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Advancing precision medicine in companion animal oncology: Integrating AI, advanced radiology, and surgical innovation

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Abstract

Precision medicine (PM) is bringing about a paradigm shift in the companion animal oncology. PM approach consider a unique treatment and method of diagnosing for each patients. in essence of PM, new cutting-edge technology such as artificial intelligence (AI) hand in hand to novel imaging approach and surgical innovation improving the cancer management. This review examines open-access and published English-language articles containing keywords such as AI, advanced radiology, surgical innovation, and precision medicine in the field of companion animals from 2014 to 2025 in PubMed, Scopus, Web of Science, and Google Scholar. The PM principles have changed surgical oncology, including the integration of oncogenomics, the use of minimally invasive techniques, and robotic-assisted procedures that make it easier to move around. In addition, AI makes these surgical frontiers even bigger by helping with detailed preoperative planning, real-time guidance during surgery, and objective skill training. Also, AI has pivotal role in enhancing diagnostic accuracy, automating image segmentation, and bolstering clinical decision support within modern radiology. This paper also talks about how useful intraoperative imaging is for quickly checking the margins and new precision medicine technologies like Next-Generation Sequencing (NGS), liquid biopsies, and non-coding RNAs for finding and predicting diseases. AI has recently sped up frameworks for comparative oncology, which has made the translation medicine easier. On the other hand, the PM method has its own problems, like high costs and the need for experts to handle big issues. It needs clear rules for sharing data and teams of experts from different fields. This integrated framework is very important for raising the standard of animal care, coming up with new ideas, and making a big difference in both human and animal medicine.

1. Introduction

In these recent decades companion animals have been living longer than ever before due to recent advancement in animal nutrition, improved animal welfare, better hygiene practice, and overall medical development (Tanaka et al. 2020). Consequently, malignant neoplasia has emerged as a significant mortality factors in aged dogs globally particularly in countries such as Sweden, the United States, the United Kingdom, and Japan, where it contributes to 15-30% of mortality rates (Inoue et al. 2015; O'Neill et al. 2013). The recent novel diagnostic techniques and therapeutic strategies have been implemented to prevent and detect cancer; yet, cancer imposes a heavy burden on the healthcare system (Zaorsky et al. 2017). However, new discoveries in cancer genetics (Barot et al. 2023), defining tumor-specific molecular profiles (Malone et al. 2020), and coming up with new treatment methods like advanced nanomaterials (Taheriazam et al. 2023), and ways to fight drug resistance (Hashemi et al. 2023) are making it possible for more creative and targeted treatments (Ghasemi et al. 2016).

As a result, the conventional "one-size-fits-all" style of thinking about medicine is slowly being replaced by PM. PM is a means to make illness prevention and treatment programs that are unique to each person based on their genetics, environment, and lifestyle (König et al. 2017; Wang et al. 2016). This paradigm puts the patient first and tries to make treatment as effective as possible by picking the optimum therapies for each type of cancer or patient profile (Bu et al. 2016), while concurrently minimizing unnecessary diagnostic procedures, therapy-related costs, and adverse side effects (Penet et al. 2014). PM is all about gathering a lot of data and using advanced analysis to turn information about individual patients into helpful clinical insights (Kraus et al. 2018). Similar to human oncology, the paradigm shif towards adopting PM in small animal oncology marks a new approach (Chon et al. 2024; Lajmi et al. 2024). PM in veterinary oncology means integrating advanced diagnostic tools, such as genomic profiling and innovative molecular imaging techniques. These tools provide crucial data basis for the development of targeted medicines and the optimisation of surgical procedures for companion animals (Gola et al. 2021; Gray et al. 2020; Mealey et al. 2019). This new approach of treating neoplasms is a big change from the traditional methods. The collaboration of experts in contemporary pharmaceuticals, advanced surgical methods, and, most importantly, cutting-edge diagnostic imaging necessitates collaborative multidisciplinary efforts across many fields (Lajmi et al. 2024; Thamm 2019).

The evolving of PM in pet animals heavily depends on the advanced imaging and surgical methods (Yitbarek and Dagnaw 2022). Comparative oncology offers a variety of benefits for both groups, researching in various fields such as understanding tumour microenvironment characteristics like the enhanced permeability and retention (EPR) effect for improved drug delivery and imaging contrast (Gray et al. 2020; Thamm 2019). The surgical oncology progress, particularly in the development and refinement of minimally invasive procedures (Balsa and Culp 2019), sophisticated image-guided interventions (Favril et al. 2018), and novel ablative technologies designed to maximize tumor eradication while minimizing patient morbidity (Kudnig and Séguin 2022). Many of these advanced imaging biomarkers, targeted therapeutic strategies, and advanced surgical techniques were first developed and tested in humans. However, the basic ideas behind them could be very useful for improving cancer care in companion animals (Ren et al. 2022; Ruan et al. 2020). However, for these complex new technologies to be successfully translated and integrated into routine small animal oncology practice, they need to be carefully adapted, thoroughly validated, and kept up with by radiologists, oncologists, surgeons, and other veterinary specialists (Furdos et al. 2015; Han et al. 2024a). This review provides a comprehensive analysis of how the strategic integration of AI with advanced radiology and innovative surgical techniques is currently advancing precision medicine in companion animal oncology.

2. Methods

In this article, open-access peer-reviewed articles that were published in English between January 2014 and May 2025 were assessed. Search strategies combined keywords and subject headings related to three core domains: (1) companion animal oncology (e.g., "dog," "cat," "canine," "feline," AND "cancer," "tumor," "oncology"); (2) key technologies and approaches (e.g., "Artificial Intelligence," "Machine Learning," "Radiology," "CT," "MRI," "PET," "Radiomics," "Imaging Biomarkers," "Surgery," "Surgical Oncology"); and (3) the central theme ("Precision Medicine," "Personalized Medicine"). The keywords were searched via PubMed, Scopus, Web of Science, and Google Scholar. Publications that were eligible included original research articles and review papers that looked at the development, validation, or use of new radiological techniques, artificial intelligence, and/or new surgical techniques in the context of precision oncology for dogs and cats. The case reports, conference abstracts, articles in languages other than English, or studies that weren't directly related to using these technologies in companion animal oncology were not included. After looking at the titles and abstracts, full-text articles were looked at again to see if they should be included. To meet the goals of this review, data about the study's goals, methods, technological applications (in AI, radiology, and surgery), relevance to precision medicine, main findings, and limitations were systematically gathered and put together in a narrative.

3. Results

3.1 Advances in diagnostic radiology for companion animal oncology

Diagnostic radiology has evolved in the way of transitioning from a discipline primarily focused on anatomical depiction to one that increasingly incorporates functional and molecular data to guide cancer care (Nagata 2019). Although the classic radiographic techniques are still valuable for initial cancer staging, they are now substantially augmented by advanced cross-sectional modalities such as computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET). These technologies, which can be improved by AI-driven analyses, give more detail and new types of information (Hennessey et al. 2022; Hespel et al. 2022; Mattoon and Bryan 2013; O'Connor et al. 2017). So, modern imaging goes beyond just looking at the structure of a tumour to give important information on its physiology, metabolism, and microenvironment. This helps with the molecular characterization that is needed for precision oncology (Spinu-Popa et al. 2021). Modern veterinary diagnostic imaging is mostly about finding out how the body works and how it looks in a way that can be linked to the genetic and molecular profiles of tumours (Yitbarek and Dagnaw 2022). For example, functional imaging tools let us see what the main biological processes, such as metabolism and proliferation of a tumour are.For example, tracers like 2-deoxy-2-[^{18}F]fluoro-D-glucose (^{18}F-FDG) and 3'-deoxy-3'-[^{18}F]fluorothymidine (^{18}F-FLT) can be used in PET imaging to see and measure changes in energy metabolism and increased cell growth, respectively. These assessments can be performed shortly after initiating cancer therapy to predict treatment response early in both preclinical and clinical veterinary settings (De Bruycker et al. 2018; Jensen and Kjaer 2015; Joshi et al. 2017). Other translatable techniques from human practice include oxygen-enhanced MRI for quantifying tumor hypoxia (Fleming et al. 2015) and advanced CT applications, such as virtual simulation for precise radiotherapy planning (Mi et al. 2016).

The unifying concept behind these advances is that of imaging biomarkers (IBs)—clinically measurable characteristics derived from medical images that capture normal biological processes, pathogenetic processes, or response to therapeutic intervention (Colombe et al. 2022; O'connor et al. 2017). IBs are gaining crucial roles in veterinary oncology to detect cancer, diagnose, stage, and assess treatment response, offering non-invasive and generally cost-effective approaches (Perera et al. 2022). Their integration allows for quantification of tumor biology and treatment response, resulting in personalized treatment strategies (Chiu and Yen 2023; Perera et al. 2022). This is supplemented by radiomics as well, which involves high-throughput extraction of quantifiable features from imaging to yield imaging signatures that are correlated with the underneath genomics and can be used for predicting clinical outcomes (Able et al. 2021; Basran and Porter 2022). Preclinical molecular imaging with PET and MRI plays a central role in this field by enabling the development and validation of quantitative IBs that connect animal model studies to applications in veterinary oncology (Aguiar et al. 2019; Buck et al. 2018; Kovacs et al. 2018). Furthermore, the fusion of multimodal imaging modalities, combining data from CT, MRI, PET, and ultrasound, significantly increases the specificity of diagnosis and therapy planning (Giardino et al. 2017). Combined imaging is particularly advantageous in veterinary oncology for accurate surgical planning as well as post-treatment follow-up. For instance, contrast-enhanced CT or MRI defines tumor margins with high resolution, which is critical for planning minimally invasive or complicated oncologic surgery. A comparative summary of these and other imaging modalities routinely employed in veterinary oncology is presented in Table 1. These modalities also allow the production of three-dimensional (3D) tumor reconstructions, which are very useful in the assessment of invasion into surrounding tissues, predicting

Table 1. Comparative overview of oncology imaging modalities for veterinary applications

Imaging modality	Key features and advantages	Potential veterinary applications
Computed Tomography	High-resolution detailed anatomy, rapid acquisition	Staging, tumor volume delineation, pre-surgical mapping
Magnetic Resonance Imaging	Superior soft tissue contrast, functional imaging options	Assessing tumor boundaries and vascular invasion
Positron Emission Tomography	Metabolic and functional assessment, early response prediction	Monitoring treatment efficacy, mapping metabolic activity
Ultrasound	Real-time imaging, accessibility, cost-effectiveness	Fine-needle aspirates guidance, localized tumor evaluations

problems in surgery, and reconstructive planning (Lajmi et al. 2024; Yitbarek and Dagnaw 2022).

3.2 Impact of artificial intelligence (AI) and machine learning (ML) in veterinary diagnostic radiology

AI, in the form of machine learning (ML) and deep learning (DL) algorithms, is emerging as a revolutionizing force in modern veterinary diagnostic radiology, and oncology is no exception. These technologies excel at managing complex, high-dimensional imaging datasets and delivering powerful decision-support tools for practitioners, yet not replacements for experienced radiologists (Burti et al. 2024). One of the clinical rollout's key principles is maintaining a "human-in-the-loop" approach, whereby AI augments human judgment to ensure clinical responsibility and patient safety (Goisauf and Cano Abadia 2022). The applications of AI in veterinary oncologic imaging are diverse and expanding exponentially. AI algorithms can significantly streamline radiology workflow by automating the labor-intensive processes such as image segmentation—the precise delineation of tumor borders and organs at risk—which is so critical for accurate radiotherapy planning and surgical guidance (Cohen and Gordon 2022; Leary and Basran 2022). Furthermore, AI software is being developed for detecting and classifying neoplastic lesions on various imaging modalities with increased sensitivity, and for enhanced diagnostic consistency between practices (Burti et al. 2024; Schmid et al. 2022). Such consistency is also vital for the standardized implementation of precision therapies.

Besides lesion detection and segmentation, AI enables precision oncology through the potential for more sophisticated analysis of imaging biomarkers and radiomic features. ML models are capable of picking up subtle patterns in imaging data that are not detectable by the human eye and mapping them to underlying tumor biology, genetic signatures, or treatment responses (Aguiar et al. 2019). These roles involve patient stratification, where AI can aid in the categorization, animals based on imaging characteristics of their tumors for prognosis or for tailoring treatment protocols for the maximum therapeutic effect and limiting inappropriate interventions or toxicity (Pang et al. 2021; Shaikh 2022; Yousefirizi et al. 2022). For instance, AI could predict responsiveness to targeted therapies in tumors according to pre-treatment imaging features, a concept with very high similarity in human oncology (Sadeghi et al. 2023; Zandieh et al. 2023a). While the substantial clinical evidence for most such AI applications in veterinary medicine is ongoing, potential benefits for encouraging personalized oncologic therapy are large. Continued progress, however, relies on the development of disease-specific, standardized imaging data for training of strong AI models and the establishment of strict methodologies for their translation into clinical use (Aguiar et al. 2019).

3.3 Precision medicine in companion animal surgical oncology

Surgical intervention has long been a cornerstone of cancer treatment in companion animals with the greatest possibility of cure or acceptable palliation if removal of the tumor can be accomplished (Pratschke 2016). Traditional surgical oncology relies on the methods of precise identification of the tumor, accurate anatomical resection with adequate margins, and evaluation of the overall condition of the patient to avoid morbidity and optimize quality of life (Orencole and Butler 2013). But the new paradigm of PM is in the process of revolutionizing this field, towards a more individualized and biology-based strategy of surgical cancer treatment (Dreyer et al. 2020). Precision surgical oncology in companion animals aims to individualize surgical strategies according to the distinctive characteristics of each patient and his/her corresponding cancer, integrating molecular and genetic insights with advanced-level technological innovation (Argento et al. 2025; Soria et al. 2018). This is a shift from the exclusive reliance on gross anatomical features to incorporating improved understanding of tumor biology. The impetus for this shift is oncogenomic, since with improved genomic sequencing and molecular profiling, one can determine specific genetic mutations and pathways that caused a specific animal's cancer (Goodwin et al. 2016). Such oncogenomic information might guide decisions on the necessity and extent of surgery and, in conjunction with successful targeted therapy, enable more conservative resections, or identify the need for more aggressive approaches in certain molecular subtypes (Hirsch et al. 2016). This results in a powerful synergy in which molecular diagnosis informs surgical planning and perioperative management, and correctly executed surgery can optimize the windows for observing after adjuvant treatment (Argento et al. 2025).

The utilisation of PM in the real sense in veterinary surgical oncology is also reflected in the employment of novel surgical techniques and technologies designed to optimise precision and minimise invasiveness (Fonseca-Alves et al. 2021). Minimally invasive surgery (MIS), including laparoscopic and thoracoscopic surgery, is increasingly being utilized in companion animal oncology. MIS has the benefits of reduced postoperative pain, shorter recovery times, and less tissue trauma, which are particularly useful in small animal patients where access to the surgical site may be poor and morbidity from conventional open surgery may be high (Borah et al. 2025; Buote 2024; Kudnig and Séguin 2022; Mayhew 2014). Besides MIS, robotic surgical systems, though not as prevalent in veterinary medicine presently as they were in human health care, can offer enhanced 3D visualization, better instrument dexterity, and tremor elimination, with the potential to allow surgeons to enter intricate anatomical regions more accurately (Borah et al. 2025; Hoeckelmann et al. 2015; Wright 2017). Further, the development of advanced surgical simulators is also changing training as veterinary surgeons are able to hone complex oncologic procedures in a secure environment (Aramini et al. 2023). These technological and cognitive breakthroughs, driven by PM principles, are projected to improve oncologic and overall welfare and quality of care for dogs and cats with cancer.

3.4 The role of artificial intelligence in surgical oncology

AI is fundamentally transforming surgical oncology by delivering powerful tools to enhance decision-making and technical execution along the perioperative continuum. Incorporating ML, DL, and computer vision, AI employs complex algorithms to analyze gigantic datasets, recognize patterns, and provide predictive information, thereby changing traditional surgical paradigms (Chang et al. 2020; Han et al. 2024b; Morris et al. 2023). The application of these technologies in surgical oncology is designed to improve accuracy, safety, and outcomes for patients, with significant translational potential to companion animal health. AI plays a role in preoperative planning in risk stratification and the development of personalized surgical plans. AI systems can integrate multidimensional patient-specific data—like advanced imaging, genomic profiles, proteomics, and clinical laboratory findings—to predict variables such as tissue response to surgery, likelihood of residual disease, and postoperative morbidity (Abbasi and Hussain 2024; Mirchi et al. 2020). For instance, ML algorithms on big clinical datasets, such as NSQIP in human surgery, have proved superior to traditional models in predicting surgical complications and, by that extension, allow personalized perioperative planning (Collaborative et al. 2020; Hassan et al. 2023; Yeramosu et al. 2025). Such predictive models are immensely valuable in optimizing surgical approaches and minimizing patient risk in complex oncologic operations.

During the intraoperative phase, AI is significant in providing real-time guidance and performance enhancement. Computer vision, one of the most crucial subsets of AI, deciphers intraoperative video streams to identify anatomical structures, detect surgical instruments, and identify different phases of an operation, with accuracy sometimes matching that of experienced surgeons (Kennedy-Metz et al. 2021; Ward et al. 2021). This has the potential to provide the surgical team with real-time feedback, alerting them to protocol breach or alerting them to potential hazards, thereby enhancing accuracy and safety (Mascagni et al. 2022). Furthermore, real-time image segmentation with AI and AR overlays can provide surgeons with precise visual cues, improving targeting accuracy (Bain et al. 2024). Robotic-assisted surgery is particularly benefited by AI integration, with ML algorithms enhancing instrument tracking, enabling automation of settings based on tissue characteristics, removal of smoke from surgical videos, and facilitating the identification of safe planes of dissection (Fard et al. 2018; Iftikhar et al. 2024; Knudsen et al. 2024). The inherent precision of robotic instruments, combined with AI-driven motion scaling and tremor reduction, allows for more accurate movement within constrained areas, with the potential to achieve improved resection margins and reduced complications in complicated oncologic procedures (Hwang and Hunt 2020; Wright 2017). Aside from direct surgical assistance, AI advancements are also improving surgical training and skill assessment. AI-powered simulators and performance metrics tools can provide objective measurement, detect technical faults, and provide personalized feedback, thereby accelerating the learning curve for complex oncologic procedures and helping to maintain high standards of surgical care (Navarrete-Welton and Hashimoto 2020; Varghese et al. 2024). The application of such diverse AI applications to daily veterinary surgical oncology can improve the precision and success of cancer surgery in companion animals but requires dedicated research, validation, and adaptation to species-specific demands.

3.5 AI-assisted surgical workflow and perioperative planning

Adding artificial intelligence to the overall surgical process is propelling an increasingly integrated, data-driven, and smarter perioperative process, from initial patient screening to post-op management. AI-enhanced surgical workflow leverages processing power to parse and combine massive volumes of patient data and inform decision-making at each critical point (Nardone et al. 2024). The aim is to enhance the efficiency, safety, and personalization of surgical cancer treatment. In the preoperative phase, AI systems contribute by creating personalized surgical plans through the analysis of imaging data, patient history, genomic profiles, and predictive models of treatment response or potential complications, as detailed previously. This step makes the next step in the surgery more informed. AI goes beyond direct guidance during the intraoperative phase to help with managing workflow. Real-time computer vision systems built into the surgical environment can keep an eye on the steps of the procedure, predict the instruments that will be needed, and send alerts or suggestions to the surgical team. This helps ensure that best practices are followed and that the procedure is as efficient as possible (Jalote-Parmar and Badke-Schaub 2008; Navarrete-Welton and Hashimoto 2020). Ongoing analysis of the surgical field assists dynamic decision-making and intraoperative readjustment. Finally, after the operation, AI can assist in predicting recovery trends, identifying at-risk patients for complications for early treatment, and optimizing follow-up care schedules. The following figure is a conceptual representation of this AI-powered surgical workflow with significant AI contributions along the perioperative continuum (Fig. 1). The implementation and introduction of such integrated AI-enabled processes in veterinary cancer surgery could substantially streamline complex cancer procedures, increase utilization, and eventually improve the quality and standard of care.

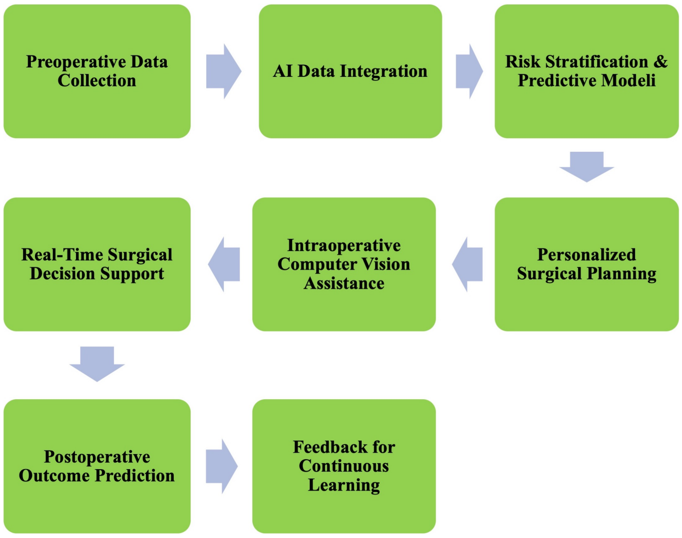

Fig. 1. *Conceptual overview of this AI-assisted surgical workflow*

3.6 Intraoperative imaging and real-time sugical guidance

While detailed preoperative imaging forms the cornerstone of surgical planning, the advent of advanced intraoperative imaging (IOI) modalities has significantly expanded the ability of the surgeon to achieve precise tumor resection and make important real-time decisions intraoperatively during oncologic surgery (Alam et al. 2018; Lauwerends et al. 2021). These tools provide immediate visual feedback, enabling avoiding the pitfalls of relying solely on preoperative data, which can't always compensate for tissue displacements and changes during surgery. Different IOI techniques are being found useful. Real-time intraoperative ultrasound has a dynamic, cost-effective, and radiation-free method of imaging soft tissue lesions, guiding biopsies, and confirming resection margins (Moiyadi 2016; Nagaya et al. 2017). Intraoperative CT (ICT) provides high-resolution cross-sectional imaging directly in the operating room, enabling updated anatomical information for complex resections and immediate verification of surgical goals, such as hardware placement or extent of tumor removal (Grozdanić et al. 2024; Kumar et al. 2021).

A particularly impactful advancement is fluorescence-guided surgery (FGS), a form of intraoperative molecular imaging. FGS utilizes systemically or locally administered fluorescent contrast agents that selectively accumulate in tumor tissue or highlight specific biological processes. Specialized camera systems then enable real-time visualization of these fluorescent signals, helping surgeons to more accurately delineate tumor margins, identify residual tumor deposits, detect involved lymph nodes, or visualize critical normal structures (Azari et al. 2021; Hussain and Nguyen 2014). Key advantages of FGS include its relative safety (often non-ionizing), ease of integration into surgical workflows, and demonstrated ability in human clinical trials to improve the completeness of tumor resections and reduce local recurrence rates (Azari et al. 2021; Singhal 2016). The translation of various FGS agents and systems holds considerable promise for companion animal oncology (Lee et al. 2023).

Data from these IOI modalities can be integrated with surgical navigation systems, providing augmented reality overlays or co-registration with preoperative plans to guide the surgeon with enhanced spatial awareness (Hu et al. 2018). The merging of these is important for maximizing tumor cytoreduction without leaving behind vital healthy tissues. In veterinary oncology in companion animals, where tumor presentations vary extensively and working areas can be compromised anatomically (Shaye et al. 2015), the precision that IOI offers is particularly valuable. It is capable of minimizing risks of protracted anesthesia or multiple surgeries by maximizing the rate of success of the first treatment (Birettoni et al. 2017; Cabon et al. 2016). The continuous innovation and development of IOI technology are thus foundations for improving precision surgical oncology objectives in veterinary medicine.

3.7 Innovations in precision cancer management for companion animals

Development in PM of oncology in companion animals is stimulated by a series of significant technological and conceptual innovations, enhancing diagnostic accuracy, prognostic capability, and individualization of treatment strategies (Domrazek and Jurka 2024). This advancement is shifting veterinary cancer management away from traditional paradigms, ushering in new optimism for enhanced outcomes. While cancer in companion animals, particularly canine animals, is a predominant cause of morbidity and mortality, these advancements are paving the way for more effective and personalized management (Alvarez 2014; Fleming et al. 2011). A cornerstone of this progress is advanced genomic profiling, primarily through NGS. NGS techniques have revolutionized the ability to comprehensively analyze cancer genomes in dogs and cats, offering high sensitivity and accuracy in detecting genetic alterations, specific mutations, and molecular subtypes that drive tumor development and progression (Brunetti et al. 2023; Flory et al. 2024; Flory et al. 2022; Ruiz-Perez et al. 2024). This specific genomic information allows veterinarians to identify specific therapeutic targets, predict medication responses, and classify patients into subpopulations for optimal treatment plans (Alshammari et al. 2025; Bahcall 2015). The data revealed by NGS in domesticated animals also contributes significantly to comparative oncology in general, accelerating research and allowing the development of novel therapies on the board of species, including humans (Marconato et al. 2013; Oh and Cho 2023; Simpson et al. 2022; Varshney et al. 2016). This exhaustive genomic information that is condensed compared to traditional methods in Table 2. Based on genomic information, liquid biopsies are rapidly becoming an extremely useful, less intrusive diagnostic tool in veterinary oncology. These tests analyze circulating tumor-derived material, such as cell-free DNA (cfDNA) and other markers in blood or other fluids, that are shed by tumor cells (Colombo et al. 2021; Flory et al. 2022; Kim et al. 2021). Liquid biopsies have the potential to be valuable in early cancer detection, tracking treatment response, identifying minimal residual disease, and identifying emergent resistance mutations, all with much less invasiveness than traditional tissue biopsies.

Table 2. Comparison of traditional diagnostic methods versus next-generation sequencing (NGS)-based approaches in veterinary oncology

Diagnostic method	Traditional techniques	NGS
Sensitivity	Moderate	High, enables detection of low-frequency variants
Throughput	Single or few targets at a time	Simultaneous analysis of hundreds of genes
Invasiveness	Often requires tissue biopsy	Liquid biopsy available; non-invasive
Cost Efficiency	Lower upfront cost	High initial investment but reduced cost per target over time
Data Complexity	Limited molecular insights	Comprehensive genomic landscape insights

Besides, the roles of non-coding RNAs (ncRNAs) in cancer biology are being well recognized. MicroRNAs (miRNAs) and long non-coding RNAs (lncRNAs) although they are not translated into proteins, are essential regulators of gene expression and play roles in cancer progression, metastasis, and drug resistance (Hashemi et al. 2024; Mirzaei et al. 2023; Sabouni et al. 2023; Taheriazam et al. 2023; Zandieh et al. 2023b). In veterinary oncology, both miRNAs (Fish et al. 2020; Srisawat et al. 2025) and lncRNAs (Hitte et al. 2019; Zhang et al. 2023) are being investigated as stable and readily detectable biomarkers. Their potential for diagnostic, prognostic, and theranostic applications could further refine personalized treatment pathways within the PM framework (Bolha et al. 2017; Cavaliere et al. 2021; Yuan et al. 2020). Collectively, these innovations in genomic sequencing, liquid biopsies, and ncRNA analysis are enhancing the ability to detect tumors earlier, develop more targeted therapies, improve survival rates, and ultimately enhance the quality of life for companion animals with cancer (Chon et al. 2024). They exemplify the multidisciplinary collaboration inherent in the PM ecosystem, bringing together researchers, diagnostic laboratories, and clinicians to deliver tailored cancer care. This collaborative and translational process is illustrated in Fig. 2.

3.8 Challenges and future opportunities in precision veterinary oncology

The integration of advanced imaging, AI, and molecular innovations into precision veterinary oncology holds immense promise for transforming cancer care in companion animals. However, the widespread clinical adoption and sustained progress of these sophisticated approaches are contingent upon successfully navigating several notable challenges (Petzschner 2024). It is overcoming these challenges that holds the secret to translating today's research gains into tomorrow's clinical advances, yet these very challenges also offer

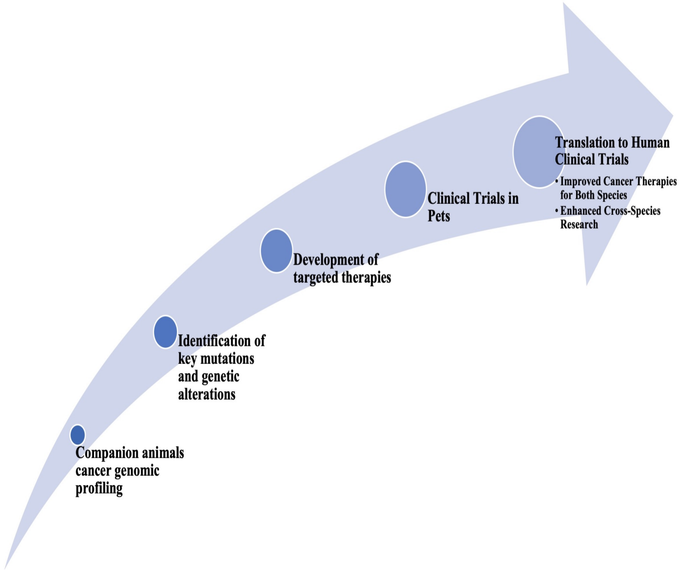

Fig. 2. *The collaborative cycle in comparative oncology research. This flowchart illustrates the key stages and interactions in comparative oncology, highlighting how research involving naturally occurring cancers in companion animals (e.g., genomic analysis, preclinical trials) informs and accelerates the development and validation of targeted therapies and diagnostic approaches for both veterinary and human patients, fostering a reciprocal translational impact.*

significant opportunities for development, collaboration, and strategic thinking for the field in general. One group of barriers relates to financial and infrastructural hurdlesThe cutting-edge technologies that underpin precision oncology—including advanced imaging systems like PET-CT, NGS platforms, specialized AI software, and robotic surgical units—necessitate substantial capital investment and incur significant ongoing operational expenditure (Duffy 2016; Lajmi et al. 2024). Such high costs can considerably limit access to these technologies, particularly for smaller veterinary practices or those operating in resource-constrained environments. In line with this, it will be essential to the broader access the development of more affordable diagnostic and therapeutic products, as well as innovative financing mechanisms (Kasztura et al. 2019). Beyond financial considerations, data management and interoperability present further complex issues. Precision medicine is inherently data-intensive, relying on the effective integration and analysis of diverse datasets, including genomic, proteomic, imaging, clinical, and patient-reported outcomes Beyond finance, data management and interoperability are other difficult issues. Precision medicine is by its nature data-dependent, based on the effective integration and evaluation of disparate datasets, including those genomic, proteomic, image, clinical, and patient-reported outcomes (Kraus et al. 2018). Current limitations include the lack of data format standardization across platforms and institutions, the prevalence of siloed information systems, and the infrastructure lack for large-scale secure data storage, ethical sharing, and advanced computational analysis. These factors can impede collaborative research efforts and the development of robust, generalizable AI models (Edsjö et al. 2023; Naithani et al. 2021; Petzschner 2024). Coupled with these are the regulatory and ethical considerations that emerge with rapidly advancing technologies. The pace of innovation outstrips the development of clear regulatory frameworks for novel diagnostics, targeted therapies, and AI algorithms in veterinary medicine. Furthermore, ethical issues of data privacy, informed consent for data utilization, ownership of biological data, and equitable access to innovative therapies must be diligently and continuously addressed (Goisauf and Cano Abadia 2022; Korngiebel et al. 2017).

One of the most important enablers for the success of precision veterinary oncology implementation is human expertise, yet educational and specialized training needs constitute another significant challenge. Effective use and interpretation of precision approaches necessitates advanced levels of interdisciplinary proficiency in genomics, bioinformatics, sophisticated imaging interpretation, AI literacy, and data science in veterinary practitioners. There is thus a pressing need to augment veterinary curricula with these subjects and to develop specialized continuing professional development programs to equip the workforce with the necessary skills (McGrath and Ghersi 2016; Nightingale et al. 2025). Despite these challenges, the path forward is rich with future opportunities and strategic directions that can propel the field. Fostering multi-institutional and international collaborative initiatives is paramount. The establishment of standardized protocols for data collection, quality control, and analysis, along with the creation of shared, ethically governed data repositories, can help overcome current fragmentation and significantly accelerate research progress (Stenzinger et al. 2023). Developing regional or national centers of excellence in precision veterinary oncology could further serve as vital hubs for cutting-edge research, specialized training, and the broader dissemination of validated best practices (Lloyd et al. 2016).

Moreover, leveraging the principles of comparative oncology by strengthening partnerships between veterinary and human oncology research centers offers profound mutual benefits. Naturally occurring cancers in companion animals frequently share important molecular, genetic, and pathological similarities with their human counterparts. This makes them invaluable comparative models for investigating disease mechanisms and for validating novel diagnostic tools (such as liquid biopsies and advanced imaging techniques) and innovative therapeutic strategies, thereby accelerating the translational research pipeline for both human and animal patients (Chon et al. 2024; Lloyd et al. 2016; Pang and Argyle 2016).Continued technological advancements, particularly in AI and computational tools, will also be critical. Future development should focus on creating more interpretable, robust, and rigorously validated AI algorithms specifically tailored for veterinary applications. The availability of user-friendly computational platforms that can seamlessly integrate and analyze multimodal data at the point of care will empower clinicians to make more informed, timely, and personalized treatment decisions (Duggirala et al. 2025; Sisodiya 2021). Finally, a concerted focus on demonstrating value and improving accessibility will be essential. Rigorous studies evaluating the clinical utility and cost-effectiveness of precision oncology approaches are needed to justify their integration into standard care. Concurrently, research into developing more affordable diagnostic tests and targeted therapies will be key to ensuring that the benefits of precision medicine can reach a wider spectrum of companion animals across diverse veterinary care settings (Das et al. 2024). Successfully navigating the existing challenges while strategically capitalizing on these emerging opportunities requires a dedicated and collaborative effort from all stakeholders, including researchers, clinicians, industry partners, regulatory bodies, and funding agencies. Such commitment will be paramount in fully realizing the transformative potential of precision medicine for improving the lives of companion animals diagnosed with cancer.

4. Conclusions

The new approach to combat tumors is the establishment of advanced diagnostic radiology, AI tools, and PM principles in companion animal oncology. This review has highlighted how AI-enhanced imaging techniques deliver crucial anatomical and functional insights for improved diagnosis, staging, and treatment planning. Concurrently, the integration of advanced molecular profiling (including NGS and novel biomarkers) with innovative, minimally invasive, and image-guided surgical approaches—all increasingly by AI and unified under the spectrum of PM. Despite the significant benefits and promise offered by precision veterinary oncology, it presents indispensable challenges on its own. The most notable issue is the need for substantial investment in the AI sector and high-tech tools. Additionally, data transparency and collaboration across multiple sectors are common structural challenges. Still, the rapid pace of technological progress and the potential for comparative oncology will strengthen the collaborative research. Altogether, to make PM a key part of cancer management, we need to keep working on creating, testing, and using these advanced diagnostic and therapeutic methods. These kinds of efforts are necessary to improve the outcomes of treatment for companion animals, and they will keep giving us useful information about specific treatment for each patient.

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