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NEUROANATOMY, DIGITAL ATLASES, AND TEMPLATES OF BRAINS OF DOMESTIC ANIMALS (CAT, DOG, PIG, HORSE and SHEEP) USING MAGNETIC RESONANCE IMAGING

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ABSTRACT. Over the last two decades, neuroscience has witnessed an explosion in the utilization of non-invasive imaging methods (particularly MRI) that are used to investigate to study the brain. Providing accurate and detailed imaging, MRI has a significant impact on figuring out the anatomy and functioning of the brain. In recent years, researchers studying on veterinary science have seen MRI as an indispensable tool themselves. It is essential to understand the anatomy of the normal brain in order to explain many of the pathological processes. This review focused on neuroanatomical studies, atlases and templates generated from the brains of domestic animals (cat, dog, pig, horse, donkey, cattle, sheep, goat, camel) using MRI from the 1980s to the present. Its data were summarized under three main parts. Firstly, the cross-sectional anatomy of the brain created using MRI was examined. Afterward, digital atlases and templates, which have had an essential place in modern neuroimaging analysis (such as registration, segmentation and three-dimensional reconstruction) in recent years, were summarized. Finally, in vivo or ex vivo studies in which crucial white matter tracts in the brain are three-dimensionally modeled with DTI (Diffusion Tensor Imaging) in domestic mammals were reviewed. Several studies examining the neocortex by DTI were also included in the review in this section. There were also neuroanatomy studies conducted with MRI in several specific species in this review. In conclusion, this review focused on the importance of MRI in neuroimaging of the brain in domestic animals.

Keywords: Brain, digital atlas, domestic animals, MRI, neuroanatomy, template.

MANYETİK REZONANS GÖRÜNTÜLEME KULLANILARAK EVCİL HAYVANLARIN (KEDİ, KÖPEK, DOMUZ, AT ve KOYUN) NÖROANATOMİSİ, DİJİTAL ATLASLARI ve BEYİN ŞABLONLARI

ÖZET. Sinirbiliminde, Manyetik Rezonans Görüntüleme (MRG) başta olmak üzere non-invaziv görüntüleme yöntemlerinin kullanımı ile büyük ilerlemeler gözlenmektedir. MRG, beyin anatomisini ve beynin işleyişini anlamada önemli bir etkiye sahiptir. Veteriner hekimlikte MRG, yumuşak dokuların görüntülenmesinde ve hastalıkların teşhisinde önemli bir yere sahiptir. Bu kapsamda birçok patolojik süreci açıklamak için normal beyin anatomisinin bilinmesi önemlidir. Bu derlemede, 1980'lerden günümüze evcil memelilerin (kedi, köpek, domuz, at, eşek, sığır, koyun, keçi, deve) beyinlerinde MRG kullanılarak oluşturulan nöroanatomik çalışmalar, atlaslar ve şablonlara odaklanılmıştır. Beynin nöroanatomisinin yanında, modern nörogörüntüleme analizlerinde önemli bir yere sahip olan dijital atlaslar ve şablonlar özetlenmiştir. Son olarak, evcil memelilerde beyindeki önemli ak madde yollarının Diffüzyon Tensör Görüntüleme (DTG) ile üç boyutlu olarak modellenmesi üzerinde durulmuştur. Ayrıca evcil memelilerin yanısıra sinirbiliminde önemli araştırmalar yapılan spesifik türlere de yer verilmiştir. Sonuç olarak bu derlemede MRG'nin evcil memelilerde beynin görüntülenmesindeki önemi üzerinde durulmuştur.

Anahtar Kelimeler: Beyin, dijital atlas, evcil memeliler, MRG, nöroanatomi, şablon.

Makale atıf

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INTRODUCTION

Every living organism must respond to environmental changes to survive. As a result, they can to react to physical and chemical stimuli from their surroundings. The nervous system receives stimuli and regulates responses to adapt to changes caused by these stimuli. Managing reactions is its primary responsibility, making it the most complicated of the body's systems. It establishes a connection with events occurring within the organism's body and its environment throughout its lifespan (Tecirlioğlu, 1983; Yıldırım, 2000; König et al., 2004; Dursun, 2008; Dyce et al., 2010). In anatomy, the nervous system is divided into two parts: the central nervous system and the peripheral nervous system. The central nervous system consists of the brain and the spinal cord (Tecirlioğlu, 1983; Yıldırım, 2000; König et al., 2004). The brain is an organ that controls or regulates the body's functions. It is responsible for the regulation and coordination of the rest (parts of the nervous system other than the brain, such as the spinal cord, cranial nerves, and spinal nerves) of the nervous system (König et al., 2004). Magnetic Resonance Imaging (MRI) is primarily preferred in non-invasive neuroimaging of the central nervous system, especially the brain (Basso et al., 2021). It is known that MRI is more successful than other non-invasive imaging methods in imaging soft tissues such as the brain, spinal cord, muscles, and joints (Eriş, 2008; Tuncel, 2008).

MRI provides a high soft tissue contrast and has a high spatial resolution and few safety drawbacks. There are three basic principles in non-invasive imaging: transmission (Radiography and Computed Tomography), reflection (ultrasound), and emission (MRI). MRI uses a strong magnet, necessitating the use of non-ferrous anesthetic and monitoring equipment during scans. During scanning, tissues are stimulated with radiofrequency, generating images through emission and capturing the returning radio waves from the stimulated tissues. Different sequences are obtained depending on the time at which the returning wave is captured and the type of radio wave (duration, phase, frequency) emitted (Asyalı, 2006; Gilbert et al., 2010; Manso-Díaz et al., 2021). A cross-sectional image is obtained from MRI, just like CT. However, unlike CT, MRI uses radio waves instead of ionizing radiation. MRI is a medical image technique with the highest soft tissue contrast resolution and is commonly used in clinics. It effectively detects pathological tissues, enabling precise and accurate examination of various diseases. In MRI, the localization of any structure in three dimensions can be determined by obtaining sections in different planes without changing the position (Kumaş, 2007; Eriş, 2008; Tuncel, 2008; Gilbert et al., 2010).

In the last two decades, Neuroimaging in Veterinary Science has gone through major advances and has become increasingly important in animal neurology. MRI is frequently used to examine the normal brains of domestic animals (Schmidt et al., 2012; Schmidt et al., 2019). In this context, the studies conducted on the brains of healthy domestic animals by MRI were summarized in three parts.

CROSS-SECTIONAL ANATOMY OF THE BRAIN OF DOMESTIC ANIMALS BY MRI

MRI is frequently used in veterinary science to image soft tissues, especially the brain. For these images obtained from healthy animals, it is very important to know the localization (Figure 1) of the brain in the skull and neuroanatomy (Figure 2) to interpret clinical findings (Leigh et al., 2007).

The first studies on the cross-sectional anatomy of the brain using MRI in domestic animals were conducted in carnivores. In this field, the anatomy and pathological findings of the brain are examined using MRI. Cross-sectional anatomy of the brain has been examined by MRI in domestic animals such as cat (Buonanno et al., 1982; Hudson et al., 1995; Smith et al., 2001; Rathjen et al., 2003; Mogicato et al., 2011a; Gray-Edwards et al., 2014; Przyborowska et al., 2017; Przyborowska et al., 2018; Martínez et al., 2021; McGregor et al., 2023), dog (Panciera et al., 1987; Kraft et al., 1989; Kärkkäinen et al., 1991; Kii et al., 1997; Couturier et al., 2005; Leigh et al., 2007; Kang et al., 2009; Martín-Vaquero et al., 2011; Mogicato et al., 2011b; Oto, 2017; Bakıcı et al., 2019; Hecht et al., 2019; Arribarat et al., 2022; Jacqmot et al., 2022; Barton et al., 2023), pig (Marcilloux et al., 1993; Sørensen et al., 2000; Oto et al., 2011; Schmidt, 2014), horse (Chaffin et al., 1997; Arencibia et al., 2001; Vazquez et al., 2001; Stuckenschneider et al., 2014; Schmidt et al., 2019), donkey (Oto, 2007; Abdel Maksoud et al., 2021), cattle (calf brain) (Schmidt et al., 2009a; Schmidt et al., 2009b; Schmidt et al., 2012), sheep (Schmidt et al., 2012; Bakıcı et al., 2020; Aydoğdu, 2021), goat (Schmidt et al., 2012) and camel (Arencibia et al., 2004; Arencibia

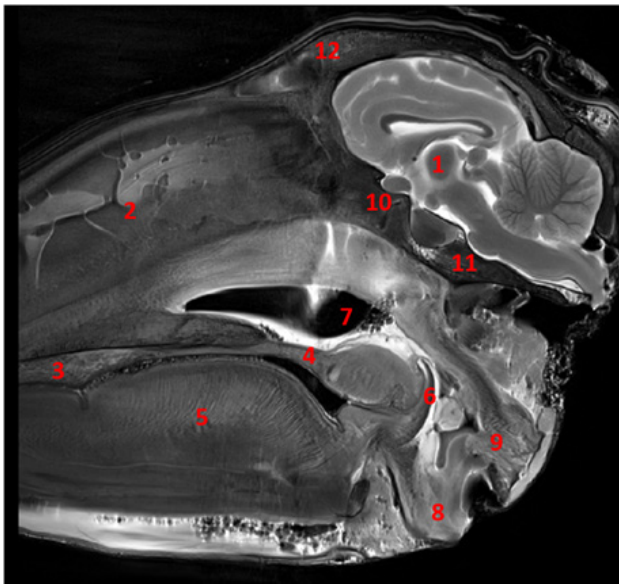

Figure 1. Sagittal T2W (T2 weighted) image of sheep head. Brain (1), nasal septum (2), hard palate (3), soft palate (4), tongue (5), epiglottis (6), nasopharynx (7), larynx (8), esophagus (9), presphenoid (10), basisphenoid (11), and frontal bone (12).

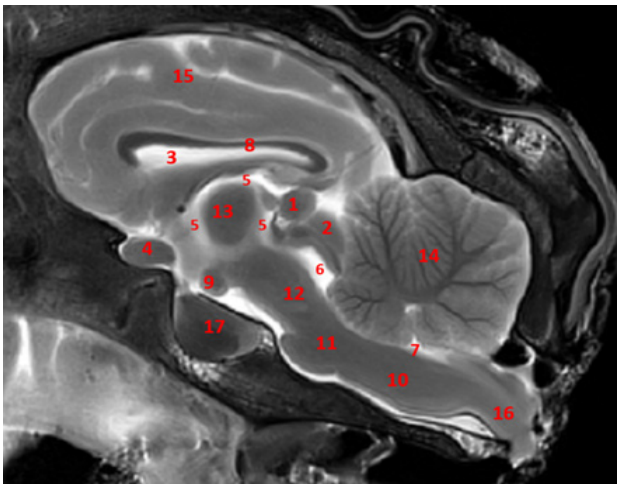

Figure 2. Cross-sectional anatomy of sheep brain. T2W (T2 weighted) image. Epithalamus/epiphysis (1), tectum (corpora quadrigemina) (2), lateral ventricle (3), optic chiasm (4), third ventricle (5), mesencephalic aqueduct (6), fourth ventricle (7), corpus callosum (8), mammillary body (9), medulla oblongata (10), pons (11), cerebral peduncles (12), thalamus (13), cerebellum (14), cerebral hemispheres (15), spinal cord (16).

et al., 2005; Abedellaah et al., 2015; Ben et al., 2019). The neuroanatomy of the brain in domestic animals has been revealed in detail with images obtained from healthy animals.

Apart from domestic animals, the cross-sectional anatomy of the brain has been examined using MRI in white whale (*Delphinapterus leucas*) (Marino et al., 2001a), killer whale (*Orcinus orca*) (Marino et al., 2004a), bottlenose dolphin (*Tursiops truncatus*) (Marino et al., 2001b), common dolphin (*Delphinus delphis*) (Marino et al., 2001c; Oelschläger et al., 2008), spinner dolphin (*Stenella longirostris orientalis*) (Marino et al., 2004b), California sea lion (*Zalophus californianus*) (Montie et al., 2009), Bengal tiger (*Panthera tigris tigris*) (Jáber Mohamad et al., 2016), silver fox (*Vulpes vulpes*) (Rogers Flattery et al., 2023), brown bear (*Carnivora, Ursus arctos L., 1758*) (Sienkiewicz et al., 2019), black (*Diceros bicornis*) and white (*Ceratotherium simum*) African rhinoceroses (Bhagwandin et al., 2017).

STEREOTAXIC, DIGITAL ATLASES AND TEMPLATES USED IN NEUROSCIENCE RESEARCH

Structural and Diffusion Tensor Imaging (DTI) brain atlases and templates are important tools used for conducting neuroscience research, and their clinical practices are increasing. Brain atlases and templates play a crucial role in neuroimaging analysis of brain structure and functions in neuroscience (Dickie et al., 2017; Hess et al., 2018). In order to carry out the neuroimaging analysis of images acquired from the brains of domestic animals by MRI, these atlases and templates are frequently used in image preprocessing methods (Figure 3). This review focused on all atlases and templates acquired from the brains of domestic animals with DTI and structural MRI.

Atlases and templates of the brains of domestic animals such as cats (Stolzberg et al., 2017; Johnson et al., 2020a), dogs (Datta et al., 2012; Robinson et al., 2016; Czeibert et al., 2019; Nitzsche et al., 2019; Johnson et al., 2020b; Liu et al., 2020), pigs (Saikali et al., 2010; Conrad et al., 2014; Gan et al., 2014; Schubert et al., 2016; Zhong et al., 2016; Villadsen et al., 2018; Benn et al., 2020; Chang et al., 2020; Fil et al., 2021; Norris et al., 2021; Knoernschild, 2022), horses (Johnson et al., 2019) and sheep (Ella and Keller, 2015; Nitzsche et al., 2015; Ella et al., 2017; Banstola and Reynolds, 2022; Shen et al., 2023) were created.

In addition to domestic animals, there are also atlases and templates for rhesus macaque (McLaren et al., 2009; Frey et al., 2011; Calabrese et al., 2015a; Feng et al.,

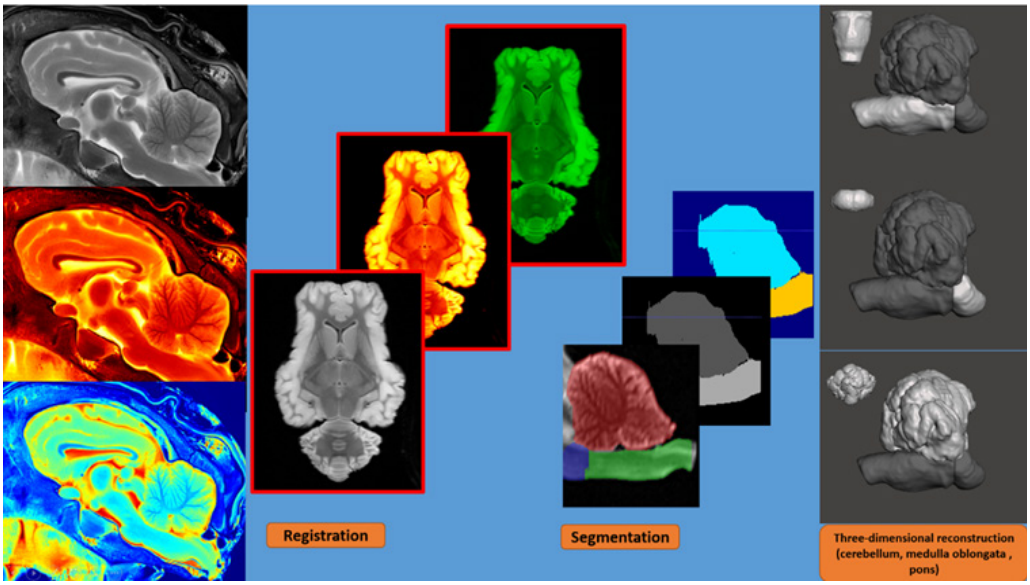

Figure 3. Several image analyses are used in images acquired from the brain by MRI.

2017; Reveley et al., 2017; Moirano et al., 2019; Liu et al., 2020; Rushmore et al., 2021) and marmoset (Hashikawa et al., 2015; Liu et al., 2018; Woodward et al., 2018; Risser et al., 2019; Zhu et al., 2023), which are extensively studied in neuroscience. These atlases and templates are available both in vivo and ex vivo. Templates (both ex vivo and in vivo) created using structural MRI and DTI are also available for ferrets with a relatively large white matter volume and a gyrencephalic brain among rodents (Hutchinson et al., 2017). Furthermore, a digital atlas (ex vivo) of the Nile crocodile (*Crocodylus niloticus*) forebrain is available (Billings et al., 2020).

DIFFUSION TENSOR IMAGING (DTI) OF DOMESTIC ANIMALS' BRAIN

Diffusion tensor imaging is a popular MRI technique widely used in brain research to identify the orientation of white matter tracts (Basser et al., 1994; Assaf and Pasternak, 2008). It measures the impact of tissue architecture on the diffusion-weighted signal by examining the movement of water molecules and detects the characteristics of water diffusion within brain tissue. Thus, virtual dissection and three-dimensional representation of white matter tracts are achieved with fiber tracking (tractography) (Alexander et al., 2007; Catani and De Schotten, 2008).

In domestic animals, crucial white matter tracts of the brain are modeled three-dimensionally by DTI. Critical fiber pathways and parts of the neocortex of the brain of domestic animals are highlighted with images obtained by DTI. In domestic animals, important white matter tracts and several structures belonging to the neocortex have been demonstrated by DTI in the brains of cats (Ronen et al., 2003; Ronen et al., 2006a; Ronen et al., 2006b; Takahashi et al., 2010; Takahashi et al., 2011; Dai et al., 2016; Jacqmot et al., 2017; Das and Takahashi, 2018; Barry et al., 2019; Johnson et al., 2020a; Andrews et al., 2022a), dogs (Jacqmot et al., 2013; Hartmann et al., 2014; Anaya Garcia et al., 2015; Robinson et al., 2016; Jacqmot et al., 2017; Jacqmot et al., 2020; Barry et al., 2021; Andrews et al., 2022a; Andrews et al., 2022b), pigs (Dyrby et al., 2011; Zhong et al., 2016; Bech et al., 2018; Bech et al., 2020; Benn et al., 2020), horses (Boucher et al., 2020), sheep (Lee et al., 2015; Peruffo et al., 2019; Pieri et al., 2019; Pirone et al., 2021; Gerussi et al., 2022; Graïc et al., 2023), and camels (Cartiaux et al., 2023).

CONCLUSION

This review focused on studies conducted on the brains of domestic animals using MRI, which has become an indispensable tool in veterinary science. It consisted of neuroanatomy, atlases, templates, and DTI studies performed on healthy domestic animals using MRI from the 1980s to the present. The studies on domestic animals such as cats, dogs, pigs, horses, donkeys, cattle, sheep, goats, and camels were summarized. In these studies, the neuroanatomy of the brain was presented in detail with non-invasive images acquired by MRI from the brains of healthy cats, dogs, pigs, horses, donkeys, cattle, sheep,

goats, and camels. Furthermore, similar studies conducted with MRI in some specific species other than domestic mammals were also included in the collection.

Our effort here is to provide information to scientists and veterinarians interested in conducting MRI research on domestic animals' brains. Furthermore, it is to create a collection of domestic animals that will guide researchers.

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