Regeneration of irradiated salivary glands with stem cell marker expressing cells

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ABSTRACT

Stem cell therapy could be a potential way for reducing radiation-induced hyposalivation and improving the patient’s quality of life. However, the identification and purification of salivary gland stem cells have not been accomplished. This study aims to better characterize the stem/progenitor cell population with regenerative potential residing in the mouse salivary gland.

Mouse submandibular gland tissue, isolated cells and cultured 3 days old salispheres were tested for their expression of stem cell markers c-Kit, CD133, CD49f, and CD24 using immunohistochemistry for tissue and flow cytometry for cells. Mice were locally irradiated with a single dose of 15 Gy and transplanted with cells expressing defined markers.

Cells expressing known stem cell markers are localized in the larger ducts of the mouse salivary gland. Cells isolated from salivary gland tissue (day 0) and those from day 3 salispheres also express these markers: c-Kit (0.058% vs. 0.65%), CD133 (6% vs. 5%), CD49f (78% vs. 51%), and CD24 (60% vs. 60%, respectively). Intra-glandular transplantation of these cells into irradiated salivary glands of mice resulted in stem cell marker-specific recovery of salivary gland function.

Different stem cell-associated markers are expressed in mouse salivary gland cells, which upon transplantation are able to regenerate the irradiation-damaged salivary gland.
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1. INTRODUCTION

Every year more than 500,000 new patients are diagnosed with head and neck cancer worldwide. The treatment for these patients is usually radiotherapy either alone or in combination with surgery and chemotherapy. Radiation-induced damage to normal tissues may result in organ dysfunction, and/or cause a reduction in the patient’s post-treatment quality of life. Radiotherapy of head and neck cancer patients, which often involves co-irradiation of the salivary glands, can lead to hyposalivation. This mostly irreversible side effect can result in the development of xerostomia, a multi-faceted syndrome including symptoms, such as oral dryness and infections, dental caries, and difficulties with speech and food mastication. Even with unilateral sparing and Intensity Modulated Radiation Therapy (IMRT) approximately 40% of these patients develop hyposalivation and consequential life-long complaints. To date, no satisfactory clinical management of xerostomia exists. Transplantation of salivary gland stem cells may offer a potential treatment for radiation-induced hyposalivation. As a model, radiation-induced salivary gland damage in rodents develops in a very similar way as in patients. Salivary glands of rodents consist of several cell types, similar to humans: acinar cells which are responsible for water and protein secretion, myoepithelial cells surrounding the acini and ducts, and ductal cells which mainly modulate the composition of the saliva. The ductal system consists of intercalated, striated/granular convoluted tubules and excretory duct cells. Regeneration of the salivary gland after ductal obstruction (leading to acinar cell atrophy) has been attributed to putative stem cells residing in the ductal compartment. Complete recovery of the gland is induced within a week of ductal obstruction. Increased proliferation of these stem/progenitor cells seems to underlie the protective effect of prophylactic pilocarpine and KGF treatment on radiation-induced damage to the parotid gland. Interestingly, we recently showed that transplantation of duct derived c-Kit+ stem/progenitor cells in mice rescued salivary glands from irradiation damage. Furthermore, human salivary gland excretory ducts also contain c-Kit+ cells similar to rodent excretory ducts. Other preclinical studies, however, suggest that CD49f and CD29 might also be used as stem cells markers for the salivary gland. In other glandular tissues stem cells are identified by using the markers CD49f, CD133 and CD117 (c-Kit), and specifically CD29 and CD24 for mammary gland. Furthermore, since we have observed that also some of the cells in the c-Kit- population may have regenerative potential further characterization of the stem/progenitor pool is warranted. Therefore, the aim of this study was to better characterize stem/progenitor populations with regenerative potential residing in the...
mouse salivary gland by using c-Kit, CD133, CD49f, and CD24/CD29 as potential stem cell markers. In mice, the presence of these markers was investigated in submandibular gland and cultured salispheres. Subsequently, cells expressing these markers were isolated by fluorescence activated cell sorting and transplanted into salivary glands of irradiated recipients after which the saliva secretion was assessed as a measure of gland function.

2. MATERIALS AND METHODS

2.1. Animals

8–12 week old female C57BL/6 mice were purchased from Harlan (The Netherlands). The mice were maintained under conventional conditions and fed ad libitum with food pellets (RMH-B, Hope Farms B.V., Woerden, The Netherlands) and water. All experiments were approved by the Ethical Committee on animal testing of the University of Groningen.

2.2. Immunohistochemical analysis of salivary gland

Mice were desanguinized under isoflurane anesthesia and the submandibular glands were carefully dissected. In order to perform immunohistochemical staining extirpated mouse submandibular glands were incubated for 30 h at room temperature in 4% buffered formaldehyde. Following dehydration, the tissue was embedded in paraffin and sliced into 5 µm sections. The sections were dewaxed and labeled for the following markers: c-Kit (1:75) (R&D Systems, Minneapolis, MN; MAB1356), CD24 (1:100) (Santa Cruz Biotechnology, Santa Cruz, CA; SC-7034), CD133 (1:50) (Abcam, Cambridge, MA; ab19898), CD49f (1:50) (Santa Cruz Biotechnology, Santa Cruz, CA; SC-6596). Visualization for bright field microscopy was accomplished by adding specific secondary biotin carrying antibodies (Dako, Carpinteria, CA), an avidin–biotin-horse radish peroxidase complex (ELITE ABC Kit, Vector Laboratories, Burlingame, CA) and the diaminobenzidine (DAB) chromogen. Nuclear counterstaining was performed with hematoxylin. Control sections without primary antibodies did not show positive immunostaining.

2.3. Isolation of salivary gland stem cells

Following submandibular gland dissection, salivary gland cells were isolated and cultured as published previously.16, 15, 23 Cell suspensions were prepared by first mechanically disrupting the gland, followed by enzymatic digestion with Collagenase type II and Hyaluronidase enzymes and CaCl₂. After filtering, the cell suspension was plated in non-coated 12 wells plates at 400,000
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Per gland 2–4.6 × 10⁶ cells could be isolated. The culture medium consisted of DMEM/F12 (Gibco, Carlsbad, CA), penicillin, streptomycin, glutamax, EGF (20 ng/mL), FGF-2 (20 ng/mL), N2 (1/100), insulin (10 lg/mL), and dexamethasone (1 mM). Fresh medium was added every 3 days. All growth factors were purchased from Sigma–Aldrich (St. Louis, MO), except for N2 (Gibco, Carlsbad, CA).

2.4. Flow cytometric analysis

Cultured cells growing in spheres were dissociated using 0.05% trypsin–EDTA (Gibco, Invitrogen). Pacific Blue™ anti-mouse CD117 (c-Kit) (Biolegend 105808, San Diego, CA), PE anti-human/mouse CD49f (Biolegend 313613, San Diego, CA), PE anti-mouse Prominin 1 (CD133) (eBioscience 12-1331-82, San Diego, CA), FITC anti-mouse CD24 (BD Biosciences 101820) and FITC anti-rat CD29 (BD Biosciences BD555005, Pharmingen) antibody incubations were performed at 4°C for 20 min, followed by a wash step in PBS/0.2% bovine serum albumin (BSA). Finally, Propidium Iodide (PI, 1 µg/mL) was added to the cells before analysis using a FACS LSR-II Flow Cytometer (BD). At least 50,000 events for each measurement were recorded. Data were analyzed by FlowJo software (Tree Star, Ashland, OR). Gates for viable c-Kit⁺, CD24⁺, CD29⁺, CD133⁺, and CD49f⁺ were set by using isotype controls for Pacific Blue, PE and FITC. Due to a difference in the isotype controls for isolated and cultured c-Kit⁺ cells the gates were different (see Supplementary Figure. S1).

2.5. Irradiation and saliva collection from mouse salivary glands

Salivary glands were locally irradiated with a single dose of 15Gy (Precision X-ray Inc. – X-rad 320, 200kV, 20mA, 1.843 Gy/min). This dose is known to induce hyposalivation without compromising the general health of the animals. At 120 days post-irradiation saliva flow rate was determined. Animals were placed in a restraining device after pilocarpine injection (2.5 mg/ kg, s.c.). Saliva was collected for 15 min, and the quantity was determined gravimetrically, assuming a density of 1g/ml for saliva. Percentage flow rate of saliva of an animal is calculated by denoting the pre-irradiation saliva as 100%. The principle behind this functional assay is that in vivo regeneration is the most rigorous test for stem cell function.

2.6. Intra-glandular injection of cultured cells

Day 3 cultured spheres were collected and dissociated by 0.05% trypsin–EDTA for trans-
plation studies. Cell sorting from dissociated spheres for c-Kit+, c-Kit−, CD133+ and CD49f+, and CD24+ /CD29+ cells was performed using MoFlo flow cytometer (Dako, Carpinteria, CA). After sorting the cells were suspended in an equal volumes of alpha-MEM (Gibco, Invitrogen, Carlsbad, CA) containing 2% of fetal calf serum (Gibco, Invitrogen, Carlsbad, CA) and Indian Ink (1:200 dilution) solution to visualize the injected fluid. Thirty days post-irradiation, under general anesthesia using a 28G needle and a microliter Syringe (Hamilton, Reno, NV), both submandibular glands of irradiated mice were injected with 5 µL of cell suspension with 5000 CD133+ or 150 c-Kit+ and 67096 CD49f+ or 5000 CD24+/CD29+ cells.

3. RESULTS

3.1. Expression of stem cell markers in murine submandibular gland – in tissue and in culture

To investigate whether mouse submandibular glands express stem cell markers, we performed immune-histochemical staining on mouse submandibular gland tissue for known stem cell markers c-Kit, CD133, CD24, and CD49f (Fig.1). Positive staining for c-Kit, CD133, CD24, CD29 (not shown), and CD49f was observed solely in cells within the excretory duct of the submandibular gland. This indicates that, as expected, the major ducts of the mouse submandibular gland contain putative stem/progenitor cells expressing multiple stem cell markers.

Recently, we showed that salispheres cultured from dispersed mouse submandibular gland express the stem cell marker c-Kit and are able to differentiate and self-renew in vitro. Therefore, we quantified the number of cells.
Regeneration of irradiated salivary glands with stem cell marker expressing cells expressing other stem cell markers.

To investigate the presence and potential enrichment of these markers in our salispheresculture, we fluorescently labeled cells from freshly dissociated mouse submandibular gland tissue (Fig. 2) and from 3 days old salispheres (Fig. 3).

**Figure 2:** Stem cell associated marker expression was observed immediately after isolating murine salivary gland cells. Flow cytometric analysis of single cells obtained from submandibular glands revealed the presence of c-Kit ((A) CD117), CD49f ((B) Integrin alpha-6), CD133 ((C) Prominin 1) and CD24 (D) expressing cells. Positive populations are gated according to isotype controls. The numbers in the gates represent percentage of viable cells positive for certain stem cell-marker.

**Figure 3:** Stem cell associated cell surface marker expression was observed in 3-day cultured salispheres. Flow cytometric analysis of single cells obtained from salispheres revealed the presence of c-Kit ((A) CD117), CD49f ((B) Integrin alpha-6), CD133 ((C) Prominin 1) and CD24 (D) expressing cells. Positive populations are gated according to isotype controls. The numbers in the gates represent percentage of viable cells positive for certain stem cell-associated marker.
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Analysis of flow cytometry data shows that from freshly isolated cells from mouse submandibular gland, approximately 6% express CD133, 78% CD49f, 60% CD24, and only 0.058% c-Kit. Interestingly, in 3-day salisphere cultures we observed that the expression levels of CD133 (5.0 ± 3.8%), CD49f (51 ± 12%) and CD24 (60 ± 13%) remained relatively stable but c-Kit expression increased more than 10-fold to 0.65 ± 0.93% (all n 3). Interestingly, no cells were found to express both CD133 and c-Kit (Supplementary Figure.S1). These data indicate that culturing salivary gland cells as salispheres enriches the cultures for c-Kit positive cells.

3.2. Regenerative potential of stem cell markers expressing mouse submandibular gland cells

To investigate the regenerative potential of cells expressing these stem cell markers, we transplanted selected cells from day 3 salispheres into irradiated submandibular glands of mice, measured their saliva production and compared the results with irradiated, non-transplanted control animals (Fig.4). The number of cells transplanted was dependent on the number that could be isolated from one donor gland, varies in a range of 4–5 million on day 0. One hundred and twenty days post-irradiation a significant increase in saliva production was observed in mice transplanted with as few as 300 c-Kit+ cells and in mice transplanted with 10,000 CD133+ cells. We also observed an increase in the saliva production of mice transplanted with 134,000 CD49f+ cells, and 10,000 CD24+/CD29+ cell populations. c-Kit data are partially taken from Lombaert et al.16.

Figure.4: Functional recovery of irradiated salivary glands following transplantation with marker-expressing cells is dependent on cell phenotype. Percentage of control (non-irradiated) flow rate of saliva at 120 days post-irradiation, from 10 irradiated non-transplanted mice (IR) and from 12 mice transplanted with 300 c-Kit+, six mice with 10,000 CD133+, four mice with 134,000 CD49f+, and four mice with 10,000 CD24+/CD29+ cell populations. c-Kit data are partially taken from Lombaert et al.16.
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Regeneration obtained with c-Kit^+ and CD133^+ cells.

One hundred and twenty days post-irradiation a significant increase in saliva production was observed in mice transplanted with as few as 300 c-Kit^+ cells and in mice transplanted with 10,000 CD133^+ cells. We also observed an increase in the saliva production of mice transplanted with 134,000 CD49f^+ cells, and 10,000 CD24^+/CD29^+ cells but less potently than the regeneration obtained with c-Kit^+ and CD133^+ cells. These results suggest that mouse submandibular cells expressing multiple stem cell markers are capable of regenerating the submandibular gland after local transplantation in the irradiated gland.

4. DISCUSSION

Salivary glands of head and neck cancer patients undergoing radiotherapy might be damaged as a side effect of irradiation, resulting in impairment of saliva production. To these patients stem cell therapy is an attractive option for restoring the irradiation-damaged salivary gland. The aim of the present study is to further characterize putative stem/progenitor cells with regenerative potential present in the salivary gland, using a mouse model.

From previous studies^{16} we know that there might be a population of stem/progenitor cells, negative for c-Kit, but which can contribute to gland restoration. Interestingly, we found expression of multiple stem cell markers in mouse salivary gland, such as CD24, CD49f, and CD133. These immuno-histochemical findings reveal that cells expressing these stem cell markers are located in the ducts of the salivary gland, where it has been suggested that tissue stem cells reside^{16}.

Interestingly, we observed a variable intensity of immunohistochemical staining which indicates that some cells express these markers to a greater extent than others. This high expression might reflect their stem cell potential, and is supported by the fact that cells with greatest expression of stem cell markers are the most potent stem cell population in mammary gland^{22}.

By flow cytometry, we found that mouse submandibular cells on day 0 express high levels of CD24 and CD49f, but low levels of CD133 and c-Kit. The c-Kit marker and to a lesser extent CD133 are enriched during culture under high growth factor conditions, which may indicate positive selection for cells with stem cell characteristics.

Day 3 salspheres express high levels of CD49f, which were shown in another study to be co-expressed with Thy-1 in stem/progenitor cells of salivary glands of mouse^{24}, rat^{18}, and human^{19}. CD49f was also expressed in stem cells of other glands like mouse prostate gland^{20}.
CD24 expressed in day 3 spheres could also be a potential stem cell marker in salivary gland, as it is reported that CD24 contributes to stem cell activity, when co-expressed with CD29 in mammary gland\textsuperscript{22}. However, the high frequency of CD24\textsuperscript{+} cells in salispheres makes it unlikely that CD24 can be used as a single stem cell marker, but CD24 may be more usefully employed in combination with other markers. We found that CD24\textsuperscript{+}/CD29\textsuperscript{+} cells represent a subpopulation of cells, which contributed to regeneration in some mice transplanted with this population. Other combinations of marker expression with CD24 may also be worthwhile testing, in terms of defining the optimal cell phenotype for stem or progenitor cells in the mouse salivary gland. Our \textit{in vivo} transplantation results indicate that c-Kit\textsuperscript{+} cells show more stem cell like characteristics than CD133\textsuperscript{+}, CD49f\textsuperscript{+}, and CD24\textsuperscript{+}, as they were able to rescue salivary gland dysfunction with as few as 300 cells. Our previous studies using serial transplantations with c-Kit\textsuperscript{+} cells definitively established it as stem cell marker in the salivary gland, making further studies with combinations of other markers with c-Kit a high priority. Moreover, c-Kit cells were shown to be able to rescue the irradiated salivary gland in a serial transplantation experiment\textsuperscript{16}, indicating self-renewal ability, an essential characteristic of stem cells. This potential still has to be determined for the other stem cell marker expressing cells.

The aim of our studies on salivary gland stem cells is to rescue irradiation damaged salivary gland in head and neck cancer patients. Therefore, it would be very desirable to be able to obtain maximum regeneration with the most efficient combination of stem and progenitor cells, especially when a low amount of donor tissue is available. In this respect, it is interesting to mention that we could not find c-Kit/CD133 double positive cells in the mouse salivary gland culture system, indicating that salispheres may contain different subpopulations. Therefore, it might be a better option to combine c-Kit\textsuperscript{+} cells with CD133\textsuperscript{+} (or CD49f\textsuperscript{+}) progenitor like cells, facilitating early and prolonged restoration of irradiation damaged salivary gland.

In conclusion, this study showed that different stem cell markers are expressed in mouse salivary gland. Combinations of these putative stem cell populations from mouse salivary gland may provide the best regeneration of the irradiation damaged salivary gland, since transplantation of a mixture of progenitor and stem cells may be clinically the most promising treatment.

\section*{5. ACKNOWLEDGEMENTS}
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6. SUPPLEMENTARY INFORMATION

**Figure S1:** FACS plots of isotype controls and c-Kit/CD133. Isotype controls for c-Kit staining. (A) Immediately following isolation, (B) 3 days after isolation, and (C) for both c-Kit and CD133, 3 days after isolation. Flow cytometry for c-Kit and CD133 showed no co-expression of these markers (D).

7. REFERENCES


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