

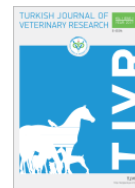


TJVR 2026; 10(2):158

Turkish Journal of Veterinary Research

<https://dergipark.org.tr/tr/pub/tjvr>

e-ISSN: 2602-3695



Global research trends of magnetic resonance imaging in veterinary anatomy: a bibliometric analysis

Osman Yılmaz ¹ Sadi Elasan ² ¹ Department of Anatomy, Faculty of Veterinary Medicine, Van Yüzüncü Yıl University, Van, Türkiye² Department of Biostatistics, Faculty of Medicine, Van Yüzüncü Yıl University, Van, Türkiye

Correspondence: Osman Yılmaz (osmanyilmaz@yyu.edu.tr)

Received: 26.02.2026

Accepted: 06.05.2026

ABSTRACT

Objectives: Magnetic Resonance Imaging (MRI) is essential in veterinary anatomy, providing high-resolution visualization of intricate soft tissues and complex structures. This study aims to analyze global MRI publications in veterinary anatomy using bibliometric methods to reveal trends, research networks, and thematic clusters.

Methods: In this study, MRI studies in veterinary anatomy conducted worldwide between (1983-2025) were investigated. For this purpose, 1012 studies were examined as a result of searches made in the Web of Science (WOS) database using the keywords “Veterinary Anatomy, Magnetic Resonance and MRI”. Following the elimination of unsuitable studies and non-article publications, 994 articles were analyzed. All data were analyzed using VOSviewer software.

Results: A total of 31,981 citations were made to the 994 articles examined in the WOS database. The average number of citations per article is 32, and the H-index is 77. A significant increase has been observed in both the number of articles and citations since 1996. The fact that a large proportion, such as 94.7%, of the publications are in the fields of “Veterinary Medicine, Medical Imaging, Neuroscience, Anatomy, and Morphology” indicates the high prevalence of MRI research within these disciplines. The countries producing the most publications are the USA (50.10%), the UK (11.17%), Germany (9.36%), and Spain (8.05%), respectively, while Türkiye (3.72%) ranks 11th in this field. When the generated bibliometric map is examined, it is observed that keywords such as “Magnetic resonance, anatomy, MRI, dog, horse, and brain” are located at the center, establishing strong correlations with each other, and that the studies generally focus on these subjects.

Conclusions: Our findings demonstrate significant momentum in MRI-based veterinary anatomy research and an expanding global network. This study offers critical insights into current trends and future research directions.

Keywords: Magnetic resonance, MRI, Veterinary anatomy

INTRODUCTION

This research examines global trends in magnetic resonance imaging (MRI) studies in veterinary anatomy; the bibliometric analysis conducted in this field highlights the impact of MRI studies on

scientific research and their potential for future development. The findings indicate that MRI research in veterinary anatomy is an expanding field and that this method makes valuable contributions to interdisciplinary scientific studies.

Veterinary anatomy education and research have evolved from traditional cadaver dissection methods, which historically formed their cornerstone, to a digital and dynamic paradigm provided by medical imaging technologies (Brenton *et al.*, 2007). Magnetic Resonance Imaging (MRI), located at the center of this technological transformation, has become a "gold standard" offering high-resolution and superior contrast images, particularly regarding soft tissue morphology, by analyzing proton density through strong magnetic fields and radio waves. While computed tomography (CT) demonstrates high success in detailing bony tissues and morphometric 3D reconstructions, MRI offers unique morphological detail in the *in vivo* and *ex vivo* examination of complex soft tissue structures such as the central nervous system (CNS), ligaments, tendons, and internal organs (Wisner and Zwingenberger, 2015; Jeong *et al.*, 2020; Yitbarek and Dagnaw, 2022). Evaluated from a clinical perspective, the most critical contribution of MRI to veterinary anatomy is that it allows for the simultaneous examination of anatomical structures in their natural positions, non-invasively, and in different planes (axial, sagittal, coronal, etc.) thanks to its superior contrast resolution. This multi-planar imaging capability is of vital importance, especially in neuroanatomy research, for determining the ventricular system, the differentiation of gray and white matter, and the topographic boundaries of brainstem structures (Thrall, 2017). Furthermore, the integration of advanced sequences such as functional MRI (fMRI) and diffusion tensor imaging (DTI) enables the mapping of anatomical data with physiological processes, distinguishing the modality from the limited penetration depth of ultrasonography (USG) and the radiation risk of CT (Brunel *et al.*, 2025; Vickram *et al.*, 2025).

In today's digitalizing veterinary medicine, volumetric analyses performed via MRI data and artificial intelligence (AI)-based automated segmentation techniques form the basis of "virtual dissection" platforms and 3D digital atlases in anatomy education. These technological advancements not only optimize clinical diagnosis and surgical planning processes but also assume a strategic role in multidisciplinary fields such as comparative anatomy, forensic veterinary medicine, and the morphological screening of endangered species (Kundakcı and Atay, 2023; Kapoor, 2024; Xiao *et al.*, 2025). Increased accessibility to MRI technology and the

optimization of costs have triggered the growth of scientific literature in this field on a global scale, both quantitatively and qualitatively (Yılmaz, 2024; Duro *et al.*, 2025). However, despite the widespread use and increasing clinical importance of MRI in veterinary anatomy, the lack of bibliometric studies analyzing global research trends, intellectual networks, and thematic development processes from a holistic perspective is noteworthy. Covering the literature between 1983 and 2025, this study aims to map the global development trajectory of MRI research in veterinary anatomy and to identify the most influential research areas and strategic focal points that will emerge in the future.

MATERIALS and METHODS

To guarantee the reliability of this study and the precision of its outcomes, we implemented a structured data acquisition approach combined with specific network analysis tools. Adopting these protocols facilitated the gathering and evaluation of the most extensive and up-to-date datasets available in literature. Additionally, processing this data offers the scientific community critical insights into emerging patterns, future trajectories, and the impact of magnetic resonance imaging within the field of veterinary anatomy. We identified worldwide publication tendencies by investigating key metrics, including top-performing authors, leading nations, and high-frequency keywords.

Data collection method and search strategy

This bibliometric analysis queried the "Web of Science Core Collection (WOS, Clarivate Analytics, Philadelphia, PA, USA)" database to investigate global trends regarding the future and influence of magnetic resonance imaging in veterinary anatomy from 1983 to 2025 (data access date: 31.12.2025). An initial search string comprising the terms "Veterinary Anatomy, Magnetic Resonance, MRI" yielded 1012 records. After filtering non-article document types, records published prior to 1983, and irrelevant entries, a total of 994 articles remained for the final dataset. Extracted metadata for analysis included titles, authorship, publication years, source journals, and citation metrics. Access to these materials was secured through the digital library portal of Van Yüzüncü Yıl University, with English selected as the primary search language.

As a multidisciplinary platform, WOS served as the primary source for bibliometric data, allowing for a detailed examination of publication growth,

institutional activity, and keyword mapping. All retrieved articles were subjected to a meticulous review process to ensure data integrity.

Network analysis

To map global tendencies and significant research themes in veterinary medicine MRI studies, we employed "VOSviewer (version 1.6.20, Leiden University, The Netherlands)" alongside "Biblioshiny (version 2.0)" running on "R-Studio (R version 4.2.2)". VOSviewer facilitated the visualization of complex datasets, enabling a thorough investigation of collaborative networks, research currents, and emerging topics. Concurrently, the open-source R-based tools, Bibliometrix and Biblioshiny, provided an interactive interface for conducting visual and bibliometric assessments. These platforms efficiently present key indicators, including publication volume, citation impact, and keyword distribution.

Bubble maps

VOSviewer-generated "bubble maps" were utilized to illustrate the clustering of publications based on occurrence frequency within the research domain.

In these visualizations, bubbles represent specific keywords or clusters, with their dimensions proportional to their frequency of appearance. Additionally, color coding is applied to categorize related subjects, while spatial proximity indicates strong interrelationships between specific items or groups.

RESULTS

The WOS database query yielded a final set of 994 published articles. Cumulatively, these documents garnered 31,981 citations, which adjust to 30.933 when self-citations are excluded. The dataset exhibited an average citation count of 32 per article alongside an H-index of 77. A noticeable upward trajectory in both citation volume and publication output has been recorded, most prominently starting from 1996. Figure 1 illustrates the distribution of these metrics over time. An analysis based on selected keywords reveals that terms such as "magnetic resonance, anatomy, MRI, dog, horse, and brain" occupy the most extensive and interconnected thematic clusters (Figure 2).

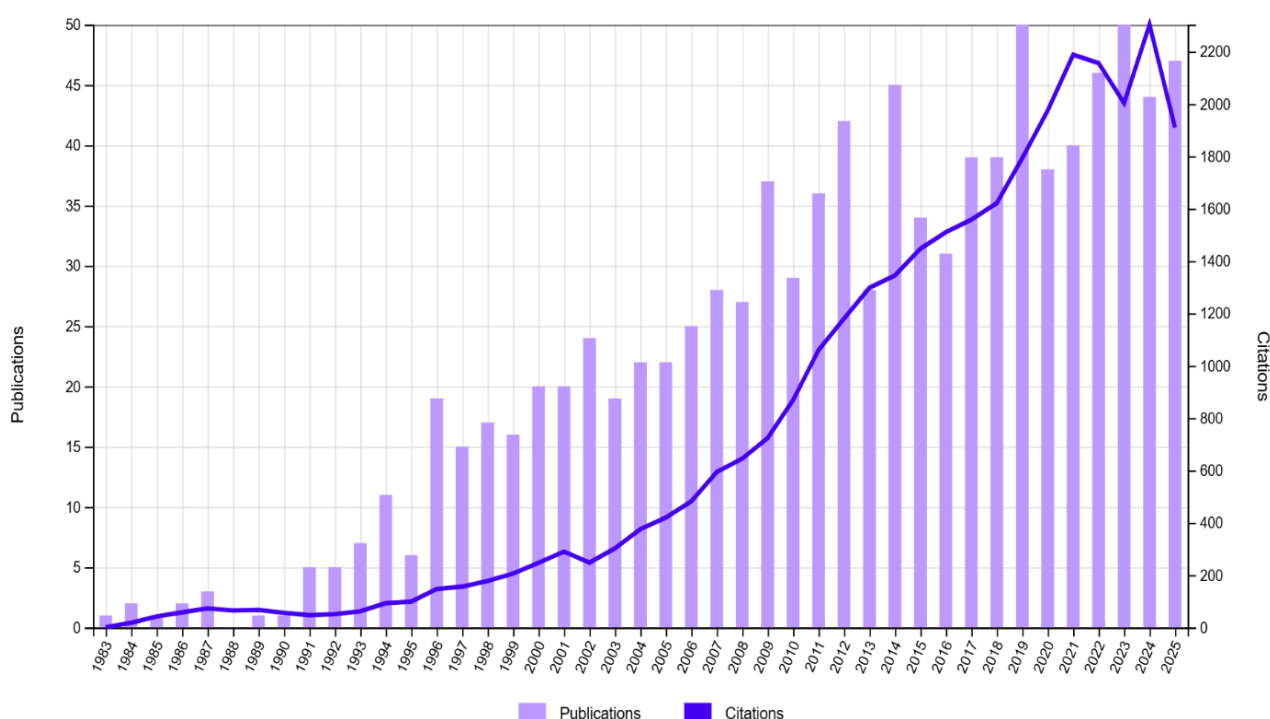


Figure 1. Frequency of publications and citations by year (last access 31.12.2025).

Regarding subject categories, the highest concentration of articles appeared in Veterinary Sciences (45.3%), followed by Medical Imaging (17.6%), Neuroscience (13.1%), and Anatomy and

Morphology (8.15%). Table 1 details the distribution of publications across research areas. In terms of geographic origin, the USA led with the highest output (n=498; 50.1%), trailed by the UK

(11.2%), Germany (9.4%), and Spain (8.1%). Contributions came from 66 nations globally, with Türkiye ranking 11th ($n=37$; 3.7%). Table 2 lists the top 15 countries producing 25 or more publications. In addition to the publication volumes, the interactions and geographical distribution of the research were analyzed. The international collaboration network map illustrates collaboration between countries through lines, where the thickness denotes the strength of collaboration, and the size of circles reflects the level of international collaboration (Figure 3). Furthermore, bibliographic coupling analysis was performed for countries, establishing correlations by evaluating the number of shared references (Figure 4). Finally, the scientific production density graph depicts the global intensity of studies in this field; as the color shifts to dark blue, the number of studies increases, while grey areas represent regions where no studies have been conducted (Figure 5).

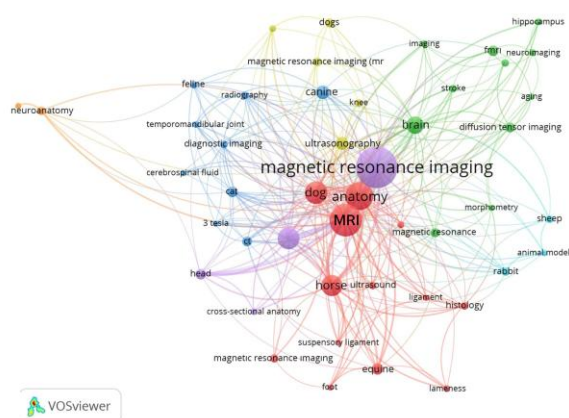


Figure 2. Keyword analysis reveals the association of the topic with specific keywords and the frequency of their usage.

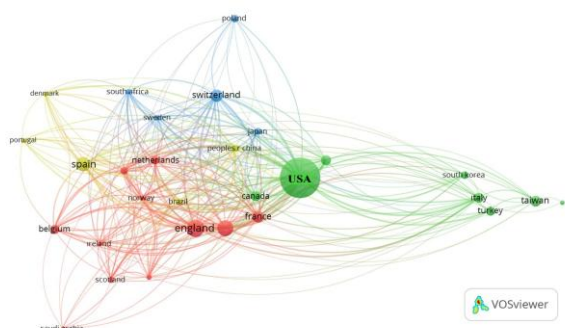


Figure 3. International collaboration network map regarding MRI research in veterinary anatomy (lines indicate collaboration between countries; thickness denotes the strength of collaboration, and the size of circles/text reflects the level of international collaboration).

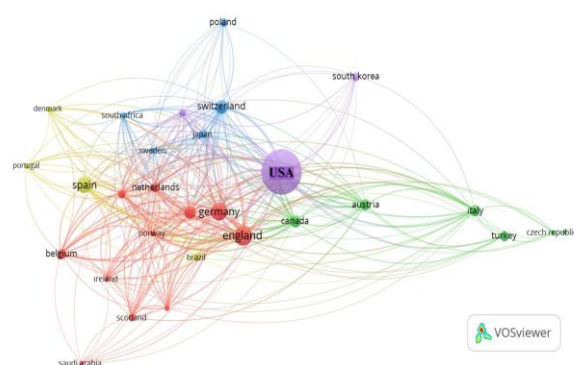


Figure 4. Bibliographic coupling analysis of countries in the field of veterinary anatomy MRI research (the correlation between items was established by evaluating the number of shared references).

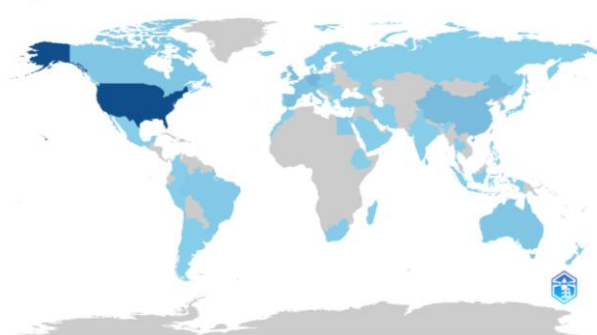


Figure 5. The scientific production density graph of MRI studies in veterinary anatomy by country (dark blue indicates a higher number of studies, while grey represents regions with no conducted studies).

The leading institutions in this domain included the US Department of Veterans Affairs (20%), the Veterans Health Administration VHA (19.9%), and the University of California System (12.9%). Notably, the majority of top-tier affiliations were based in the United States. Table 3 displays 15 of these entries out of the 994 records analyzed.

An examination of Web of Science Indices showed that the vast majority of papers were indexed in the “Science Citation Index Expanded (SCI-Expanded)” at 95.8%. This was followed by the “Conference Proceedings Citation Index - (CPCI-S)” (3.4%), “Emerging Sources Citation Index (ESCI)” (3.1%), and the “Social Sciences Citation Index (SSCI)” (2.9%) (Table 4). Consequently, it is evident that MRI research in veterinary anatomy is primarily published within the SCI-E framework.

Table 1. Categories of publications.

Research Areas	Record Count	% of 994
Veterinary Sciences	450	45.272
Medical Imaging	175	17.606
Neurosciences	130	13.078
Anatomy and Morphology	81	8.149
Zoology	39	3.924
Orthopedics	38	3.823
Surgery	35	3.521
Psychiatry	32	3.219
Agriculture	29	2.918
General Internal Medicine	23	2.314
Science Technology, Other Topics	23	2.314
Cardiovascular System, Cardiology	21	2.113
Research Experimental Medicine	17	1.710
Biochemistry, Molecular Biology	14	1.408
Cell Biology	13	1.308

Showing 15 out of 81 entries

Table 3. Top affiliations ranking.

Affiliations	Record Count	% of 994
US Department of Veterans Affairs	199	20.020
Veterans' Health Administration VHA	197	19.819
University of California System	128	12.877
University of California San Diego	61	6.137
Harvard University	53	5.332
Harvard University Medical Affiliates	50	5.030
University of London	44	4.427
Universidad de Las Palmas de Gran Canaria	35	3.521
University of Murcia	35	3.521
University of Texas System	32	3.219
University of California San Francisco	31	3.119
University System of Ohio	31	3.119
Harvard Medical School	30	3.018
University of California Davis	30	3.018
University of Zurich	30	3.018

Showing 15 out of 1622 entries

Table 2. Countries with at least 15 publications.

Countries/Regions	Record Count	% of 994
USA	498	50.101
England	111	11.167
Germany	93	9.356
Spain	80	8.048
Switzerland	62	6.237
France	54	5.433
Taiwan	47	4.728
Canada	45	4.527
Austria	43	4.326
Italy	42	4.225
Türkiye	37	3.722
Belgium	34	3.421
Netherlands	30	3.018
Australia	25	2.515
Egypt	25	2.515

Showing 15 out of 66 entries

Table 4. Web of science categories index.

Web of Science Index	Record Count	% of 994
Science Citation Index Expanded (SCI-Expanded)	952	95.775
Conference Proceedings Citation Index-SCI (CPCI-S)	34	3.421
Emerging Sources Citation Index (ESCI)	31	3.119
Social Sciences Citation Index (SSCI)	29	2.918
Conference Proceedings Citation Index-(CPCI-SSH)	4	0.402
Book Citation Index-Science (BKCI-S)	3	0.302

DISCUSSION

This study elucidates the development of the field over approximately the last 40 years and its interaction with other imaging modalities by bibliometrically analyzing the use of Magnetic Resonance Imaging (MRI) in veterinary anatomy literature. The obtained 994 articles and 31,981 citations reinforce the characteristic of MRI as a source of "high-quality data" in veterinary anatomy. The momentum observed particularly since 1996 is a result of the reflection of the digital revolution in medical imaging onto the discipline of veterinary anatomy.

When examined in terms of literature volume compared to other bibliometric studies in the field of veterinary anatomy, it was reported that Computed Tomography (CT) studies evaluated by Yılmaz (2025b) between 1990-July 2025 numbered 1608, while Ultrasonography (USG) studies evaluated by Yılmaz (2025a) between 1983-November 2025 numbered 693. In the presented study, it was determined that MRI publications in the field of veterinary anatomy evaluated between 1983-2025 numbered 994. This situation indicates that CT and USG are more accessible than MRI in veterinary anatomy studies due to reasons such as imaging speed, ease of accessibility, and short imaging times. However, when citation counts per article are examined in these studies and our study; MRI (32 citations/article) surpasses the modalities of USG (19 citations/article) and CT (13.7 citations/article). This indicates that MRI studies offer more specific, in-depth anatomical details and are accepted as a more fundamental reference source in the field of veterinary anatomy.

VOSviewer was used as a powerful data visualization tool to analyze collaboration networks, research trends, and future research topics in detail (Van Eck and Waltman, 2023). Additionally, Bibliometrix and Biblioshiny, free research software operating in the R language, offer an interactive platform that enables bibliometric and visual analyses. These methods increase the accuracy and reliability of the research while facilitating a better interpretation of the obtained data (Aria and Cuccurullo, 2017). The analyses performed provide a broad perspective on the development of magnetic resonance imaging applications in veterinary anatomy through diagrams and maps showing the significant points of the research, the research process, and publication dynamics over time.

Keyword analyses demonstrate that each of the three modalities dominates different areas in veterinary anatomy. While the concepts of "3D printing, morphometry and bone" in CT literature (Yılmaz, 2025b) and "regional anesthesia, real-time imaging and soft tissue" in USG literature (Yılmaz, 2025a) stand out; MRI literature is focused on "brain, CNS (central nervous system) and neuroanatomy" (Wisner and Zwingenberger, 2015). This distinction indicates that MRI's unique capability in soft tissue contrast directly determines modality preference in neuroanatomical research. Another critical finding detected in our study is the convergence of all three modalities at the point of "Artificial Intelligence (AI)" and "Digital Transformation." The success of 3D models produced from CT data in surgical simulation (Yılğör Huri and Oto, 2022; Kundakcı and Atay, 2023; Kapoor, 2024) and the clinical precision in nerve blocks performed under USG guidance (Marhofer and Chan, 2007) are giving way to automated segmentation and functional mapping in the MRI literature (Vickram *et al.*, 2025). The success of deep learning algorithms on MRI data signals that the concepts of "digital cadaver" and "virtual anatomy atlases" will become standard in education in the future.

Bibliometric maps clearly reveal the thematic areas and technological transformation prominently in veterinary MRI literature. The high-frequency use of key terms in our analysis results such as "neuroanatomy," "brain mapping," "diffusion tensor imaging (DTI)," "functional MRI (fMRI)," "cross-sectional anatomy," and "soft tissue contrast" indicates that technological integration and advanced imaging sequences drive scientific production in this field (Wisner and Zwingenberger, 2015; Yitbarek and Dagnaw, 2022; Vickram *et al.*, 2025). These technologies offer critical contributions in terms of both diagnostic accuracy and the depth of educational materials, especially in the detailed non-invasive examination of the central nervous system and musculoskeletal soft tissues. It has been determined that high-resolution cross-sectional anatomy data and digital brain atlases obtained specifically from MRI data have become widespread in veterinary anatomy teaching and neurosurgical simulations; thus, a digital and functional dimension has been added to classical dissection-based education (Thrall, 2017; Hussain *et al.*, 2022).

Upon examining the bibliometric map (Figure 2) in this presented analysis, it is observed that keywords

such as "magnetic resonance," "anatomy," "MRI," "dog," "horse," and "brain" are located at the center, establishing strong correlations with each other. Generally, these results prove that developing MRI technology and advanced sequence analyses play a decisive role in the future of Veterinary Anatomy education and research. This situation reveals that technological integration is not merely an academic trend but also provides tangible benefits in the process extending from theoretical anatomical knowledge to the clinical application phase by strengthening individualized treatment strategies in neurological and orthopedic diseases and evidence-based veterinary medicine.

Two main trends drawing attention in the field of veterinary MRI in recent years are AI-supported advanced image analyses and multi-modal data integration. Thanks to deep learning algorithms and convolutional neural networks (CNN)-based automated segmentation techniques, complex soft tissue images and neuroanatomical structures obtained from MRI data can be analyzed with high precision in a much shorter time; this technological transformation significantly accelerates clinical decision-making and surgical planning processes (Wilson *et al.*, 2022; Elasan and Yilmaz, 2025; Vickram *et al.*, 2025). Furthermore, multidisciplinary approaches where MRI is synthesized with CT, ultrasonography, and radiological data both expand the scope of research and facilitate comparative and functional analyses (fMRI, DTI, etc.) in veterinary morphology (Xiao *et al.*, 2025). The bibliometric analysis conducted in this study has systematically revealed these orientations in the MRI field, defined thematic clusters and existing research gaps in the literature, and presented strategic data and a comprehensive perspective to guide future veterinary anatomy research.

On a global scale, Türkiye's position shows an interesting variation according to modalities. Türkiye ranks 5th in the world in veterinary anatomy CT studies (Yilmaz, 2025b), 11th in MRI studies, and 16th in USG studies (Yilmaz, 2025a). These data reveal that veterinary anatomists in our country have become a global force in technological integration, especially in CT-based anatomical, morphometric, and 3D modeling studies, and exhibit a rising trend in the field of MRI.

Literature reviews conducted and the findings of this study indicate that MRI has become a reliable imaging method in veterinary anatomy that supports clinical diagnostic processes and allows

for detailed and non-invasive evaluation of anatomical structures, and accordingly, scientific publications are steadily increasing on a global scale (Wisner and Zwingenberger, 2015; Yitbarek and Dagnaw, 2022; Vickram *et al.*, 2025). Furthermore, this study has determined global trends and thematic clusters related to MRI studies in veterinary anatomy, revealing which specific areas research focuses on, such as neuroanatomy, soft tissue morphology, and cross-sectional anatomy, and in which countries the highest productivity is achieved. Additionally, by identifying key study areas, projections are offered regarding which areas of specialization (e.g., functional MRI and artificial intelligence integration) MRI technology and advanced sequence analyses will be used more intensively in the future and which researchers may take a leading role in this process.

CONCLUSION

In conclusion, this bibliometric analysis, which examines worldwide trends and publication dynamics of MRI research in veterinary anatomy, is based on a detailed analysis of 994 articles obtained as a result of an extensive literature review. Within the scope of the analysis, the most influential countries, academic institutions, authors, publication outlets, and keyword networks have been systematically identified. The results obtained shed light on the future development of MRI usage in veterinary anatomy, providing an important reference source for researchers for new studies to be conducted in this field.

REFERENCES

- Aria M, Cuccurullo C. An R-tool for comprehensive science mapping analysis. *J Informetr.* 2017; 11(4):959-975.
- Brenton H, Hernandez J, Bello F, *et al.* Using multimedia and web 3D to enhance anatomy teaching. *Comput Educ.* 2007; 49:32-53.
- Brunel M, Schäfer VS, Recker F. Bringing anatomy to life: the role of clinical ultrasound in undergraduate medical education—a systematic review. *Ultrasound J.* 2025; 17:39.
- Duro S, Gündemir O, Szara T. Editorial: The integration of clinical veterinary anatomy and diagnostic imaging. *Front Vet Sci.* 2025; 12:1602545.
- Elasan S, Yilmaz O. Comprehensive global analysis of future trends in artificial intelligence-assisted veterinary medicine. *Vet Med Sci.* 2025; 11(3):e70258.
- Hussain S, Mubeen I, Ullah N, *et al.* Modern diagnostic imaging technique applications and risk factors in the medical field: A Review. *Biomed Res Int.* 2022; 2022(1):5164970.

- Jeong Y, Woo EJ, Lee S.** Bibliometric analysis on the trend of the computed tomography (CT)-related studies in the field of forensic science. *Appl Sci.* 2020; 10(22):8133.
- Kapoor K.** 3D visualization and printing: An "Anatomical Engineering" trend revealing underlying morphology via innovation and reconstruction towards future of veterinary anatomy. *Anat Sci Int.* 2024; 99(2):159-182.
- Kundakcı YE, Atay E.** Bibliometric and visualized analysis of global research on technology in anatomy education from 1987 to 2021. *Eur J Anat.* 2023; 27(4):517-528.
- Marhofer P, Chan VW.** Ultrasound-guided regional anesthesia: current concepts and future trends. *Anesth Analg.* 2007; 104(5):1265-1269.
- Thrall DE.** Textbook of veterinary diagnostic radiology. 7th ed. Philadelphia: WB Saunders; 2017.
- Van Eck NJ, Waltman L.** VOSviewer manual for VOSviewer version 1.6.20. Leiden: Universiteit Leiden, CWTS; 2023.
- Vickram AS, Infant SS, Chopra H.** AI-powered techniques in anatomical imaging: Impacts on veterinary diagnostics and surgery. *Ann Anat.* 2025; 258:152355.
- Wilson DU, Bailey MQ, Craig J.** The role of artificial intelligence in clinical imaging and workflows. *Vet Radiol Ultrasound.* 2022; 63(Suppl 1):897-902.
- Wisner ER, Zwingenberger AL.** Atlas of small animal CT and MRI: Skull. USA: Wiley-Blackwell Publishing; 2015. p.55-68.
- Xiao S, Dhand NK, Wang Z, et al.** Review of applications of deep learning in veterinary diagnostics and animal health. *Front Vet Sci.* 2025; 12:1511522.
- Yılğör Huri P, Oto Ç.** 3D printing in veterinary medicine. *Ankara Univ Vet Fak Derg.* 2022; 69(1):111-117.
- Yılmaz O.** Artificial intelligence-assisted veterinary anatomy: The role of digital transformation in education and clinical practice. In: Demirel AF, Yılmaz O, eds. *Uygulamalı Bilimlerde Güncel Çalışmalar-II*. 1st ed. Ankara: IKSAD Publishing; 2024. pp.3-30.
- Yılmaz O.** Global trends in ultrasonography research in veterinary anatomy. *Int J Adv Nat Sci Eng Res.* 2025a; 9(12):90-98.

Yılmaz O. The use of computed tomography in veterinary anatomy studies: A bibliometric analysis on global trends and research networks. *Van Vet J.* 2025b; 36(3):213-218.

Yitbarek D, Dagnaw GG. Application of advanced imaging modalities in veterinary medicine: A Review. *Vet Med Res Rep.* 2022; 117-130.

ACKNOWLEDGMENTS

Author contributions: OY and SE designed the study. OY collected the data. SE performed statistical analysis. OY and SE participated in drafting and revising the manuscript. OY: Osman Yılmaz, SE: Sadi Elasan.

Financial Disclosure: The authors declared that this study has received no financial support.

Conflict of Interests: The authors declared that there is no conflict of interests.

Additional information: All authors have read and agreed to the published version of the manuscript Correspondence and requests for materials should be addressed to OY.

Reprints and permissions information is available at <https://dergipark.org.tr/tr/pub/tjvr/policy>

Publisher's note Dergipark remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access: This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.



© The Author(s) 2026