Establishment and Characterisation of Metastatic Extraskeletal Ewing Sarcoma Mouse Models

CARMELO CERRA*, MICHAEL A. HARRIS* and CHRISTINE J. HAWKINS

Department of Biochemistry and Genetics, La Trobe Institute for Molecular Science, La Trobe University, Melbourne, VIC, Australia

Abstract. Background/Aim: Ewing sarcomas most commonly arise in the bones, but can also manifest as extraskeletal tumours in soft tissues. Metastases from extraskeletal Ewing sarcomas occur in more diverse anatomical sites than skeletal tumours, and have poorer survival rates. Few animal models replicate the extraskeletal form of Ewing sarcoma, and those that have been developed do not reflect the widespread metastatic spread of these cancers. Materials and Methods: Luciferase-expressing Ewing sarcoma cells derived from a muscle tumour were intramuscularly or intravenously injected into nude mice. Results: Both models achieved metastatic spread to numerous sites including the lungs, liver, kidneys, and brain. We characterized the cellular composition of primary and metastatic tumours, observing a greater level of immune cell infiltration in metastases compared to primary intramuscular tumours. Conclusion: These pre-clinical models will hopefully facilitate the evaluation of novel therapies and contribute to better understanding the disease progression of metastatic extraskeletal Ewing sarcoma.

Sarcomas are a rare group of bone and soft tissue cancers of mesodermal origin. They usually originate in the bone, cartilage or soft tissue and are classified based on their histology and chromosomal translocations (1). Ewing sarcoma is a ‘round cell sarcoma’ which was first identified by James Ewing in 1921, when treating a 14 year old girl with a fractured ulna (2). It is the second most common bone cancer, behind osteosarcoma, and is most frequently diagnosed during adolescence (3). Although Ewing sarcoma usually develops in bones such as the pelvis and femur, a substantial minority of tumours arise in soft tissues (4-6). These extraskeletal (or extraosseous) Ewing sarcomas are rare in children, but account for up to half of adult Ewing sarcoma diagnoses (7-9). Approximately a quarter of Ewing sarcoma patients have detectable metastases at diagnosis (10). Metastatic spread of skeletal Ewing sarcoma occurs most commonly to the lungs, other bones, and bone marrow (11). Extraskeletal Ewing sarcoma spreads most frequently to the bones or lungs (12) but approximately 14% are metastases within other organs, such as abdominal organs, the peritoneum, brain, or heart (12, 13). Current treatments for Ewing sarcoma involve neo-adjuvant chemotherapy, typically with vincristine, doxorubicin, cyclophosphamide, ifosfamide and etoposide, followed by surgery and/or radiotherapy (5). The incorporation of multiagent chemotherapy increased 5-year survival rates for localized disease from approximately 10% to 70% (14, 15). Unfortunately, these therapies are less effective against Ewing sarcoma metastases, especially those derived from extraskeletal primary tumours: only a quarter of those patients survive for five years or more (7). The metastatic predilection of extraskeletal Ewing sarcoma differs from the more common skeletal form of the malignancy, so it is conceivable that optimal therapies for metastases emanating from skeletal versus extraskeletal Ewing sarcomas may differ.

The establishment and characterisation of authentic Ewing sarcoma mouse models would provide a means to better understand the metastatic processes and to evaluate potential new drug candidates in a preclinical setting. Although Ewing sarcomas feature distinct oncogenic chromosomal translocations (16), efforts to create genetically-engineered mouse models of this cancer type have so far been unsuccessful (17). Instead, available models entail introducing Ewing sarcoma cell lines or patient-derived tumour material into mice. Subcutaneous introduction of Ewing cells or patient-derived tumour material into mice can be tumourigenic, and the resulting xenografts can
manifest authentic gene expression and tumour architecture (18-21). However, they do not necessarily recapitulate the tumour microenvironment or metastatic pathways, nor the bioavailability of candidate therapies that researchers may wish to test. Some orthotopic models of skeletal Ewing sarcomas have been established, via introduction of skeletal Ewing sarcoma cells into the tibia or femur (22-25). Ewing cell lines generated from bone tumours, like TC71 (26) or SK-ES1 (27, 28), have also been xenografted into the gastrocnemius muscle of SCID/beige mice (29).

To our knowledge, only one orthotopic model of extraskeletal Ewing sarcoma has been published. The A673 cell line, which was derived from a Ewing sarcoma that arose in the muscle (30-32), was tumorigenic upon injection into the gastrocnemius muscle of BALB/c nude mice (33-36). An urgent priority for Ewing sarcoma research is the identification of more effective therapies for metastatic disease. Our goal in this study was to create a model of metastatic extraskeletal Ewing sarcoma that reflects the diverse metastatic spread experienced by patients. In previous work, most mice that received injections of A673 cells into the gastrocnemius muscle developed lung pulmonary metastases 40-60 days post primary tumour resection (34-36), however spread to other anatomical sites was not observed. Interestingly, intratibial inoculation of A673 cells provoked metastases to other bones as well as the lungs (24), suggesting that the site of implantation can influence the pattern of metastatic spread. One aim of this study was to evaluate the metastatic potential of A673 cells following injection into the tibialis anterior, as mice tolerate quite large primary tumours in this muscle and osteosarcoma cell implantation into this site was tumorigenic and metastatic (37, 38).

Intravenously injecting immunodeficient mice with millions of A673 cells (so-called “experimental metastasis”) only yielded lung metastases (33, 35, 39, 40). In models of other cancer types, the efficiency of experimental metastasis could be substantially enhanced by transiently depleting natural killer (NK) cells prior to the intravenous injection of cells (41, 42). Using this approach, metastases derived from the osteosarcoma cell line 143B were detected in many organs, including the lungs, liver, kidneys, and brain (37, 41). In this study, we explored the possibility that NK depletion may enhance the efficiency of experimental metastasis in the context of extraskeletal Ewing sarcoma, and perhaps facilitate spread to organs other than the lungs, modelling the diversity of metastatic sites observed clinically. For each of these approaches, we documented tumour growth, spread and cellular composition.

Materials and Methods

Cell culture. Human A673 Ewing Sarcoma cells (provided by Dr Lucy Coupland) were authenticated by short tandem repeat (AGRF, Melbourne, Australia). They were cultured in DMEM media (Invitrogen, Waltham, MA, USA) supplemented with 10% FBS and cultured at 37°C in a humidified atmosphere of 5% CO₂. A673 cells were transfected with the pcDNA3.1(+)/Luc2=tdT plasmid (Addgene, Watertown, MA, USA) (43), a gift from Christopher Contag, to express luciferase and dTomato genes. Limiting dilution was used to isolate dTomato positive clones (44).

Animal studies. Animal experiments were conducted in accordance with Australian Code of Practice for the Care and Use of Animals for Scientific Purposes, as approved by the La Trobe Animal Ethics Committee (approval AEC 17-76). Five to six-week-old BALB/c- Foxn1nu/Arc (“nude”) mice were purchased from the Animal Resource Centre (Canning Vale, WA, Australia). Mice were housed at the La Trobe Animal Research facility in individual ventilated cages, with 12-h light/dark cycling and unrestricted access to food and water. Mice were monitored for tumour related symptoms and weighed each day. Euthanasia was performed by CO₂ asphyxiation or cervical dislocation.

Tumour implantation and imaging. Mice bearing intramuscular A673-luc tumours were generated by injecting 50,000 A673-luc cells resuspended in 20 μl of a 1:1 mixture of media and cultrex (Trevigen, Gaithersburg, MD, USA) into the left tibialis anterior muscle while under isoflurane induced anaesthesia. Experimental metastases were achieved by injecting 500,000 A673-luc cells intravenously 24 hours-post intraperitoneal injection of 50 μl of anti-asialo GM1 (Fujifilm Wako, Osaka, Japan) or saline. Mice were imaged twice weekly and tumour burden quantitated as previously described (37).

Flow cytometry. Primary intramuscular tumours and metastases large enough to be excised from healthy tissue were minced with a scalpel blade and digested in PBS containing 0.1% collagenase and 0.2% dispase II (Sigma Aldrich, St. Louis, MO, USA) at 37°C for 30 min with shaking at 800 rpm and passed through a 70 μm cell strainer. Single cells were stained as previously described (37) with these antibodies: F4/80-PE-Cy7 clone BM8 #25-4801-82 (ThermoFisher Scientific Scoresby, Scoresby, VIC, Australia), Ly-6G-APC clone 1A8 #560599 (BD Biosciences, Franklin Lakes, NJ, USA), and CD335/NKP46-BV421 clone 29A1.4 #562850 (BD Biosciences, Franklin Lakes, NJ, USA), and were analysed using FlowJo 10.7 (BD Biosciences) software.

Tissue processing and histology. Tissue was processed, stained and sectioned as previously described (37).

Statistical analysis. All statistical analyses were performed using Prism 9.0 software (GraphPad, San Diego, CA, USA).

Results

Transient depletion of natural killer cells facilitated formation of A673 Ewing sarcoma metastases. Our aim in this study was to establish and characterise models of extraskeletal Ewing sarcoma that could be used to evaluate the efficacy of novel therapies. Human A673 Ewing sarcoma cells were selected because they were derived from a muscle...
Ewing tumour (30-32). The cells were engineered to express the reporter enzyme luciferase to enable in vivo monitoring of tumour development and spread after their introduction into BALB/c nude mice.

We previously reported that transient depletion of natural killer (NK) cells by injecting mice with the anti-asialo GM1 antibody facilitates efficient formation of metastases in BALB/c nude mice after intravenous injection of osteosarcoma cells (41). We therefore explored the impact of NK depletion on metastasis after intravenously injecting luciferase-expressing A673 cells. Previous studies used two million A673 cells to achieve experimental metastases (33, 39, 40). We used fewer cells in the hope of achieving extravasation-mediated metastases rather than embolisms.

All five mice injected with half a million A673-luc cells without NK depletion remained tumour-free at the experimental endpoint, 28 days after cell injection (Figure 1A and B). Six of the 20 mice that received anti-asialo a day before injection with 500,000 cells developed metastases that were detectable in vivo within 28 days (Figure 1A and B). More sensitive ex vivo imaging revealed that an additional three NK-depleted mice harboured metastases. Metastases were detected ex vivo in multiple organs, including the lungs, liver, kidneys, brain, and heart, in addition to bones and muscles (Figure 1A, C and D).

We conclude that NK depletion boosts the efficiency of experimental metastasis for Ewing sarcoma, as it did for osteosarcoma (41), and Ewing metastases formed in multiple anatomical sites. However, using up to half a million cells only produced metastases in half of the animals, illustrating the inefficiency of this approach.

Injection of A673 cells into the tibialis anterior consistently resulted in the formation of distant metastases. A673 cells were injected intramuscularly into the gastrocnemius muscle in other studies that failed to detect extra-pulmonary metastases (34, 36), however we opted for the tibialis anterior muscle as we had previously observed that osteosarcomas created via cell inoculation into this muscle were well-tolerated and formed metastases in multiple organs (37, 38). In previous studies, authors injected millions of cells intramuscularly, which necessitated resection of the primary tumour to allow the mice to survive long enough for lung metastases to develop (34, 36). As tumour resection is invasive and not always complete, we injected ten mice with only 50,000 A673-luc cells, in the hope that a smaller primary tumour in a well-tolerated site would allow the mice to survive longer, giving more time for cells to metastasise from the primary tumour. One mouse developed a subcutaneous tumour, presumably reflecting incorrect needle placement – that mouse was excluded from the experiment. Another failed to develop a tumour by 70 days after cell injection. The remaining eight mice injected with A673-luc cells developed intramuscular tumours (Figure 2A and B). Invasion of the tumour cells into the surrounding muscle was confirmed by haematoxylin and eosin staining (Figure 2C). Mice were kept alive for a maximum of 70 days, but were euthanised if/when their primary tumour exceeded 1 cm3 or became ulcerated, or the limb bearing the tumour became paralysed. Most had to be euthanised within four weeks of cell inoculation (Figure 2D). Although bioluminescence from metastases was not evident in vivo, ex vivo analyses revealed that all mice bearing intramuscular tumours harboured metastases in their lungs, liver, heart, kidneys, brain, and one mouse also bore a metastasis in its left hamstring (Figure 2A, E and F). None of these metastases provoked symptoms requiring euthanasia within 70 days of cell inoculation. Other organs were imaged ex vivo for the presence of bioluminescent metastases, but none were detected.

Ewing sarcoma metastases had higher immune cell infiltration than primary intramuscular tumours. Having established metastatic models of extraskeletal Ewing sarcoma in the presence and absence of primary tumours, we next characterised the cellular composition of the primary tumours and metastases. This study used BALB/c nude mice, which have vastly reduced numbers of adaptive immune cells. They do, however, possess innate immune cells including macrophages (45), which are the most abundant infiltrating cell type in clinical Ewing sarcoma specimens (46, 47), and NK cells and neutrophils, which are minor constituents of patient tumours (46, 47). Most cells in the primary xenografts and metastases were A673-luc cells, with very few infiltrating immune cells (Figure 3A and B). Interestingly, natural killer cells accounted for a significantly larger proportion of cells within metastases than primary tumours (Figure 3C), which may have contributed to the inconsistent formation of metastases after intravenous injection of cells into NK-depleted animals. There were also larger proportions of neutrophils and macrophages in metastases than primary tumours, however these differences were not statistically significant (Figure 3C).

Discussion

Compared to skeletal Ewing sarcomas, which metastasise preferentially to the lung, bone and bone marrow, extraskeletal Ewing sarcomas feature more extensive metastatic tropism (12, 13). It was therefore surprising that previous reports of mouse models of this form of the disease, which typically involved introducing unlabelled A673 cells into the tail vein and/or gastrocnemius muscle, only mentioned lung metastases (33-35, 39, 48). While it is possible that those researchers may have overlooked metastases elsewhere, other studies used luciferase-expressing cells, which would have facilitated detection of
Figure 1. Intravenous administration of 500,000 A673-luc cells in BALB/c nude mice that were injected with saline or anti-asialo GM1 24 hours prior to injection of cells. (A) Compiled in vivo bioluminescence images of mice. Sites of metastases that were detected ex vivo in each mouse are indicated below the images. (B) Bioluminescence within the chest, abdomen, extremities, and head were measured over time. Individual mice with detectable signals at day 28 are specified with I.D. numbers to the right of the curves. The signal detection limit was 20,000. The mice in each group with undetectable bioluminescence at each timepoint are indicated under each graph in the region labelled “ND” (not detected). (C) Bioluminescence of resected tissue was measured after mice were euthanised. (D) Representative ex vivo images of tissue containing metastases.
Figure 2. Intramuscular injection of 50,000 A673-luc cells into the tibialis anterior muscle of BALB/c nude mice. (A) Compiled in vivo bioluminescence images of mice. Sites of metastases that were detected ex vivo in each mouse are indicated below the images. (B) Bioluminescence reflecting primary tumour growth in the legs was measured. The signal detection limit was 20,000. The mice with undetectable bioluminescence at each timepoint are indicated under each graph in the region labelled “ND” (not detected). (C) Two primary tumours were analysed by haematoxylin and eosin staining (scale bars=50 µm). (D) Survival after intramuscular injection of cells was monitored. (E) Bioluminescence of resected tissue was measured after mice were euthanised. (F) Representative ex vivo images of tissue containing metastases.
Figure 3. Immune cell profiling of A673-luc primary intramuscular tumours and metastases. Immune cell profiling was performed on (A) three primary intramuscular tumours (circles) and (B) four metastases (squares). (C) A graphical summary of the data is provided.
even small metastases. Those researchers failed to detect extrapulmonary metastases after injection of A673 cells into the gastrocnemius muscle (36) or only observed spread to the lungs and bones after intratibial inoculation (24). In contrast, we detected metastases in numerous sites following either intravenous injection of luciferase-labelled A673 cells into transiently NK-depleted animals or due to spontaneous spread from primary tumours in the \textit{tibialis anterior} muscle. The diverse metastatic pattern achieved in these models could enable evaluation of the efficacy of candidate treatments against metastases located in various organs.

The difference in metastatic tropism achieved in this study compared to previous reports could be due to differences in the cells or methods used to introduce them into the mice. The short tandem repeat genotype of our A673 cells matched published profiles (49-51) but it is possible that our cells have subtle genetic or epigenetic changes that account for their more diverse metastatic predilection.

It is also possible that the methods used in this study have contributed to the enhanced ability of A673 cells to colonise multiple organs and tissues. Temporary depletion of NK cells prior to intravenous injection of cells increased metastatic efficiency. Without this pre-treatment, none of the mice injected with 500,000 A673 cells developed metastases, yet metastases arose in various organs of many of the animals whose NK cells had been transiently depleted. In previously published experimental metastasis experiments, 2-5 million A673 cells were used, and only lung metastases were reported (33-35, 39). We hypothesise that NK cells may have a particularly pronounced impact on the spread of A673 cells to organs other than the lungs. Consistent with that notion, the only previous model that demonstrated extra-pulmonary metastasis of A673 cells employed NOD/SCID mice (24), which lack NK cells (52).

Published intramuscular models involved injecting two million A673 cells into the murine gastrocnemius muscle. We assume this large number of cells was required to achieve reproducible tumourigenicity using this method. Researchers who used this approach to investigate metastases resected primary tumours when they reached 800-1000 mm\textsuperscript{3} to extend survival until metastases formed. Lung metastases formed in most animals on which this procedure was performed within 60 days of cell implantation (34-36). In this study, almost all mice developed tumours following injection of only 50,000 cells into the \textit{tibialis anterior} muscle: 40-fold fewer cells than are evidently required to reliably form tumours upon implantation into the gastrocnemius muscle. The \textit{tibialis anterior} tumours were universally metastatic to the lung, heart, liver, kidney, and brain by the time primary tumour growth necessitated euthanasia. Although the mice had to be euthanised due to primary tumour size or symptoms before their metastases could be imaged \textit{in vivo}, the consistency of the metastatic pattern suggests this model could be used to assess the impact of candidate therapies on metastatic burden. Resection of the primary tumour would presumably enable the mice to survive long enough for the metastases to be detectable \textit{in vivo}, and ultimately to provoke symptoms. It seems that introducing A673 cells into the \textit{tibialis anterior} rather than gastrocnemius muscle boosts the efficiency of tumourigenesis and facilitates spread to a greater diversity of sites. Further research will be needed to explore whether differences between these muscles with respect to their vascularisation or other anatomical or physiological features account for the apparent difference in metastatic potential of these primary tumours, and whether this mirrors clinical observations.

Prior work demonstrated minor immune cell involvement in Ewing sarcomas, contrasting with osteosarcomas (53). Our intramuscular model recapitulates this, as scarce immune cell infiltration was identified in both primary and metastatic tumours. It was interesting that the metastases that we analysed contained a higher frequency of innate immune cells than the primary intramuscular tumours. Further work will be needed to explore whether muscles provide a less hospitable microenvironment for these innate immune cells than the metastatic sites we examined. Unfortunately, it is currently unclear whether this trend also exists in patient specimens, as very little is currently known about the cellular composition of Ewing metastases (10). However, the observation that Ewing metastases contained more PD-L1-expressing cells than primary tumours (54) suggests immune profiles of metastases and primary tumours may differ.

This study established two novel mouse models of extraskeletal Ewing sarcoma that feature diverse sites of metastatic spread, reflecting clinical patterns of metastatic tropism. An orthotopic model in which luciferase-expressing A673 Ewing sarcoma cells were introduced into the \textit{tibialis anterior} muscle of mice yielded highly efficient and reproducible primary tumours and invariant spread to the lungs, heart, liver, kidneys and brain. Macrophages, neutrophils and NK cells were rare in these primary tumours, but were more plentiful in metastases. Transient depletion of natural killer cells increased the efficiency and extent of metastatic spread of A673 cells in an experimental metastasis model. We hope that these experimental models will help researchers to gain a better understanding of this disease and to test future therapies that may improve outcomes for extraskeletal Ewing sarcoma patients.

**Conflicts of Interest**

The Authors declare no conflicts of interest in relation to this study.

**Authors’ Contributions**

MAH and CJH designed the experiments. CC and MAH conducted the experiments. MAH and CC analysed the data. MAH, CC and CJH and wrote the manuscript. CJH supervised the project and obtained funding.
Acknowledgements

The authors would like to thank Lucy Coupland for the A673 cells, the La Trobe Institute for Molecular Science BioImaging Facility for assistance with flow cytometry and microscopy, and the La Trobe Animal Research and Training Facility for assistance with animal experiments. This study was funded by grants from the Kids’ Cancer Project, Cancer Council Victoria and Tour de Cure.

References


41 Quintanilla-Martinez L, Kovar H, Staege MS, Müllertidow C and Jänicke R: Molecular dissection of the mechanism by which EWS/FLI1 expression compromises actin cytoskeletal integrity and cell adhesion in Ewing sarcoma. Mol Biol Cell 25:3<241::aid-gcc6>3.0.co;2-7


44 Patel MR, Chang YF, Chen YI, Bachmann MH, Yan X, Contag CH and Gambhir SS: Longitudinal, noninvasive imaging of T-cell effector function and proliferation in living subjects. Cancer


Received July 26, 2021
Revised August 5, 2021
Accepted August 6, 2021