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Immunohistochemical examination of immune cells in adipose tissue of rainbow trout (*Oncorhynchus mykiss*) following intraperitoneal vaccination

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ABSTRACT

Mammalian perivisceral adipose has been shown to play an important role in the regulation of the peritoneal immune responses. Recently it has been demonstrated that peritoneal antigens are collected by leukocytes within the visceral adipose mass, and a broad range of immunomodulatory genes are differentially expressed in adipose tissue after intraperitoneal vaccination in rainbow trout. To assess the immune cell component in adipose, immunohistochemical analysis was used to examine B-cell, T-cell and antigen presenting cell (APC) numbers and distribution in rainbow trout adipose tissue 24 and 72 h post vaccination in comparison to control fish. The results of this study support previous work on mammals with omental milky spots in naïve fish found to contain APCs and T-cells which then increased in size, number and complexity following vaccination. It suggests that following peritoneal stimulation the visceral adipose mass in fish likely plays an important role in vaccine antigen uptake and presentation by APCs, as well as subsequent T-cell activation and differentiation.

1. Introduction

Oil-adjuvanted vaccines used in aquaculture are injected directly into the peritoneal cavity, which in mammals and fish contains a wide range of immune cells [1–4]. While the resident cell population can vary between teleost species [5,6], the composition in rainbow trout (*Oncorhynchus mykiss*) is dominated by myeloid cells and lymphocytes [7–9]. The injection of vaccines (or other inflammatory agents) into the peritoneal cavity of fish generates a rapid change in composition as well as an increase in the number of cells present [8–14], although foreign-body inflammatory reactions can be maintained in the cavity for several months post-vaccination in salmonids [14–22].

Mammalian perivisceral adipose (also referred to as the omentum) has been shown to influence and be influenced by adjacent and embedded lymphocytes, and plays an important role in the regulation of peritoneal immune responses [23]. The visceral adipose mass is also capable of capturing bacteria and other antigenic particulates from the peritoneal cavity [23–25], and promoting immunity against them [23]. Immune cells and numerous pro-inflammatory, anti-inflammatory and immune-modulating proteins and peptides (including cytokines) have been identified in mammalian adipocytes [23,26,27]. Omental milky spots (MS) contain antigen presenting cells (APCs), T- and B-cells and are thought to play a key role in the transitioning of leukocytes from blood through the omentum to the peritoneal cavity and back [28].

Pignatelli et al. [29] demonstrated that peritoneal antigens are collected by leukocytes in rainbow trout visceral adipose. These leukocytes transcribe marker genes for different leukocyte subpopulations, and are likely responsible for the secretion of a range of immune cytokines [29]. The establishment of a mature adipocyte phenotype has been shown to be associated with high activity of immune genes in Atlantic salmon (*Salmo salar*) [30], and teleost adipocytes have been shown to constitutively express pro-inflammatory cytokines and genes relating to the interferon response [29,30]. Alongside evidence demonstrating that rainbow trout visceral adipose is capable of responding to viruses [29], bacteria, and pro-inflammatory cytokines [31], it can be concluded that teleost adipose is an immunologically active tissue. Furthermore, the work of Veenstra et al. [32] established that a broad range of immunomodulatory genes are differentially

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expressed in adipose tissue after intraperitoneal (ip) injection of oil-adjuvanted bacterial vaccines and revealed a relationship between adipose tissue immune function and the development of vaccine-induced adhesions.

Since it has been suggested that cellular mechanisms occurring immediately post-vaccination within adipose tissue may contribute to the development of adhesions and potentially be involved in the adaptive immune response [32], in the present study we assessed immune cell distribution in rainbow trout visceral adipose tissue following injection of an oil-adjuvanted vaccine into the peritoneal cavity, using immunohistochemistry. The results of this work showed that MS in naïve fish contain APCs and T-cells and that following an ip administration of oil-adjuvanted vaccines MS increase in number, size and complexity and are associated with vaccine remnants. Overall the results of this work suggest that the visceral adipose mass in fish likely plays an important role in the uptake and presentation of vaccine antigens and subsequent T-cell activation and differentiation following peritoneal stimulation.

2. Methodology

A total of 12 juvenile rainbow trout weighing approximately 60 g (College Mill Trout Farm, Perthshire, U.K.) were maintained in 400 L tanks at the University of Aberdeen aquarium facility supplied with recirculating freshwater at 14 °C. Fish were fed *ad libitum* daily with commercial pellets (EWOS) and were acclimated for at least two weeks prior to vaccination. All trials were carried out in compliance with the Animals (Scientific Procedures) Act 1986 by a UK Home Office license holder and approved by the ethics committee at the University of Aberdeen. Fish were anaesthetised by immersion with 2-phenoxyethanol (Fluka) and each fish given an intraperitoneal (ip) injection with either 0.1 mL of phosphate buffered saline (PBS) or a water-in-oil adjuvanted vaccine posterior to the pelvic girdle. The aqueous phase of the vaccine was a formalin-killed whole-cell *A. salmonicida* bacterin (pre-inactivation titre of 1.55×10^9 cfu/mL) suspended in BHI Media and provided by Elanco Animal Health Ltd. (Victoria, P.E., Canada) while the oil phase was comprised of Montanide™ ISA 761 VG (Seppic, France). The water-in-oil emulsions was prepared at a 70:30 oil:water ratio 48 h prior to vaccination using a high shear mixer (IKA Ultra Turrax Tube Drive) and was tested for stability prior to use.

Visceral adipose located around the internal organs was harvested from freshly killed trout (n = 3 per treatment group per time point) at 24 and 72 h post injection (hpi). These timings were chosen based on the previous study of Veenstra et al. [32]; where the transcript response of immune genes was studied in adipose tissue at 3, 14 and 28 days post-vaccination. In that study gene modulation was already maximal at day 3 in the majority of cases, and so here that timing was included together with an earlier time point to assess whether changes were occurring before this. The tissue was stored in Bouin's Solution (Sigma) for 18 h, washed 3x in PBS, then left in PBS for 3–5 h. Samples were then stored in 70% ethanol (Sigma) before being embedded in paraffin and sectioned at 5 um onto silane-coated glass slides (Microscopy and Histology Core Facility, University of Aberdeen). Immunohistochemistry for each antibody (Table 1) was performed using reagents from the REAL Dako Envision detection kit (Dako UK Ltd) using a Dako autostainer (Dako) as described previously [34] at the Department of Pathology, NHS Grampian Biorepository (Aberdeen, UK). The antibodies used included a B (IgM) and T (CD3) cell marker, and two markers of antigen presenting cells (APCs), MHC-II and CLEC4T1. In the case of the APC markers CLEC4T1 is related to DC-SIGN (see discussion). Primary antibody dilutions used for immunohistochemistry are described in Table 1. The sections were evaluated by light microscopy using a Zeiss Axioscop 40 (Microscopy and Histology Core Facility, University of Aberdeen).

3. Results

The number of CLEC4T1, MHC-II, CD3 and IgM positive cells was found to vary between treatment groups and time points. These results indicate that changes in expression and distribution of APCs, T- and B-cells occur in rainbow trout adipose tissue following vaccination.

CLEC4T1 staining was observed in areas analogous to the centre of clostridial MS located on the periphery of the omentum tissue and in cells encircling apoptotic adipocytes-crown like structures (CLS) in the naïve fish (Fig. 1A and C). At 24 and 72 hpi, large quantities of CLEC4T1 positive cells were observed infiltrating the adipose tissue, primarily associated with areas of vaccine-induced cellular damage (Fig. 1B) as well as strongly presenting within newly developed clostridial MS within the adipose tissue (Fig. 1D).

MHC-II positivity in naïve fish was observed in macrophage-like cells located within adipocyte junctions and in some cell clusters (Fig. 2A and C), but was not associated with CLS (Fig. 2C). The largest amount of anti-MHC-II staining was observed at 24 hpi in the vaccinated group and was associated with granulomatous cell clusters and areas of vaccine-infiltration (Fig. 2B). By 72 hpi the quantity of MHC-II positive cells decreased in the vaccinated group, but staining of small clusters of mononuclear cells within the adipose tissue and associated with MS was still apparent (Fig. 2D).

CD3 was detectable in the adipose tissue of naïve fish, in the cytoplasm of single mononuclear cells found in cell clusters within adipose (Fig. 3A), and in some structures analogous to clostridial MS found on the periphery of adipose tissue (Fig. 3C). In vaccinated fish at 24 hpi the staining appeared much stronger, and was present in an increased number of peripheral MS, as well as newly developed clostridial MS structures throughout the tissue (Fig. 3B). By 72 hpi staining was still clearly present within MS of vaccinated fish, although weaker than seen in the 24 hpi fish. In vaccinated fish, CD3 positive MS were associated with CLS (Fig. 3D). The increase in CD3 positive stained structures in cells located within milky spots can be observed in greater detail in Fig. 4.

IgM positive cells were not found in the control fish (Fig. 5A and C). However, following vaccination cells staining positive for IgM could be observed within adipocyte junctions at 24 hpi (Fig. 5B). Staining was still present but weaker at 72 hpi in individual cells, occasionally associated with MS (Fig. 5D). Staining was also present within blood vessels in the vaccinated groups, presumed to be soluble IgM in the blood (Fig. 5D).

Table 1
Antibodies used for immunohistochemical analysis.

Antibody	Type	Dilution	Dilutant	Reference/Source
IgM (4C10)	Monoclonal	1:5	Dako antibody dilutant	[33]
CD3-γδ	Monoclonal	1:15	Dako antibody dilutant	Vertebrate Antibodies Ltd
MHC-IIβ	Rabbit polyclonal	1:200	PBST[a]	Vertebrate Antibodies Ltd
CLEC4-T1	Rabbit polyclonal	1:500	Dako antibody dilutant	[45]

[a] PBST = Phosphate Buffered Saline with Tween 20 (Sigma).

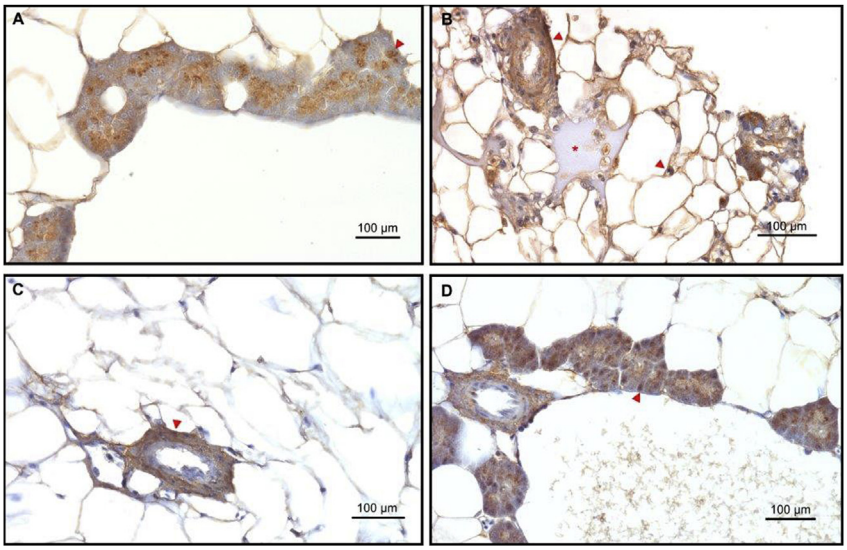

Fig. 1. Arrow heads (red) point to representative positive staining of CLEC4T1 in rainbow trout adipose tissue. A: 24 hpi unvaccinated; B: 24 hpi vaccinated; C: 72 hpi unvaccinated; D: 72 hpi vaccinated (star = vaccine remnant). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

As teleost adipose has been found capable of sequestering antigens from the peritoneal cavity [29], and immune-related genes were transcriptionally upregulated as early as 72 h after ip vaccination [32], in this study we aimed to further characterize the relationship between vaccine-induced stimulation of the peritoneal cavity and adipose immune cell response up to 72 h post injection via immunohistochemical analysis. The results of this study were found to be broadly similar to what has been described previously in regards to mammalian adipose clostridial milky spots (MS). MS associated with peritoneal adipose tissue (omentum) have been described in a number of species [35] including fish [29]. They have been shown to contain macrophages, APCs, T- and B-cells [28] and to have important biological functions within the peritoneal cavity [3,36–39] and omentum [23,28], acting as a gateway through which circulating cells, antigens, particulates and pathogens are collected from the peritoneal cavity to promote a variety of immune responses [40–42]. Following stimulation in mammals, the increases in the number and size of MS occur alongside an influx of leukocytes within MS [3], as appeared to be happening in the current study. It is worth noting that viral stimulation did not alter the size or number of MS in rainbow trout adipose [29].

Dendritic cells (DCs) and macrophages are regarded as the key APCs of the immune system and play an important role in the transition of innate immunity to adaptive immunity. In mammals MS are considered to be the site of origin of peritoneal macrophage precursors [43]. An influx of macrophages into the peritoneal cavity has been described in salmonids following stimulation [8,44]. *C*-type lectin (CLEC) domain family 4-T1 is a rainbow trout transmembrane protein thought to be closely related to the well-characterised CLEC4 family protein CD209/DC-SIGN [45]. It, along with MHC class-II proteins are found on DCs/macrophages and help present extracellular antigens to CD4 positive cells and to promote the rapid activation of T- and B-cells [28]. The lack of MHC-II positive staining cells within MS supports previous observations in trout [29], however the presence of CLEC4T1 positive cells within these structures demonstrates that APCs (potentially DC or macrophage precursors) are present within MS in naïve fish, in accordance with previous work on mice [46]. Additionally, crown-like structures (CLS), described as clusters of macrophages surrounding dead adipocytes in obese mammalian adipose [14,47], were observed to be strongly CLEC4T1 positive in naïve and vaccinated rainbow trout. As the results in the present study showed that there was little to no overlap in staining patterns of CLEC4T1 and MHC-II, it indicates that within trout adipose tissue these markers are expressed on distinct cell populations at these time points. The key function of immature DCs is capturing and processing antigens which trigger full maturation, and in

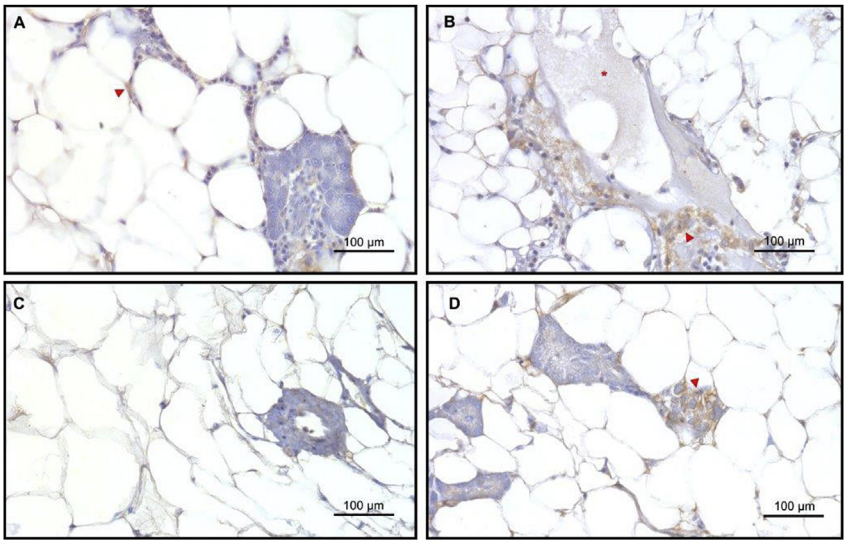

Fig. 2. Arrow heads (red) point to representative positive staining of MHC-II in rainbow trout adipose tissue. A: 24 hpi unvaccinated; B: 24 hpi vaccinated; C: 72 hpi unvaccinated; D: 72 hpi vaccinated (star = vaccine remnant). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

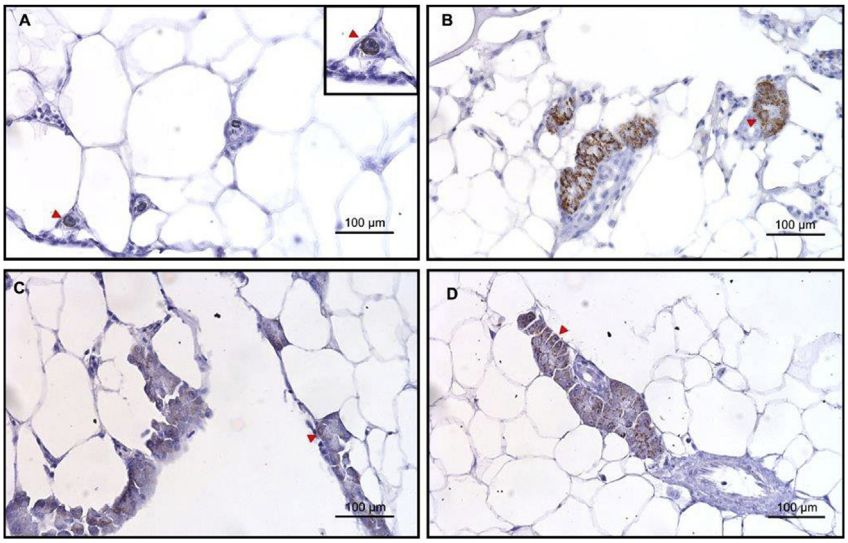

Fig. 3. Arrow heads (red) point to representative positive staining of CD3-γδ in rainbow trout adipose tissue. A: 24 hpi unvaccinated; B: 24 hpi vaccinated; C: 72 hpi unvaccinated; D: 72 hpi vaccinated. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

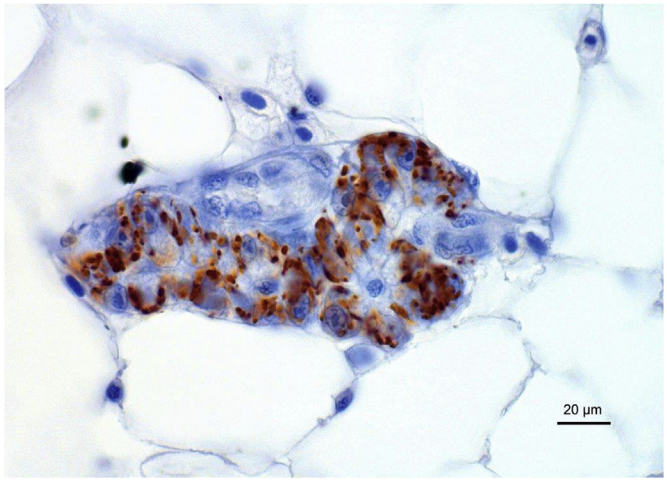

Fig. 4. CD3-γδ positive stained cells in a rainbow trout adipose tissue milky spot at 24 h post-vaccination.

time leads to the assembly of antigen-MHC-II complexes which are capable of stimulating T-cells [48–50]. As it has been demonstrated that bacteria can stimulate DC maturation [51,52], it is likely that in teleosts APCs preferentially begin production/maturation of CLEC4T1 to facilitate ingestion and presentation of foreign substances with MHC-II complexes playing a larger role at a later time point than studied here.

Lymphocytes are the second major cellular component of normal mammalian MS [38,53,54]. More recent studies [23,28] show that the omentum can support the activation of CD4 and CD8 positive lymphocytes and mount T cell-dependent B-cell responses to peritoneal antigens. CD3 is part of the T-cell receptor complex on the cell surface which aids activation of naïve T cells [55] and is in rainbow trout considered a good pan-T-cell marker [56]. The present study reveals the presence of CD3 positive cells in clostridial MS on the periphery of adipose tissue in naïve fish, in distinct areas separate to CLEC4T1 positive cells within MS. An increase in staining intensity was observed at 24 hpi (which reduced by 72 hpi) in MS, which supports work in mammals showing that the omentum effectively operates as a site for early antigen presentation, with a rapid turnover of lymphocytes [28]. As CD3 positive MS were also found to be associated with CLEC4T1 positive CLS, it strongly advocates that following vaccination APCs play

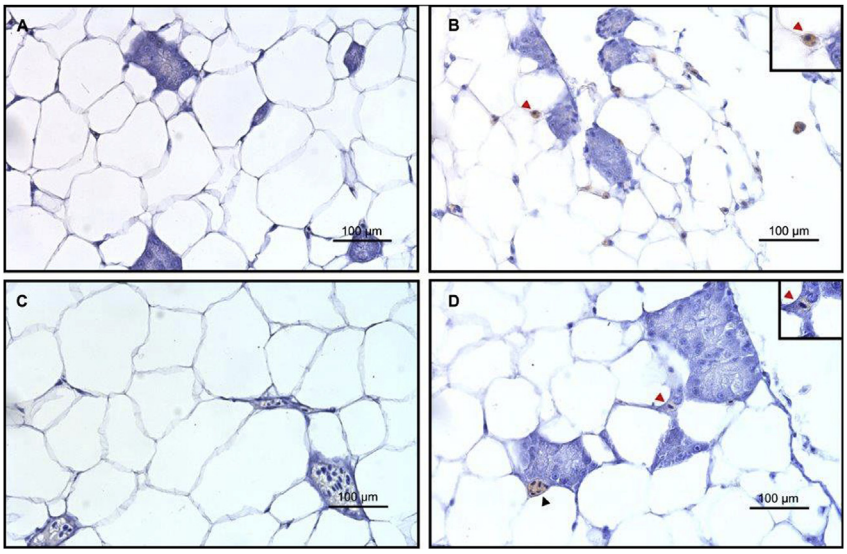

Fig. 5. Arrow heads (red) point to representative positive staining of IgM in rainbow trout adipose tissue. Arrow head (black) shows staining in blood vessels. A: 24 hpi unvaccinated; B: 24 hpi vaccinated; C: 72 hpi unvaccinated; D: 72 hpi vaccinated. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a large role in antigen uptake, presentation and subsequent T-cell activation in trout adipose tissue MS.

Immunoglobulin (Ig) M is the most ancient and prevalent Ig in fish. It can be expressed on the surface of B-cells or secreted as an antibody. In this study no evidence of IgM positive staining in milky spots was observed, in agreement with work on rainbow trout by Pignatelli et al. [29] but in contrast to mammalian studies [23]. Pignatelli et al. [29] identified IgM positive cells in the interstitial space between adipocytes within visceral adipose and Ballesteros et al. [57] found that IgM transcript level could be increased in adipose in response to oral vaccination. The present study found evidence of IgM positive cells in interstitial spaces in naïve fish which increased in number following vaccination.

In conclusion, the immunohistochemical results of this paper show that naïve teleost MS contain APCs (CLEC4T1 positive cells) and T-cells (CD3 positive cells). Following the administration of an ip oil-adjuvanted vaccine, MS in rainbow trout adipose increased in number, size and complexity and may play a significant role in T-cell activation and differentiation via APCs.

Declarations of interest

None.

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