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This is the author's manuscript

Original Citation:

Availability:
This version is available http://hdl.handle.net/2318/153716 since 2016-01-08T16:50:36Z

Published version:
DOI:10.1007/s00262-014-1645-5

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(Article begins on next page)
This is an author version of the contribution published on:
Riccardo F, Aurisicchio L, Impellizeri JA, Cavallo F.

The importance of comparative oncology in translational medicine.
In Cancer Immunol Immunother. 2015 Feb;64(2):137-48

The definitive version is available at:
DOI: 10.1007/s00262-014-1645-5
The importance of comparative oncology in translational medicine

Federica Riccardo¹, Luigi Aurisicchio², Joseph Impellizeri³, Federica Cavallo¹

¹Department of Molecular Biotechnologies and Health Sciences, Molecular Biotechnology Center, University of Turin, Turin, Italy

²Takis s.r.l., Rome, Italy

³DVM, DACVIM, MRCVS, Veterinary Oncology Services, New York, USA

Corresponding author:
Federica Cavallo
University of Turin
Molecular Biotechnology Center
Via Nizza, 52
10126, Torino
Italy
e-mail: federica.cavallo@unito.it
Abstract

Human cancer is complex to such an extent that *in vivo* pre-clinical models are needed if effective therapies are to be developed. Naturally occurring cancers in companion animals are therefore a great resource, as shown by the remarkable growth that comparative oncology has seen over the last 30 years. Cancer is a leading cause of death in companion animals now that more pets are living long enough to develop the disease, while more owners are seeking advanced and novel therapies for them as they are very much considered family members. Living in the same environments, pets and humans are often afflicted by the same types of cancer which show similar behavior and, in some species, express the same antigen molecules. The treatment of pet tumors using novel therapies is of compelling translational significance.

Précis

Cancer therapeutics has been limited to translational murine models for decades. Naturally occurring pet cancer models may provide more accurate treatment assessment and expedite approval thus furnishing potential benefit to all species battling cancer.

Keywords

Cancer models; canine tumors; tumor associated antigens; immunotherapy
The complexity of human cancer requires the use of animal models

Cancer models: from the in vitro study of tumor cell lines to in vivo murine models

Cancer is a complex biological process through which a normal cell acquires, step by step, new capabilities that cause its transformation into a tumorigenic and eventually malignant cell. An understanding of this biological complexity has spurred the development of increasingly comprehensive experimental models (Figure 1).

For many years, the study of cancer cell lines has been the elective experimental model (Figure 1a) and a valuable tool for investigating many aspects of cancer biology, such as genetic, epigenetic and cellular pathway alteration, deregulation of proliferation and apoptosis, and for the testing therapeutic drugs (1, 2). Nevertheless, heterotypic interactions between the tumor and the multiple distinct cell types of the microenvironment, including immune cells, are missing in these in vitro studies. The microenvironment evolves in response to tumor survival adaptation, thereby enabling primary, invasive and potentially metastatic growth (3). This dynamic reciprocity between tumor cells and their environment (4) sculpts the hallmarks of cancer and poses additional challenges in the design of appropriate experimental models.

A relatively easy solution is found in injecting transplantable cancer cell lines in syngeneic or immunodeficient mice (5) (Figure 1b). These transplantable models can be standardized and provide reproducible data, but are highly artifactual. They allow the three-dimensional growth of tumors and their direct interaction with the stromal microenvironment to be studied (6). However, they distort the architectural and cellular complexity of real cancers, as transplanted cells are already transformed and are injected in sufficient number to give rise to a tumor in a young and healthy host (7). Tumor cells are typically implanted subcutaneously, but the implantation into the organ of origin mimics human cancer behavior and the microenvironment more closely. Experimental results generated by orthotopic models are therefore expected to be of higher relevance (8).

A further evolution in transplantable models is found in patient-derived xenografts (PDX) (Figure 1b). These represent the heterogeneity of human cancers and take into account the natural history of the tumors and/or patients, as regards to 1) inter-patient variability, 2) the diversity of tumor cells with respect to the molecular profile and sensitivity to a specific agent and 3) intra-tumor heterogeneity. These xenografts derive directly from patient samples, without in vitro manipulation, and provide a more accurate representation of the biological
features of human tumors. Moreover, several groups have established disease-specific
xenograft panels directly from patient tumors that might better reflect a clinical response (9),
being of help for the choice of the most appropriate drug to be used for that patient. This
represents an important step forward personalized medicine but not without pitfalls. The
mouse one little by little replaces the implanted patient stroma, while the mouse immune
system is not functional and both these aspects could affect the translational value of the
results. Moreover the entire strategy of implantation of the patient tumor in mice (not always
successful) and of drugs testing may take longer becoming a race against the time for the
patient (10).

The predictive utility of tumor models depends on the fidelity with which they recapitulate
the entire evolution of the disease, including the interaction between the tumor and the
immune system, the inherent angiogenic process, tumor-associated fibroblast infiltration and
additional stromal components (11). Genetically modified mice (GEM) which have been
engineered to express oncogenes, or in which tumor suppressors have been disrupted, and
that spontaneously develop tumors are a good step forward (5) (Figure 1c). The relationships
between the tumor and the surrounding tissues are preserved, while the progression of
carcinogenesis may mimic what is observed in humans (12). The advent of GEM has
revolutionized preclinical cancer research and several successful preclinical results have been
achieved in different GEM models. Nevertheless, GEM are not devoid of pitfalls: tumor
penetration is not always complete, meaning very large experimental groups must be used.
Tumor formation takes longer than in transplantable tumors, thus greatly extending the
period of experimental observation; transgene expression is usually under the control of a
heterologous promoter, leading to non-physiologic transgene expression throughout the
tissue(s) where the promoter is activated and for the mouse entire life is (10). This may
influence the tumor microenvironment and the immune response to the transgene product
itself (13, 14). Mouse models that conditionally express a particular oncogene, in a tissue-
specific and time-controlled manner, provide new opportunities to gain insight into the
development and treatment of cancer. These conditional mice allow for the study of malignant
transformations in the context of an appropriate, non-mutated microenvironment which
more faithfully mimics the sporadic nature of human tumors (15-17).

An accurate predictive tumor model should simulate human therapeutic responses and the
evolution of resistance. As a consequence, xenografts in mice carrying the human immune
system have been proposed as an interesting pre-clinical model for the in vivo study of the
complex interaction between human tumors and the human immune system. Highly immunodeficient mice and transgenic animal models for human factors have been developed and used to generate “humanized mice” (5) (Figure 1b). However, most existing humanized mouse models cannot develop human innate immune cells, including myeloid cells and NK cells. Two mouse strains, MITRG and MISTRG, have been recently described in which four human genes which encode cytokines and that are important for innate immune cell development are knocked in their respective mouse loci (18). Human cytokines facilitate the development and function of monocytes, macrophages and NK cells that are derived from human fetal liver or adult CD34+ progenitor cells transplanted into the mice. Human macrophages infiltrate human tumor xenografts in a manner resembling that of tumors obtained from human patients. The generation of Class I and Class II HLA transgenic NOG mice is an exciting advance in humanized mice for the study of T cell responses to tumor associated antigens (TAAs). The expression of Class I and II HLA should ultimately provide the chance to pre-clinically evaluate tumor vaccination strategies in which both the generation of MHC restricted tumor-specific T cells and their therapeutic effect on tumor growth can be determined.

Large animal models, like non-human primates, allow for the study of the immune response but not cancer

While studies in rodent models offer the advantages of testing the potency and therapeutic efficacy of cancer immunotherapies or vaccines, they cannot predict efficacy when doses are scaled-up for human patients, particularly when dealing with self-tumor antigens and immune tolerance. Human and mouse immune systems show discrepancies in both innate and adaptive immunity, including leukocyte subset balance, defensins, Toll like receptors, inducible NO synthase, NK inhibitory receptors, FcR, Ig subsets, some B cell and T cell signaling pathway components, γδ T cells, cytokines and cytokine receptors, Th1/Th2 differentiation, costimulatory molecule expression and function, antigen-presenting function of endothelial cells, chemokine and chemokine receptor expression (19). This limitation can be overcome by testing vaccination regimens in large animals with immune systems which are more similar to those in humans, such as in nonhuman primates (NHPs) (Figure 1d). NHPs such as macaques are valid models to determine the safety and immunogenicity of candidate vaccines that are being developed (27). Their immune response is similar to that of humans, and within the past two decades numerous immunogenicity studies have used NHPs to test pre-clinical candidate vaccines consisting of bacterial or viral recombinant proteins. Other
studies have tested human proteins or TAA encoding vectors (28, 29). Although human and NHPs proteins share high homology, the resulting immune response may not reflect outcomes in humans, since the antigen may be recognized as a non-self protein. To assess the impact of a vaccination strategy in breaking immune tolerance, we have cloned rhesus orthologue TAA genes to generate genetic cancer vaccines (20). We have also determined how important single nucleotide polymorphisms are in breaking immune tolerance to a self-antigen like HER2/neu (21).

NHPs carry with them two important limitations: 1) cost: in general, only pharmaceutical companies or large research institutes can afford the expensive studies associated with these animals; 2) lack of efficacy: NHPs allow the immunologic assessment of a cancer vaccine to be carried out in healthy individuals but cannot be useful in determining its therapeutic efficacy and impact on tumor-induced immune suppression, since spontaneous cancer is very rare even in large NHP colonies. Therefore, while they are a relevant model for the scale up of safety and immunology studies, NHPs do not fully recapitulate cancer disease conditions and immune system impact.

**Naturally occurring tumors in companion animals: an undervalued resource**

Similarities between human and pet tumors

The study of spontaneous tumors in companion animals is gaining momentum (Figure 1e). Cancer in pets is a naturally occurring disease and as common as in humans (22). It is a leading cause of death in dogs and cats, especially now that they are living long enough to develop the disease. Several organizations are involved in advancing the knowledge of cancer in pets. These specialists include teams in veterinary surgery, radiation oncology, medical oncology and clinician/researchers (AVBC, Australia/New Zealand- http://www.avbc.asn.au/; ACVS-https://www.acvs.org/; ACVR-http://www.acvr.org/; American (www.acvim.org) and European (www.ecvim-ca.org) Colleges of Veterinary Internal Medicine, Veterinary Cancer Society, VCS).

The higher risk associated with age and behavior and, in some cases, the similar antigen expression patterns of many cancers in domestic animals mirror human disease, making the treatment of pet tumors with novel therapies critical to advancing human patient cure (23). Pet tumors develop in an intact immune system, allowing the complex interactions between the tumor and the immune system to occur. This makes tumors susceptible to the selective
pressure of spontaneous immunity and leads to the intratumoral heterogeneity and genetic instability (24, 25) that faithfully reproduce human cancers.

Dogs are the most studied. Living in close proximity with humans, dogs are afflicted by the same cancers (26-28), and provide an opportunity to address not only genetic risk for disease, but also nutritional and environmental factors that are crucial for human tumor development (29, 30). Spontaneous cancers in dogs grow over long periods of time in a syngeneic microenvironment shaped by the natural evolution of the tumor mass, and often give rise to recurrences and metastases, mimicking the progression of human tumors better than other preclinical models (31). The existence of different breeds in the dog population means that the heterogeneity in patients with the same disease reflects the diversity of human cancers.

The recent release of the entire canine genome sequence has proven that its homology with the human genome is stronger than that between mouse and human genome (32). Comparative gene expression studies have revealed close correspondence, in terms of tumor genetics and molecular targets, between canine and human tumors (33-35), thus supporting the use of canine cancer models as a mirror for what occurs in human cancer biology. The finding of common driver oncogenes and deregulated cancer pathways in dogs and humans means canine tumors act with similar biologic behavior and provide a similar response to conventional therapies (22, 23). As a result, spontaneous cancer in dogs may reproduce the biological and clinical complexity of human tumors in a manner that is not possible for other preclinical models (6) (Figure 2).

The translational power of naturally occurring pet tumors

The similarities between pets and humans with respect to anatomy, physiology, tumor onset and progression make canine tumor models a valuable tool for identifying new cancer-associated genes and for enhancing our understanding of tumor molecular biology. In addition, dog models will allow for the evaluation and development of novel diagnostic, prognostic and therapeutic applications that can benefit both dog and human cancer patients (6).

Cancer treatment in dogs includes many of the same drugs used in humans, predominantly via off-label drug use (46, 47). Dogs and humans often have the same responses to therapies and therefore studies in dogs may provide useful information about drug toxicity and the mechanisms underlying the resistance of human patients to chemotherapy. There is no “gold standard” treatment for many canine cancers and so it is possible to evaluate new agents as
first-line therapies, in combination with other treatments, or as adjunctive therapies in an expedited and efficient manner (36). Moreover, as several cancer associated genetic alterations that influence cancer progression in humans have been identified in canine cancer (33, 37, 38), testing new targeted therapies for cancer treatment holds great translational value for proof-of-concept and proof-of-target efficacy.

Naturally occurring tumors develop over long periods and constantly interact with the syngeneic immune system of the canine patients, shaping the immune response and the immune environment and mimicking the natural cancer immunoediting of human patients. Therefore, evaluating the efficacy of novel immunotherapies in animal patients may be strongly predictive of their clinical efficacy.

The rationale for evaluating therapeutics in domestic animals before in-human studies is clear: 1) they provide a unique opportunity to evaluate both the safety and activity of a novel drug and have high translational value due to the similarities between canine and human tumors; 2) they offer a valuable means to assess treatment options which can be rapidly translated to human clinical use. These data are time consuming, labor intensive and difficult to complete in conventional preclinical models or human clinical trials alone (39). Furthermore, the inclusion of dogs from different breeds provides cross-sectional value that is often higher than in studies of inbred laboratory animals (23, 40). The heterogeneity and complexity of cancer in the pet dog population also offers great opportunities for the development and optimization of molecularly guided analysis, which characterizes personalized medicine (41).

Whereas there are strict regulations for human clinical trials, there are fewer restrictions for phase I/II/III trials in domestic animals with informed consent being a necessary regulation (39). The reduced regulatory guidelines and the naturally shorter life spans of canine patients allow for the rapid development and completion of clinical trials that can assess outcomes in a 6-18 month window. This is impossible in human cancer trials (42). The value of comparative oncology trials has been increasingly recognized as a potent translational means to assess the safety, efficacy, suitable human dosage and clinically relevant endpoints of a study (43). Veterinary clinical studies are becoming an “avatar” for the human setting, providing an easier way to study human cancer and innovative strategies to battle it. A number of translational contributions have originated from studies in pets (reviewed in (23)) which include the use of several targeted kinase inhibitors (44), L-MTP-PE for the treatment of osteosarcoma (45) and the first DNA-vaccine to be approved by the United States Department of Agriculture (USDA) for the treatment of melanoma, ONCEPT (see later).
The Comparative Oncology Program and the LUPA Project: a way to provide new therapeutic opportunities for both pets and humans

The surveillance of cancer in pets has become more intense and an important challenge in the veterinary field in recent years. Pets are also members of the family for many people, thus motivating pet owners ("pet parents") to seek out advanced therapies for the management of cancer in their companion animals. The National Cancer Institute's Center for Cancer Research (CCR) of the United States established the Comparative Oncology Program (COP) in 2003 to help advance an understanding of the biology of cancer and to ascertain the benefit of novel treatments for humans by evaluating the response of these treatments in naturally occurring cancers in pet animals - primarily cats and dogs.

The COP (https://ccrod.cancer.gov/confluence/display/CCRCOPWeb/Home) designs and organizes clinical trials in collaboration with academic veterinary institutions across the United States. Pets may receive treatment under board-certified veterinary oncologists. Participation within these trials does require travel to specific veterinary academic centers, which is not always possible for even the most dedicated pet parent. The website, www.vetcancertrials.org, was developed and is maintained by the University of Missouri-Columbia Veterinary Medical Teaching Hospital and is designed for use by everyone involved in the treatment of pet animals with cancer, including pet owners, general practice veterinarians, board-certified oncologists and other specialist veterinarians. Information is provided for clinical trials from both private practices and academically based veterinarians to favor the rapid completion of clinical trials while providing progressive treatment options for pets with cancer. There are almost 90 trials listed currently and more trials are added every month. Some trials are fully funded while others require financial outlay. The site is an invaluable asset in the quest for progressive treatment options, is supported by the VCS and was originally developed by the Veterinary Cooperative Oncology Group (VCOG). VCS is a group of board-certified veterinary oncologists and associated specialists assembled to facilitate high quality veterinary oncology. VCOG also promotes collaborative investigations.

A European initiative to use dogs as a model for the study of common complex diseases in humans, including cancer, was formed and funded in 2008 by the European Commission (http://www.eurolupa.eu). The LUPA project (46) was named after the female wolf which fed the twin founders of Rome, Romulus and Remus, and was initiated to highlight how humans may benefit from genetic studies on dogs. The project consists of 22 collaborating veterinary
faculties and research centers which target five overlapping disease categories including cancer.

An example of their collective effort is the fact that SNP genotypes, collected as part of the project, are stored in a central database. LUPA partners have identified loci associated with susceptibility to several complex disorders, and more importantly have improved the dialogue between veterinary clinicians and geneticists throughout Europe and the rest of the world (47-49).

The most recent translational contribution can be found in the drug Toceranib (Palladia) from Pfizer Animal Health, now Zoetis. Like the human cancer drug Sutent, Palladia was born at Sugen, a company that was acquired by Pharmacia, which in turn was bought by Pfizer. The drug is a multi-kinase inhibitor that targets several receptor tyrosine kinases and is FDA approved for the treatment of Patnaik grade II or III, recurrent, cutaneous mast cell tumors with or without regional lymph node involvement in dogs (50).

**Cancer immunotherapy in dogs**

A limitation of cancer immunotherapy in dogs has been the relatively poor knowledge and understanding of canine immune system, mainly due to a lack of reagents, such as antibodies which are able to identify specific subpopulations. Such tools have recently become available and several studies have identified immune cells which play crucial roles in canine cancer immunology, such as T regulatory cells (51, 52), myeloid derived suppressor cells (53), NK cells (54) and tumor macrophages (55). This increased knowledge has further solidified the position of dogs as a translational model for cancer immunotherapies. The following paragraphs summarize the most relevant efforts.

**Lymphosarcoma**

An example of the translational relevance of canine cancer is non-Hodgkin lymphoma (NHL), the most common canine malignancy, which accounts for up to 24% of all reported neoplasms. The majority of canine NHL (60–80%) arise from malignant B cells, as is the case in humans (56). This disease has shown a positive association with exposure to herbicides, chemicals and with living in highly polluted areas (57-59). Significant association between the distributions of human, canine NHL and environmental factors such as waste incinerators, polluted sites and radioactive waste was found in a French study (60).
Malignant lymphosarcoma (LSA) is the most common NHL in dogs. The median age of occurrence is around 7 years (61, 62). The two standard-of-care treatments for canine B-lineage NHL are chemotherapy regimens; cyclophosphamide, vincristine and prednisolone (COP), and cyclophosphamide, vincristine, doxorubicin and prednisone (CHOP). These result in temporary remission in approximately 85% of patients, but are rarely curative, as the two-year survival rate is lower than 20% (63). A shorter but dose-intense CHOP chemotherapy schedule results in a median survival time of approximately 27 weeks (64). Combination protocols have generally been in favor, however single agent protocols have provided extended survival and should be considered (61, 65).

Due to its high frequency in the pet population and an intense medical need, canine LSA is a suitable model for innovative therapies. Recent reports have shown that canine LSA is treatable with experimental immunotherapy, such as adoptive cell therapy (66), tumor RNA-loaded, CD40-activated B cell (67) and autologous Heat Shock protein complexes (68), in addition to standard chemotherapy. These studies have reported significant delays in tumor progression and occasionally complete remission, thus demonstrating the susceptibility of this tumor type to immunotherapy. However, these personalized cell therapy agents are cumbersome and generally very expensive. For these reasons, alternative technologies which combine lower manufacturing costs and more standardized production processes are needed. Gene-based vaccines are a promising avenue. Research by some of the authors (LA, JAI) show that a genetic vaccine which targets dog telomerase reverse transcriptase was immunogenic in almost all treated animals and most importantly, in a double armed trial had a significant therapeutic impact on canine LSA (69, 70).

Monoclonal canine antibodies for the treatment of canine LSA are also attracting interest. Rituximab, a chimeric monoclonal antibody, has previously been evaluated for binding against canine B cells in NHL, but no in vivo depletion was identified (71).

Aratana (www.aratana.com) is a US company that is actively involved in this technology. They are developing AT-005 for T-cell lymphoma. AT-005 is a canine version of Campath, which is a drug developed for human targeting CD52. Similarly, AT-004 mAb provides dogs with targeted immunotherapy against the cell-surface antigen CD20, which is expressed on canine lymphoma B-cells. AT-004 depletes malignant B-cells.

Genetic vaccines and canine mAb may therefore be a convenient and uniquely targeted product which can complement standard LSA treatment.
Melanoma

Malignant melanoma (MM) is a spontaneous tumor in dogs which makes up 7% of all malignant tumors (72). It is the most common malignant neoplasm of the oral cavity (73), while other less commonly affected sites are the lips (23%), skin (11%) and digits (8%) (72). Generally, MM is detected at an advanced stage when tumor resection is rarely curative and metastases are already present. Clinical biological malignancy is mainly attributed to oral melanomas as they are almost all malignant and display a metastatic rate of up to 80% to regional lymph nodes and other organs, including the lungs, and thus mimic the clinical evolution of human disease (72, 74).

Although they differ in frequency and severity (84, 87), canine and human melanomas share many similarities, including the same anatomical sites, similar histopathology and common architectural features (88). Several studies have focused on the evaluation of tumor genetics and canine MM molecular targets, leading to the identification of common hotspot somatic mutations in dogs and humans, suggesting that common pathways contribute to the progression of the disease in both species (75, 76). A similar differential gene expression pattern in the MAPK “mitogenic” pathway and in the PI3K/Akt “survival” pathway, primarily involved in human MM tumorigenicity, have been identified in canine MM (76), laying the foundation for more rational therapeutic comparative studies. While the absence of the BRAF somatic mutation in canine MM, which mostly develops in non-UV exposed sites, is paralleled in human non-UV-linked MM which also harbors wild-type BRAF. This denotes the relevance of the canine MM model to the study of human homologous, non-UV-linked MM subtypes and the identification of new therapeutic targets for wild-type BRAF patients.

The conventional management of canine MM, and especially of the most aggressive oral type, is often as disappointing as it is in humans. Traditional treatment for canine MM involves surgery, radiotherapy and chemotherapy and is efficient in controlling the tumor locally in up to 75% of animals, whether used alone or in combination. However the 1-year survival rate does not exceed 30%, because of metastasis (77-79).

Several comparative studies of novel immunotherapy therapy protocols have been performed in dogs affected by MM and promising results have been achieved (80-84). These efforts led to the development of the first USDA-approved anti-tumor vaccine: the ONCEPT (Merial), a xenogeneic DNA vaccine targeting tyrosinase which can extend survival in dogs with locally controlled stage II-III oral MM. This vaccine is widely used and gives encouraging results (85,
Nevertheless, a recent retrospective study conducted on a limited number of dogs has questioned its efficacy (87).

ONCEPT approval spurred the development and evaluation of other vaccines. Mayayo et al. were the first to investigate the expression of chondroitin sulfate proteoglycan (CSPG)4 in canine MM (88). It is an early cell surface progression marker which is highly expressed in about 80% of human MM where it regulates tumor cell proliferation, migration and invasion (89). Mayayo and coworkers found CSPG4 expression in about 60% of canine MM (88), and labeled it as a new marker for canine MM diagnosis and a promising immunotherapy target. Two of this review's authors (FC, FR) have now tested a xenogeneic DNA vaccine against this molecule in client-owned dogs with surgically resected stage II-III CSPG4-positive, spontaneous oral MM. The disease free interval and overall survival of vaccinated dogs were significantly longer as compared to those of controls, being 477 vs 180 and 653 vs 220 days, respectively (90).

Mammary carcinoma

Canine mammary tumors (CMT) share many characteristics with human breast cancer, including histological appearance, biological behavior, hormone dependence, frequent oncogene HER-2/neu activation (91, 92) and response to conventional treatments. Human and dog gene expression data, from both tumor and normal mammary samples, show that a significant number of shared genes are deregulated in the tumors as compared to their normal counterparts. Pathway analysis of gene expression data reveals a high degree of similarity in the perturbation of many cancer-related pathways. The transcriptional relationships between different gene signatures of human breast cancer are mostly maintained in the canine sequences, suggesting CMT as translational model for human disease (107). Similarly, feline mammary tumors (FMT) show protein and gene expression profiles that are comparable to human cancers (108, 109).

Standard therapies include surgical extirpation of the gland (dog) vs. radical bilateral mastectomies (cat) followed with chemotherapy. No standard chemotherapy protocol has been reported to be effective and continued research is being pursued to offset metastasis which leads to euthanasia. Mammary tumors are associated with a high risk of metastatic disease, especially in cats, and several studies indicate that HER-2/neu expression is similar in human breast carcinoma (93). For all these reasons, CMT and FMT are ideal preclinical models with which to evaluate HER-2/neu immunotherapy. A genetic vaccine based on a
combination of adenovirus and DNA electroporation has been shown to be immunogenic in dogs (94) and some authors (LA, JAI) are currently testing its antitumor efficacy in FMT and CMT.

**Osteosarcoma**

Osteosarcoma (OSA) is a primary bone tumor that most commonly affects the medullary canal of long bone metaphyses. It is similar in humans (95) and it is estimated that over 8,000 dogs per year will be diagnosed with OSA in the United States. Common sites are the distal radius, proximal humerus, distal femur and proximal tibia, but finding OSA at other sites is not unusual. Most affected patients suffer lameness and/or the development of a firm mass at the primary site. Of the primary bone tumors reported to occur in dogs, OSA is the most common and accounts for more than 80% of all canine primary bone cancers. The average age of canine sufferers is 7 years, but can range from 6 months to more than 12 years. Amputation alleviates pain and decreases risk of pathologic fracture. Without adjuvant therapy, amputation must be considered a pain-palliative procedure only, as it does not significantly increase survival time, but improves the quality of life. Patients usually succumb to lung metastasis.

Amputation and systemic chemotherapy is the current treatment of choice for canine appendicular OSA. Postoperative systemic chemotherapy is currently used to suppress the development of metastatic disease, but is ineffective. Two meta-analysis studies have recently been published and confirmed serum alkaline phosphatase (SALP) and proximal humeral location as negative prognostic factors and gave a median survival time of 256 days (96, 97). Many patients are poor candidates for amputation, due to mitigating factors such as severe degenerative joint disease, obesity and multiple tumor sites. Some owners resist the amputation of their pets’ limbs because they are reluctant to subject them to this radical procedure.

OSA is a suitable cancer for targeting with immunotherapy due to the frequency of metastatic disease despite local control. A common feature of OSA is the expression of the TAAs HER2/neu and/or CSPG4. An autologous tumor cell vaccine, genetically engineered to express hGM-CSF (98), was once suggested to induce an immune response and give a therapeutic outcome. More recently, Advaxis has developed technology that uses attenuated, live *Listeria* as a vector to deliver a tumor-associated antigen in order to activate the patient’s immune system. This protocol has been explored in OSA affected humans and dogs.
Listeria monocytogenes strains have been engineered to induce an innate immune response and to express tumor-associated antigens which induce tumor-specific T cell-mediated immunity. In addition, tumor antigens have been fused to virulence factor listeriolysin (LLO) in the Listeria bacterium. The combination of the tumor antigen and LLO generates a strong immune response which attacks the cancer. ADXS-cHER2 is an immunotherapy treatment based on this technology that targets the HER2 oncogene. An ongoing Phase I trial at the University of Pennsylvania is treating naturally occurring OSA suffering pet dogs with ADXS-cHER2, after their standard-of-care treatment, and shows significantly prolonged overall survival over dogs that received the standard-of-care treatment without ADXS-cHER2 (Advaxis press release). On this basis, Advaxis announced that it intends to initiate a clinical program of ADXS-cHER2 for the treatment of pediatric osteosarcoma. In addition, Advaxis signed a global licensing agreement with Aratana Therapeutics, Inc. for ADXS-cHER2 for the treatment of osteosarcoma in dogs. Two authors (LA, JI) have also been evaluating HER2 immunotherapy against canine osteosarcoma using the prime/boost technology with electrogene transfer, with patient accrual ongoing.

Conclusions

Our increasing knowledge of cancer biology, its mechanisms and tumors’ complex interaction with microenvironments and immune systems are leading to a new vision of translational oncology. Investigations into new drugs and vaccines, their combinations and the assessment of biomarkers and responding histologies can now rely on a variety of animal models which are much closer to human diseases.

Comparative oncology has undergone tremendous growth in the past 30 years and the continuation of this collaborative effort can only hasten important discoveries as to the mechanics of cancer and therapeutic intervention, which will bring benefits to both dogs and humans alike. Clinical trial funding, ever the challenge, will become easier to justify with the use of naturally occurring cancer models. Indeed, the treatment of canine patients today could be of immense help for their owners tomorrow. This is the main point that, in recent years, has moved veterinarians, pathologists, researchers, clinicians and pet owners themselves to collaborate and combine knowledge and effort. The final aim is to transform the concept of comparative oncology into a more efficient and concrete tool for translational medicine.
Acknowledgements

This work was supported by grants from the Italian Association for Cancer Research (IG 5377), the University of Turin and Fondazione Ricerca Molinette Onlus. We thank Dr. Dale Lawson for his revision and editing of the manuscript. We thank Apunto 3D Visuals (www.apunto.it) for its contribution to the creation of the figures.

Conflict of interest

The authors declare no conflict of interest.
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18. 10.1074/jbc.M111.269894


Figure 1. Evolution of experimental systems towards major complexity and translatability. The study of human cancer complexity has evolved from the use of cancer cell lines (a) to the use of ever more complex in vivo systems (b, c, d, e). The use of transplantable cancer cell line models, patient-derived xenografts, in syngeneic or immunodeficient mice, and of humanized mice are significant steps towards more comprehensive experimental models (b). The advent of genetically engineered mice (GEM) that spontaneously develop tumors and thus recapitulate complete disease evolution provides the first revolution in preclinical cancer research (c). To overcome limitations in murine models, testing immunological therapies in large animals, such as nonhuman primates (NHPs) which possess immune systems which are closer to ours, has offered advantages in scaling-up doses in human patients (d). However, translational medicine research is now rapidly moving towards the study of naturally occurring tumors in companion animals which may be priceless comparative models with which to accelerate the entry of new anti-cancer therapies into the human sphere (e).
Figure 2. Mirroring the human reality: the importance of the canine avatar. The many similarities between canine and human cancers make naturally occurring tumors in companion animals a mirror of the human clinical condition. Spontaneous tumors in pet animals grow over long periods of time in a syngeneic microenvironment, experience complex interactions between the tumor and the immune system and retrace the natural evolution of human tumors (giving rise to recurrences and metastases). They therefore mimic the progression of human disease better than other preclinical models. The significant anatomical, histological and physiological similarities between pet and human cancers, in terms of tumor onset, progression and treatment, as well as the identification of common tumor genetics and molecular targets, effectively increase the translational power of canine models to accelerate the development of new antitumoral therapies in human patients. Canine tumors realistically recall the complexity of human cancers thanks to their intratumoral genetic instability and patient heterogeneity. Canine cancer models are of great translational value as avatars of human tumor behavior and therapy response.
Transplanted cell lines

Patient-derived xenografts

Humanized mice

Cell line

Riccardo et al., Figure 1
Recurrences and metastases

Scaling-up doses

Naturally develop tumors growing over long time

Syngeneic microenvironment shaped by the natural evolution of the tumor mass

Complex interactions between tumor and immune system

Anatomical, histological physiological similarities

Tumor genetics and molecular targets

Intratumoral and inter-individual heterogeneity

Scaling-up doses

Riccardo et al., Figure 2