (good agreement).
- Frontal bone: κ increased from 0.211 (poor agreement) to 0.455 (moderate agreement).
- Temporal bone: κ increased from 0.169 (poor agreement) to 0.753 (good agreement).
- Ethmoidal bone: κ increased from 0.137 (poor agreement) to 0.649 (good agreement).
- Sphenoid bone: κ was not computable pre-training due to zero positive detections, reaching 0.571 (moderate agreement) after training.



Graphic 11: Shift in inter-modality agreement (RX vs CT) expressed by Cohen's kappa in the 18 total cases.

* Statistically significant regional change (exact two-tailed McNemar's test, $P < 0.05$)

DISCUSSION

In the present study CT identified a total of 119 distinct fractures, whereas conventional radiography detected only 43 fractures. Thus, radiography successfully identified only 36.1% of the total skeletal lesions present. This overall low detection rate is highly consistent with veterinary literature. For instance, a prospective study by Bar-Am et al. (2008) reported that "only 11 of 26 (42.3%) predefined anatomic features had a mean score indicative of good identification on at least 1 radiographic view" (p.296).

It was observed that facial fractures were the most common trauma pattern in cats, with splanchnocranial fractures detected on CT in 100% of the patients (77 total fractures). This high prevalence aligns with the literature (Tundo *et al.*, 2019). Similar high frequencies of craniofacial and mandibular involvement have also been reported by Knight and Meeson (2019).

The mandible was the only bone structure where radiography demonstrated clinical utility, with a sensitivity of 73.0%, an accuracy of 78.0% and a moderate inter-modality agreement ($\kappa = 0.48$). The mandibular body is a prominent structure with minimal overlying skeletal tissue, making its fracture lines easily visible on RX. This is reflected in a very low Yield Ratio of 1.36, showing that CT was only slightly more effective than RX in this district. This low multiplier confirms that conventional radiography remains a reliable first-line screening option for mandible injuries. This is in complete agreement with Bar-Am et al. (2008) who reported that "Skull radiography is superior for visualizing the mandibular body (LL and OBL views) and dental occlusion (DV view)" (p.296) .

In stark contrast, deep facial structures such as the palatine and lacrimal bones represent severe radiographic blind spots. These deep facial bones are physically masked by the alveolar arches of the maxillary teeth and the zygomatic process. Indeed, palatine fractures were undetected on RX, yielding a sensitivity of 0.0% (κ not estimable due to constant zero variance), with a highly significant McNemar discordance ($X^2 = 8.10$, $P < 0.05$). Lacrimal fractures were identified with only 15.0% sensitivity ($X^2 = 9.09$, $P < 0.05$), with a high Yield Ratio of 6.50. This extreme multiplier demonstrates that plain radiography is virtually blind in these deep regions, making CT necessary. Skeletal injuries involving the vault and the base of the cranium carry grave prognostic significance, according to Amengual-Batle et al. (2020) "cranial vault fractures were associated with neurological deficits and worse survival" (p. 1975). In the present study, radiography demonstrated poor diagnostic agreement for both the cranial vault ($\kappa = 0.23$) and the skull base ($\kappa = 0.11$). Indeed, frontal and temporal fractures showed sensitivities of only 17% and 14% respectively. On radiographs, the dense petrous part of the temporal bone and the tympanic bullae

are heavily superimposed, hiding fissure lines. Missing injuries in this area can result in severe, permanent neurological complications, including facial nerve paralysis, Horner's syndrome and vestibular deficits. Sanroman-Llorens et al. (2020) reported that "traumatic tympanic bullae fractures seem to be rare in small animals and associated with neurological deficits and severe head trauma" (p.1). They documented that high-resolution CT was necessary to detect multiple tympanic bullae fractures that were invisible on plain radiographs.

Fractures of the sphenoid bone were completely missed on radiography, Cohen's kappa was not considered interpretable because radiographic detections were constantly zero, while McNemar's test demonstrated significant diagnostic discordance ($\chi^2 = 10.08$, $P < 0.05$). The complete blindness of radiography to sphenoid fractures represents an unacceptable risk in the triage of feline polytrauma patients, making CT mandatory.

During the pre-training evaluation, a non-specific awareness of anatomical distortion was frequently perceived in radiographs. However, pinpointing the exact fracture was impossible due to severe anatomical superimposition. Following visual training, this ambiguous perception shifted to structured identification, and specific landmarks were recognized, allowing accurate localization of fracture lines.

In the second phase of the study, radiographic reassessment following the training protocol produced a diagnostic improvement. In the primary analysis of the 13 independent test cases, 7/13 cats (53.8%) improved, 6 remained unchanged and none worsened. The exact Wilcoxon signed-rank test showed a significant global per-subject improvement ($P = 0.016$). This represents the main inferential result of the study and supports the generalizability of the learned visual patterns to radiographs not used during training.

In the descriptive subset of 5 training cases, all subjects (100%) improved, although the exact two-tailed Wilcoxon test did not reach statistical significance ($Z = -2.070$, $P = 0.063$), as expected given the very small sample size.

Finally, in the secondary full-cohort analysis, 12/18 cats (66.7%) improved and none worsened, with a highly significant paired Wilcoxon result ($Z = -3.109$, exact two-tailed $P < 0.001$). Across the five selected structures, the pooled descriptive detection proportion increased from 14/48 (29.2%) to 34/48 (70.8%). Because the full cohort contains the 5 training cases as well as the 13 independent cases, this larger overall effect should be interpreted as supportive rather than as an independent replication.

For the TMJ, visual training consolidated diagnostic certainty, advancing inter-modality agreement from moderate to good in the overall cohort ($\kappa = 0.684$). In the independent test set of 13 cases,

baseline sensitivity for the TMJ was already high (81.8%). This value remained stable post-training, demonstrating that the training effect was most pronounced in challenging neurocranial region. In feline traumatology, accurate identification of condylar and retroarticular fractures is critical, as unrecognized injuries frequently triggers severe chronic complications, including temporomandibular ankylosis. (Schwarz *et al.*, 2002; Arzi *et al.*, 2013)

In both the frontal and temporal bones, the training was successful: the sensitivity increased substantially reaching 60.0% independent cases and up to 71.4% in the overall cohort. Cohen's kappa shifted from poor values to good agreement (frontal: $\kappa = 0.649$; temporal: $\kappa = 0.649$ in independent cases). This is a positive outcome considering that diffuse soft tissues swelling and masticatory musculature can obscure the margins of the cranial vault (Meomartino *et al.*, 2021).

The most impactful result was achieved at the skull base. While sphenoid fractures were at first completely undetectable, post-training sensitivity reached 62.5% in independent cases and 66.7% across all 18 cases with moderate agreement ($\kappa = 0.562$ - 0.571). In the full cohort, the sphenoid was the only individual anatomical structure to demonstrate a statistically significant regional change on the exact two-tailed McNemar's test ($P = 0.008$). Because the sphenoid transmits cranial nerves and borders vital cerebral vasculature, identifying these fractures directly alerts the clinician to suspected traumatic brain injury or intracranial haemorrhage (Garosi & Adamantos, 2011; Platt, 2005; Lee *et al.*, 2014).

In contrast, the ethmoidal bone highlighted the physical limits of conventional radiography. Despite an apparent rise in sensitivity, reliable distinction of fractures remains challenging due to the delicate ethmoturbinate framework, combined with traumatic haemorrhage and bilateral summation (Bar-Am *et al.*, 2008; Lee, Kellman and Darling, 2014). At the individual structure level, statistical significance on McNemar's test was limited by low number of positive fractures events per site. Hence, the per-subject global score evaluated by the Wilcoxon test serves as a more informative measure of overall training efficacy.

High specificity was maintained post-training across evaluated regions. However, a single false positive in the frontal bone within the training subset indicates that visual training, while boosting sensitivity, does not completely eliminate the risk of overinterpretation.

These findings must not be interpreted as evidence that radiography interpreted by a trained eye can replace computed tomography. Emergency guidelines emphasize that "CT is the modality of choice for the investigation of head trauma" (Labruyère & Schwarz, 2013, p. 29). CT remains the gold standard because it eliminates projectional overlap and detects non-displaced micro-fractures. Instead, the true value of the educated eye lies in emergency triage: when CT is unavailable,

unaffordable, or delayed due to patient instability. An educated eye can extract vital prognostic information from RX that would otherwise be dismissed.

Several limitations of this study should be acknowledged. First, the retrospective design and relatively small sample size (18 cats) limited statistical power. Furthermore, the evaluation was performed by a single inexperienced observer, a fifth-year veterinary student, so the magnitude of the training effect cannot be assumed to generalize to observers with different levels of experience. Moreover, although a wash-out period of more than three weeks, anonymization, new case identifiers and a new presentation order were used to minimize recall bias, residual memory of individual cases cannot be completely excluded.

Finally, the long-term retention of visual learning (learning decay) was not evaluated over time. To validate these outcomes, future prospective studies are recommended. These should involve multi-observer cohorts, including veterinary students, general practitioners and board-certified radiologists.

CONCLUSION

The study confirms that computed tomography remains the gold standard for fracture detection in feline head trauma, whereas conventional radiography underestimates fracture due to complex anatomical superimposition.

However, this work indicates that part of the diagnostic limitation of radiography is perceptual as well as physical. After targeted CT-guided visual training, the inexperienced observer improved fracture recognition, and the improvement remained statistically significant in the 13 cases not used during training. The greatest gain involved difficult neurocranial structures, particularly the sphenoid. Nevertheless, even with an “educated eye”, the physical limitations of projection radiography cannot be overcome completely, and CT remains the reference standard for comprehensive evaluation and surgical planning in feline craniomaxillofacial trauma.

Nevertheless, radiography interpreted by a trained eye provides substantial clinical utility in emergency frontline triage. For instance, it can be used in settings where advanced imaging is unavailable, cost-prohibitive, or postponed due to patient instability. Under these circumstances, an educated clinician can extract vital prognostic indicators, improving early diagnostic and therapeutic decision-making in traumatized feline patients.

BIBLIOGRAPHY

- Adamantos, S. and Garosi, L. (2011) 'Head trauma in the cat. 1. Assessment and management of craniofacial injury', *Journal of Feline Medicine and Surgery*, 13(11), pp. 806–814. Available at: <https://doi.org/10.1016/j.jfms.2011.09.002>.
- Amengual-Batle, P. *et al.* (2020) 'Traumatic skull fractures in dogs and cats: A comparative analysis of neurological and computed tomographic features', *Journal of Veterinary Internal Medicine*, 34(5), pp. 1975–1985. Available at: <https://doi.org/10.1111/jvim.15838>.
- Arzi, B. *et al.* (2013) 'Computed tomographic findings in dogs and cats with temporomandibular joint disorders: 58 cases (2006-2011)', *Journal of the American Veterinary Medical Association*, 242(1), pp. 69–75. Available at: <https://doi.org/10.2460/javma.242.1.69>.
- Arzi, B. *et al.* (2020) 'Feline skull injuries: treatment goals and recommended approaches', *Journal of Feline Medicine and Surgery*. SAGE Publications Ltd, pp. 453–455. Available at: <https://doi.org/10.1177/1098612X20917603>.
- Audigé, L. *et al.* (2014) 'The first AO classification system for fractures of the craniomaxillofacial skeleton: rationale, methodological background, developmental process, and objectives', *Craniomaxillofacial Trauma and Reconstruction*, 7, pp. S6–S14.
- Bar-Am, Y. *et al.* (2008) 'The diagnostic yield of conventional radiographs and computed tomography in dogs and cats with maxillofacial trauma', *Veterinary Surgery*, 37(3), pp. 294–299. Available at: <https://doi.org/10.1111/j.1532-950X.2008.00380.x>.
- Bešenski, N. (2002) 'Traumatic injuries: Imaging of head injuries', *European Radiology*, 12(6), pp. 1237–1252. Available at: <https://doi.org/10.1007/s00330-002-1355-9>.
- Bhamburkar and Banubakode, S.B. (2021) *Veterinary Anatomy: The Regional Gross Anatomy of Domestic Animals*.
- Bonner, S.E., R.A.M., & L.J.R. (2012) 'Orofacial manifestations of high-rise syndrome in cats: a retrospective study of 84 cases. ', *Journal of Veterinary Dentistry* [Preprint].
- Buitrago-Téllez, C.H. *et al.* (2014) 'The Comprehensive AO-CMF Classification System: Radiological Issues and Systematic Approach', *Craniomaxillofacial Trauma & Reconstruction*, 7(1_suppl), pp. 123–130. Available at: <https://doi.org/10.1055/s-0034-1389565>.

- Çetinkaya, M.A. (2012) 'Temporomandibular joint injuries and ankylosis in the cat', *Veterinary and Comparative Orthopaedics and Traumatology*, 25(5), pp. 366–374. Available at: <https://doi.org/10.3415/VCOT-11-10-0146>.
- Charlotte Whatmough, C.R.L. (2006) 'Computed Tomography: Principles and Applications'.
- Constantaras, M.E. and Charlier, C.J. (2014) 'Maxillofacial Injuries and Diseases That Cause an Open Mouth in Cats'.
- Drew, L.B. and Drew, W.E. (2004a) *New Perspectives in Brain Injury The Contrecoup-Coup Phenomenon A New Understanding of the Mechanism of Closed Head Injury*.
- Drew, L.B. and Drew, W.E. (2004b) *New Perspectives in Brain Injury The Contrecoup-Coup Phenomenon A New Understanding of the Mechanism of Closed Head Injury*.
- Garosi, L. and Adamantos, S. (2011) 'Head trauma in the cat. 2. Assessment and management of traumatic brain injury', *Journal of Feline Medicine and Surgery*, 13(11), pp. 815–823. Available at: <https://doi.org/10.1016/j.jfms.2011.09.003>.
- Greco, A. *et al.* (2023) 'Imaging techniques in veterinary medicine. Part II: Computed tomography, magnetic resonance imaging, nuclear medicine', *European Journal of Radiology Open*. Elsevier Ltd. Available at: <https://doi.org/10.1016/j.ejro.2022.100467>.
- Klainbart, S. *et al.* (2022) 'Dog bite wounds in cats: a retrospective study of 72 cases', *Journal of Feline Medicine and Surgery*, 24(2), pp. 107–115. Available at: <https://doi.org/10.1177/1098612X211010735>.
- Knight, R. and Meeson, R.L. (2019) 'Feline head trauma: a CT analysis of skull fractures and their management in 75 cats', *Journal of Feline Medicine and Surgery*, 21(12), pp. 1120–1126. Available at: <https://doi.org/10.1177/1098612X18819183>.
- König, H.E. and Liebich, H.-G. (2020) *Anatomia degli animali domestici. Testo-atlante a colori*. 3rd ed. Edited by Piccin-Nuova Libreria.
- Kuo, K.W., Bacek, L.M. and Taylor, A.R. (2018) 'Head Trauma', *Veterinary Clinics of North America - Small Animal Practice*. W.B. Saunders, pp. 111–128. Available at: <https://doi.org/10.1016/j.cvsm.2017.08.005>.
- Labruyère, J. and Schwarz, T. (2013) 'CT and MRI in veterinary patients: An update on recent advances', *In Practice*, 35(10), pp. 546–563. Available at: <https://doi.org/10.1136/inp.f6720>.

- Lee, T.S., Kellman, R. and Darling, A. (2014) 'Crumple zone effect of nasal cavity and paranasal sinuses on posterior cranial fossa', *Laryngoscope*, 124(10), pp. 2241–2246. Available at: <https://doi.org/10.1002/lary.24644>.
- Mann, O. *et al.* (2022) 'CT findings and the prognostic value of the Koret CT score in cats with traumatic brain injury', *Journal of Feline Medicine and Surgery*, 24(2), pp. 91–97. Available at: <https://doi.org/10.1177/1098612X211005306>.
- Meomartino, L. *et al.* (1999) 'Temporomandibular ankylosis in the cat: a review of seven cases', *Journal of Small Animal Practice* [Preprint].
- Meomartino, L. *et al.* (2021) 'Imaging techniques in Veterinary Medicine. Part I: Radiography and Ultrasonography', *European Journal of Radiology Open*. Elsevier Ltd. Available at: <https://doi.org/10.1016/j.ejro.2021.100382>.
- Mestrinho, L.A. *et al.* (2022) 'CT characterisation and classification of feline temporomandibular joint trauma: a case series of 79 cats', *Journal of Feline Medicine and Surgery*, 24(12), pp. 1181–1186. Available at: <https://doi.org/10.1177/1098612X211066654>.
- Nutt, A.E. *et al.* (2018) 'Open-mouth jaw locking in cats: a literature review and use of CT in three cases', *Journal of Feline Medicine and Surgery*. SAGE Publications Ltd, pp. 1180–1191. Available at: <https://doi.org/10.1177/1098612X17737433>.
- Platt, S. (2005) 'Evaluation and treatment of the head trauma patient', *In Practice*, 27(1), pp. 31–35. Available at: <https://doi.org/10.1136/inpract.27.1.31>.
- Rochlitz, I. (2003a) 'Study of factors that may predispose domestic cats to road traffic accidents: Part 1', *Veterinary Record*, 153(18), pp. 549–553. Available at: <https://doi.org/10.1136/vr.153.18.549>.
- Rochlitz, I. (2003b) 'Study of factors that may predispose domestic cats to road traffic accidents: Part 2', *Veterinary Record*, 153(19), pp. 585–588. Available at: <https://doi.org/10.1136/vr.153.19.585>.
- Sanroman-Llorens, F. *et al.* (2020) 'Traumatic Tympanic Bulla Fracture in a Cat With Severe Head Trauma', *Frontiers in Veterinary Science*, 7. Available at: <https://doi.org/10.3389/fvets.2020.00372>.

- Dos Santos, L.O. *et al.* (2018) 'Traumatic brain injury in dogs and cats: A systematic review', *Veterinarni Medicina. Czech Academy of Agricultural Sciences*, pp. 345–357. Available at: <https://doi.org/10.17221/20/2017-VETMED>.
- Schwarz, T. *et al.* (2002) 'Imaging of the canine and feline temporomandibular joint: A review', *Veterinary Radiology and Ultrasound*, pp. 85–97. Available at: <https://doi.org/10.1111/j.1740-8261.2002.tb01656.x>.
- Soukup, J.W. and Snyder, C.J. (2014) 'Traumatic Dentoalveolar and Maxillofacial Injuries in Cats: Overview of diagnosis and management', *Journal of Feline Medicine and Surgery*, 16(11), pp. 915–927. Available at: <https://doi.org/10.1177/1098612X14552367>.
- Tundo, I. *et al.* (2019) 'Location and distribution of craniomaxillofacial fractures in 45 cats presented for the treatment of head trauma', *Journal of Feline Medicine and Surgery*, 21(4), pp. 322–328. Available at: <https://doi.org/10.1177/1098612X18776149>.
- Vnuk, D. *et al.* (2004) 'Feline high-rise syndrome: 119 cases (1998-2001)', *Journal of Feline Medicine and Surgery*, 6(5), pp. 305–312. Available at: <https://doi.org/10.1016/j.jfms.2003.07.001>.
- Weichert, S., Kiefer, I. and Theyse, L.F.H. (2025) 'Assessment of Fracture Distribution and Involvement of Functional Systems Following Craniomaxillofacial Trauma in 48 Cats', *Veterinary and Comparative Orthopaedics and Traumatology* [Preprint]. Available at: <https://doi.org/10.1055/a-2651-6219>.
- Woodbridge, N. and Owen, M. (2013) 'Feline Mandibular Fractures: A significant surgical challenge', *Journal of Feline Medicine and Surgery*, 15(3), pp. 211–218. Available at: <https://doi.org/10.1177/1098612X13477541>.
- Zanotti, C. (2024) 'HEAD TRAUMA IN CATS: COMPUTED TOMOGRAPHY FINDINGS AND NEUROLOGICAL ASSESSMENT'.
- Zavodovskaya, R. *et al.* (2020) 'Intra- and Extra-articular Features of Temporomandibular Joint Ankylosis in the Cat (*Felis catus*)', *Journal of Comparative Pathology*, 175, pp. 39–48. Available at: <https://doi.org/10.1016/j.jcpa.2019.12.006>.