Isolation and Functional Characterisation of a \textit{fads2} in Rainbow Trout (\textit{Oncorhynchus mykiss}) with Δ5 Desaturase Activity

Noor Khalidah Abdul Hamid\textsuperscript{1,3,*}, Greta Carmona-Antoñanzas\textsuperscript{2}, Óscar Monroig\textsuperscript{2}, Douglas R. Tocher\textsuperscript{2}, Giovanni M. Turchini\textsuperscript{1}, John A. Donald\textsuperscript{1}

\textsuperscript{1} Deakin University, School of Life and Environmental Sciences, Waurn Ponds, Geelong, Victoria, Australia, \textsuperscript{2} University of Stirling, Institute of Aquaculture, School of Natural Sciences, Stirling, Scotland, United Kingdom, \textsuperscript{3} Universiti Sains Malaysia, School of Biological Sciences, Penang, Malaysia

\* nkabdulh@deakin.edu.au

Abstract

Rainbow trout, \textit{Oncorhynchus mykiss}, are intensively cultured globally. Understanding their requirement for long-chain polyunsaturated fatty acids (LC-PUFA) and the biochemistry of the enzymes and biosynthetic pathways required for fatty acid synthesis is important and highly relevant in current aquaculture. Most gnathostome vertebrates have two fatty acid desaturase (\textit{fads}) genes with known functions in LC-PUFA biosynthesis and termed \textit{fads1} and \textit{fads2}. However, teleost fish have exclusively \textit{fads2} genes. In rainbow trout, a \textit{fads2} cDNA had been previously cloned and found to encode an enzyme with Δ6 desaturase activity. In the present study, a second \textit{fads2} cDNA was cloned from the liver of rainbow trout and termed \textit{fads2b}. The full-length mRNA contained 1578 nucleotides with an open reading frame of 1365 nucleotides that encoded a 454 amino acid protein with a predicted molecular weight of 52.48 kDa. The predicted Fads2b protein had the characteristic traits of the microsomal Fads family, including an N-terminal cytochrome b5 domain containing the heme-binding motif (HPPG), histidine boxes (HDGH, HFQHH and QIEHH) and three transmembrane regions. The \textit{fads2b} was expressed predominantly in the brain, liver, intestine and pyloric caeca. Expression of the \textit{fasd2b} in yeast generated a protein that was found to specifically convert eicosatetraenoic acid (20:4n-3) to eicosapentaenoic acid (20:5n-3), and therefore functioned as a Δ5 desaturase. Therefore, rainbow trout have two \textit{fads2} genes that encode proteins with Δ5 and Δ6 desaturase activities, respectively, which enable this species to perform all the desaturation steps required for the biosynthesis of LC-PUFA from C\textsubscript{18} precursors.

Introduction

Long-chain (C ≥ 20) polyunsaturated fatty acids (LC-PUFA) play a variety of fundamental physiological roles in vertebrates. In fish they also have an important economic aspect, as fish are the primary source of n-3 LC-PUFA in the human diet [1]. Fish, like all vertebrates, are...
Competing Interests: The authors have declared that no competing interests exist.

In general, and likely resulting from adaptation and evolution, fish can be classified into two different generic groups according to their respective fatty acid metabolism: those able to bioconvert dietary C_{18} PUFA (essential fatty acids) such as linoleic acid (LA; 18:2n-6) and ω-3-linolenic acid (ALA; 18:3n-3) into LC-PUFA; and those unable to bioconvert C_{18} PUFA into LC-PUFA, and thus requiring dietary LC-PUFA to satisfy their essential fatty acid requirements [6]. The former group is typically represented by freshwater species, low trophic level species, and the diadromous salmonids [7–12]. When the C_{18} PUFA (namely LA and ALA) are present in the diet, conversion to LC-PUFA can occur by a sequence involving alternate desaturation and elongation steps. During biosynthesis of arachidonic acid (ARA; 20:4n-6) and eicosapentaenoic acid (EPA; 20:5n-3), the pathway primarily proceeds through an initial desaturation step involving a Δ6 desaturase (for the conversion of LA and ALA to 18:3n-6 and 18:4n-3, respectively), followed by subsequent chain elongation (obtaining 20:3n-6 and 20:4n-3, respectively), and then a Δ5 desaturation (for the final biosynthesis of ARA and EPA, respectively) [13].

In mammals, the fads1 gene encodes the Fads1 protein that has Δ5 desaturase activity, and the fads2 gene encodes the Fads2 protein that has Δ6 desaturase activity [14], and both fads genes are present in amphibians, reptiles, and birds [15]. In fishes, fads1 and fads2 genes that encode proteins with Δ5 and Δ6 desaturase activity, respectively, are present in the chondrichthyan fish, catshark, Scyliorhinus canicula [15], and the predicted Fads1 and Fads2 proteins are found in the genome of the holoccephalan elephant fish, Callorhinchus milii. However, the fads1 gene has been lost in the teleost fishes, and only fads2 genes have been cloned or identified in sequenced genomes [15]. In most teleost species, fads2 encodes a protein that is a functional Δ6 desaturase [5, 12, 16–19], but there is functional plasticity in the desaturase activity in some species [15]. In zebrafish, Danio rerio and tilapia, Oreochromis niloticus, the fads2 gene encodes a bifunctional protein that has both Δ5 and Δ6 desaturation activities [20, 21]. The Atlantic salmon, Salmo salar, has four fads2 genes that encode proteins with Δ5 (one protein) and Δ6 (three proteins) desaturase activities [22, 23], respectively. Two fads genes are also present in rabbitfish, Siganus canaliculatus, which encode a bifunctional Δ5/Δ6 desaturase and a discrete Δ4 desaturase, respectively, the latter being the first report of a vertebrate Δ4 desaturase [24]. Subsequently, a further fads2 mRNA encoding a protein with Δ4 desaturase activity was isolated and characterised in Senegalese sole, Solea senegalensis [25]. Recently, two fads2 genes were cloned from pike silverside, Chirostoma estor, and found to have Δ5/Δ6 and Δ4 desaturase activity, respectively [26]. The discovery of Δ4 desaturases in some species of teleost fish indicated that they have the capacity to synthesise docosahexaenoic acid (DHA; 22:6n-3) directly from docosapentaenoic acid (DPA; 22:5n-3), and thus are independent of the classical "Sprecher" pathway that requires the elongation of DPA to 24:5n-3, its subsequent Δ6 desaturation for the production of 24:6n-3, and then a peroxisomal chain-shortening for the final synthesis of DHA [24]. Finally, Fads2 with Δ6 desaturase activity from teleosts, and especially from marine species, also show Δ8 desaturase activity [27–29], again illustrating the functional plasticity of teleost Fads2. The Δ8 activity allows for a different and parallel pathway for the bioconversion of LA and ALA into 20:3n-6 and 20:4n-3, respectively, via their elongation followed by a Δ8 desaturation, rather than the traditional Δ6 desaturation and subsequent elongation.

Rainbow trout, Oncorhynchus mykiss, are cultured commercially worldwide and they are commonly fed diets containing LC-PUFA, as these diets are important for the growth and health of the fish and they meet consumer expectations for the nutritional quality and health value of cultured fish products [30–34]. Currently, fish oil is the primary source of LC-PUFA in formulated feed for fish (aquafeed) [1, 10]. However, the finite and limited supply and increasing price of fish oil, have dictated that the aquafeed industry develop alternative...
strategies, with plant (vegetable) oils that contain no LC-PUFA being the primary option for fish oil substitution in aquafeed [1, 35–41]. The reduced levels of n-3 LC-PUFA in feeds is reflected in a reduction of EPA and DHA in fish tissues, even in species with documented capabilities of bioconverting dietary ALA into n-3 LC-PUFA, such as rainbow trout [42, 43], which can have important consequences for human consumption.

Given the importance of LC-PUFA composition and metabolism in fish for nutritional reasons, it is essential to have a full understanding of the enzymes involved in the biosynthetic pathway(s). Previously, a fads2 was isolated from rainbow trout and the encoded protein shown to possess Δ6 desaturase activity [5]. The present study reports the isolation, cloning and characterisation of a second fads2 cDNA (termed fads2b) in rainbow trout that encodes a protein with Δ5 desaturase activity. The findings provide new information about endogenous n-3 LC-PUFA biosynthesis in a commercially important teleost fish species.

Materials and Methods

Animals and tissue collection

Animal experimentation was approved by the Deakin University Animal Ethics Committee (AEC approval A41-2011). Rainbow trout, O. mykiss, were obtained from the Department of Primary Industries (Snobs Creek, Victoria, Australia) and housed in a recirculating aquaculture system (RAS) located at Deakin University, Warrnambool, Australia. The aquaculture system was equipped with an in-line oxygen generator and a physical and biological filtration plant. Water temperature (15.0 ± 0.8°C), pH (8.26 ± 0.04), and oxygen concentration (9.14 ± 0.30 mg.L⁻¹) were monitored daily. The dissolved ammonia and nitrite levels were measured weekly using Aquamerck test kits (Merck, Darmstadt, Germany), and were maintained below 0.20 and 0.25 mg.L⁻¹, respectively. The system operated on a 12:12 h light-dark cycle. All fish were fed a commercial trout diet (40% protein, 20% lipid, closed formula, Ridley Aquafeed, Australia). For experimentation, fish were humanely killed using an overdose of anaesthetic (10% AQUI-S; AQUI-S New Zealand Ltd., Lower Hutt), and the gill, liver, muscle, adipose tissue, brain, heart, intestine, kidney, pyloric caeca and stomach tissues were snap frozen in liquid nitrogen and stored at −80°C until required.

RNA isolation and cloning of rainbow trout fads2b cDNA

The liver was chosen for the isolation of rainbow trout fads2b mRNA as it is the predominant site for fatty acid synthesis in vertebrates. Briefly, approximately 20 mg of liver was added to a 1.5 mL centrifuge tube containing 10 1.0 mm silica beads (Biospec Products, Inc.) and 1 mL of TriReagent (Sigma). The tissue was mechanically disrupted using a high-speed bench top homogeniser (FastPrep24), at a speed of 6.5 M/sec for 60 sec. Isolation of total RNA was then performed according to the manufacturer’s protocol for TriReagent. For cDNA synthesis, 3 μg of RNA was reverse transcribed into first strand cDNA using oligo (dT) priming and SuperScriptII Reverse Transcriptase (Invitrogen), according to the manufacturer’s protocol. The quality of cDNA was verified by the expression of β-actin as a control mRNA (accession number: AF157514). Primers for amplification of rainbow trout fads2b were designed using Gene Runner v.3.05 and the Atlantic salmon (S. salar) sequence for fads2/Δ5 (21) as a reference sequence (NCBI database, accession number: AF478472). The primers used for amplifying rainbow trout fads2b cloning are listed in Table 1, and the PCR strategy is illustrated in Fig 1, with each step described in the legend to the figure.

Standard PCR amplification was performed in 0.2 mL thin-walled tubes using an Eppendorf Mastercycler. The 20 μL reaction mixture contained: 1 X buffer, 0.25 mM dNTP, 1.875 mM MgCl₂, 1 μM of each primer, 1 μL of cDNA, and 2 units of Taq polymerase. PCR was
### Table 1. List of primers for RT-PCR, 3’ RACE, and cloning of the fads2b coding sequence into pYES2 vector.

| Primer set | Primer sequence and amplification (5’—3’) |
|------------|------------------------------------------|
| **cDNA cloning** | |
| F1         | GGAGAAGATGCCACGGAAG                       |
| F2         | CCTGATATCACTCACTACAT                      |
| F3         | CCACAAATGGTCCAGTGTTTTT                    |
| F4         | CGGGCTTGAGCCCGATGGA                       |
| R1         | AAACATGGTCCGGGATATTCT                     |
| R2         | CTGACAACACATCAGTCATGCGCTTT               |
| R3         | CTCATCGACCAGCCGAT                          |
| R4         | CCAAATGCAAAACTTGCGAGGT                 |
| **3’ RACE** | |
| 3’RACE     | ATGACTGATGTTGTCAGGTA                      |
| **Untranslated region** | |
| 5’UTR      | AACGCTGCTGGAACATCTC                       |
| 3’UTR      | CTGACAAGGATATGAACAT                      |
| **Rainbow trout fads2b mRNA expression** | |
| Tfads2bF   | TTCCGACCAGTGGTTTTCACA                   |
| Tfads2bR   | ACAATCATGTTGTCAGGAT                      |
| **Rainbow trout fads2b primers with restriction sites** | |
| BamH1      | ATGGAGTCAGGATGGGGCCGGAG                  |
| XhoI       | TAACTCGAGGATTTATATATGGAGATACGAT         |

doi:10.1371/journal.pone.0150770.t001

Fig 1. Diagram showing the sequential steps (numbers 1 to 8 on left side of Figure) for cloning of a rainbow trout fads2b cDNA using salmon fads2b/Δ5 as a template. The primer sets for the eight PCR fragments are listed in Table 1. The rationale of each step is as follows. **Step 1**: initial amplification (672 bp) of trout fads2b; **Step 2**: 3’ RACE PCR to amplify (201 bp) from 3’ end of ORF and UTR of trout fads2b; **Step 3**: amplification (1349 bp) of trout fads2b using sequence obtained in steps 1 and 2 for primer design; **Steps 4 and 5**: confirmation of trout fads2b compared to trout fads2b/Δ6 (step 4: 593 bp, step 5: 470 bp); **Steps 6 and 7**: amplification of 5’ end of trout fads2b ORF and UTR sequences, respectively (step 6: 593 bp, step 7: 470 bp); **Step 8**: amplification (1578 bp) of full trout fads2b mRNA sequence.

doi:10.1371/journal.pone.0150770.g001
conducted under the following conditions: an initial denaturation at 94°C for 3 min, followed by 30 to 36 cycles of denaturation at 94°C for 15 sec, annealing at 58–60°C for 30 sec, and extension at 72°C for 3 to 3.5 min, and a final extension step of 72°C for 5 min. PCR products were visualised using a Syngene gel documentation system (Synoptics Ltd, UK), were then excised, and then purified using a NucleoSpin Extract II kit (Scientifix) according to the manufacturer’s protocol. Nucleotide sequences were determined by standard dye terminator chemistry using a BigDye terminator v3.1 cycle sequencing kit (Applied Biosystems) and an ABI PRISM 3100 Genetic Analyser (Deakin University).

A 3´ rapid amplification of cDNA ends (3´ RACE) method was used to obtain the 3´ untranslated region (UTR) of rainbow trout fads2b using the 3´ full RACE core set (Takara). Reverse transcription of the mRNA was performed according to the manufacturer’s protocol, with 1 μL of cDNA used as a template in the first round of PCR amplification. The reaction was performed in a total volume of 20 μL and contained: 1 x PCR buffer, 0.2 mM dNTPs, 2.5 mM MgCl₂, 1 μM of gene-specific reverse primer (Table 1), 0.5 μM 3´ end PCR primer, and 2 units of Taq polymerase. The 3´-RACE PCR reactions had an initial denaturation at 94°C for 3 min, followed by 40 cycles of denaturation at 94°C for 45 sec, annealing at 50–58°C for 30 sec, and extension at 72°C for 45 sec, with a final extension step at 72°C for 3 min. A nested PCR reaction was performed using 1 μL of double stranded cDNA from the first PCR reaction, following the same PCR condition as the first round PCR.

**Tissue distribution of rainbow trout fads2b mRNA**

The expression of rainbow trout fads2b mRNA was determined in adipose tissue, brain, gill, heart, intestine (hind gut), kidney, liver, muscle, pyloric caeca, and stomach from three animals. RNA isolation, cDNA synthesis, and PCR were performed as described above using the PCR primers detailed in Table 1. The PCR amplification was performed for 36 cycles and β-actin mRNA expression was used to validate the quality of the synthesised cDNA.

**Sequence and phylogenetic analysis**

The full-length sequences of rainbow trout fads2b and the predicted Fads2b protein were analysed using the Basic Local Alignment Search Tool (BLAST, [www.ncbi.nlm.nih.gov/blast/](http://www.ncbi.nlm.nih.gov/blast/); [44]). The molecular weight of the predicted rainbow trout Fads2b protein was determined using the tools available at [http://www.bioinformatics.org/sms/prot_mw.html](http://www.bioinformatics.org/sms/prot_mw.html). Alignment of rainbow trout Fads2b with Fads2/Δ5 desaturase and Fads2/Δ6 desaturases from Atlantic salmon and Fads1/Δ5 and Fads2/Δ6 from human was performed using the GeneDoc program and SOSUI software (http://bp.nuap.nagoya-u.ac.jp/sosui/sosui).

For phylogenetic analysis, Fads sequences were obtained from the NCBI GenBank database (www.ncbi.nlm.nih.gov/Genbank/index.html) (see S1 Table), and aligned using Clustal Omega (http://www.ebi.ac.uk/Tools/msa/clustalo/; [45]). A maximum likelihood tree was constructed in MEGA6 using the Jones-Taylor-Thornton matrix based method for amino acid substitutions. The statistical significance of each branch was evaluated by bootstrapping with 1000 replicates.

**Heterologous expression of rainbow trout fads2b in yeast**

The rainbow trout fads2b coding sequence was obtained by PCR from full-length cDNA with primers containing Bam HI and Xho I restriction sites, respectively (Table 1). This fragment and the yeast galactose-induced expression plasmid pYES2 (Invitrogen, UK) were digested with the corresponding restriction endonucleases (New England BioLabs, Herts, UK) and ligated using T4 DNA Ligase (Bioline, London, UK). The resulting plasmid construct pYES2-
fads2b was transformed into *Saccharomyces cerevisiae* (strain INVSc1) using the S.C. Easy-Comp Transformation kit (Invitrogen) and incubated for 3 days at 30°C in yeast dropout plates (-ura). A single colony of transgenic yeast was grown in *S. cerevisiae* minimal medium (-ura) (SCMM-ura) for 24 h prior supplementation with 2% D-galactose and one of the following fatty acid substrates diluted in an aqueous detergent solution: ALA, LA, eicosatrienoic acid (20:3n-3), eicosatetraenoic acid (20:4n-6), dihomoy-γ-linolenic acid (20:3n-6), docosapentaenoic acid (22:5n-3) and adrenic acid (22:4n-6). Substrate FA final concentrations were 0.5 mM for C18, 0.75 mM for C20 and 1 mM for C22 fatty acids. The fatty acid substrates (> 99% pure) and chemicals used to prepare the SCMM-ura were purchased from Sigma Chemical Co. Ltd. After 2 days, yeast were harvested and washed with Hank’s balanced salt solution containing 1% fatty acid-free bovine serum albumin prior to lipid extraction and fatty acid analyses. Yeast transformed with pYES2 containing no insert were cultured under the same conditions described above and used as control treatments. Yeast fatty acid analysis was performed as described previously [9, 12].

**Results**

**Sequencing of rainbow trout fads2b mRNA**

Overlapping fragments of a putative rainbow trout fads2b cDNA were amplified using standard and 3’-RACE PCR, which were assembled to construct a consensus sequence. The full-length putative rainbow trout fads2b cDNA contained 1578 nucleotides with an open reading frame (ORF) of 1365 base pairs that encoded a 454 amino acid protein, with 74 nucleotides in the 5’ UTR and 139 nucleotides in the 3’ UTR (Fig 2). The molecular weight of the predicted protein was 52.48 kDa. The predicted rainbow trout Fads2b protein had the typical traits of the microsomal fatty acyl desaturase family, including an N-terminal cytochrome b5 domain containing the heme-binding motif (HPPG), histidine boxes (HDXGH, HFQHH and QIEHH) and three transmembrane regions (Fig 3). The predicted rainbow trout Fads2b protein shared 94.2% identity with rainbow trout Fads2a/Δ6 (accession number: NP_001117759) and 95% identity to Fads2b of Atlantic salmon (accession number: NP_001117014.1), but was most similar (98.5%) to Fads2a of masu salmon, *Oncorhynchus masou*, (accession number: BAB63440). The rainbow trout fads2b mRNA and predicted protein sequence were deposited in the GenBank database (accession number: AFM77867).

**Phylogenetic analysis**

A neighbour-joining tree showing the phylogenetic relationship of vertebrate Fads proteins is shown in Fig 4. The vertebrate Fads proteins clustered into two primary clades, Fads1 and Fads2, with good bootstrap support. As expected, the rainbow trout Fads2a protein grouped with other salmonid Fads2 proteins.

**Tissue distribution of rainbow trout fads2b mRNA**

The expression profile of fads2b mRNA in rainbow trout tissues is shown in Fig 5. Although comparisons of mRNA expression from RT-PCR analyses have to be made cautiously, some patterns can be observed in the tissue distribution of fads2b transcripts. A relatively higher fads2b mRNA expression was found in the liver, intestine, pyloric caeca, and brain. A relatively lower fads2b mRNA expression was observed in the gill, heart and kidney. No expression was found in the stomach, muscle and adipose tissue. A similar expression profiles was found in three animals.
Functional characterisation of rainbow trout Fads2b in yeast

The ability of rainbow trout Fads2b to desaturate PUFA of the n-3 and n-6 series was determined by quantification of the relative fatty acid conversions obtained when transformed S. cerevisiae containing either the empty pYES2 vector (control), or a vector with the rainbow trout fads2b ORF insert grown in the presence of potential fatty acid substrates. For this, yeast transformed with pYES2-Fads2b were grown in the presence of Δ6 substrates (18:3n-3, 18:2n-6), Δ8 substrates (20:3n-3 and 20:2n-6), Δ5 substrates (20:4n-3 and 20:3n-6) and Δ4 substrates (22:5n-3 and 22:4n-6). The fatty acid composition of the yeast transformed with empty pYES2 (control) showed the main fatty acids normally found in S. cerevisiae, namely 16:0, 16:1 iso-mer, 18:0 and 18:1n-9, and whichever exogenous PUFA was added (data not shown). This is consistent with this yeast strain not possessing any PUFA desaturation capabilities (12). However, based on GC retention time and confirmed by GC-MS, rainbow trout Fads2b showed significant desaturation activity towards the Δ5 substrate 20:4n-3 converting it to EPA, which accounted for over 17% of the total substrate conversion (Fig 6), whereas the n-6 Δ5 substrate 20:3n-6 was desaturated to a lower extent (2% conversion) (Table 2). Additional peaks were not observed with any of the exogenously added Δ6 or Δ4 fatty acid substrates. As reported for
Fig 3. Alignment of the rainbow trout (Om) Fads2/Δ5 deduced amino acid sequence against Fads2/Δ6 from rainbow trout, Fads2/Δ5 desaturase and Fads2/Δ6 desaturases from Atlantic salmon (Ss), and Fads1/Δ5 and Fads2/Δ6 from human (Hs). Black, dark grey and grey shaded area indicates 100%, 80%, and 60% conserved regions, respectively, using the GeneDoc program. The dotted line denotes the cytochrome b5 domain, and a heme-binding motif is boxed. Three transmembrane regions (double dot-dash lined) are predicted by SOSUI software (http://bp.nuap.nagoya-u.ac.jp/sosui/sosui). Histidine boxes are underlined.

doi:10.1371/journal.pone.0150770.g003
Fig 4. Phylogenetic analysis of vertebrate Fads proteins as inferred using the Neighbour-Joining method applying a maximum likelihood approach. The position of rainbow trout Fads2b/Δ5 is marked.

doi:10.1371/journal.pone.0150770.g004
other teleost species, including the previously described rainbow trout fads2 Δ6 paralog, the newly characterised Fads2 displayed more activity towards n-3 PUFA than n-6 PUFA (Table 2) (5). It was interesting to note that 20:2n-6 (Δ11,14 20:2) and 20:3n-3 (Δ11,14,17 20:3) were desaturated in position Δ5 to produce the non-methylene interrupted (NMI) fatty acids Δ5,11,14 20:3 and Δ5,11,14,17 20:4, respectively (Table 2; Fig 6).

Discussion

Rainbow trout had previously been reported to have no dietary requirement for preformed dietary n-3 LC-PUFA, and to be able to bioconvert ALA into EPA and DHA, and that this bioconversion was relatively efficient and followed the so-called “Sprecher pathway” [7, 8, 41, 42]. As discussed above, the majority of teleost fish have a single fads2 gene that encode primarily monofunctional Δ6 desaturase proteins [5, 16–19]. However, some species deviate from this typical pattern. For example, Atlantic salmon, zebrafish, Senegalese sole, pike silverside, barramundi and rabbitfish have fads2 genes that encode Fads2 proteins with functionalities that include Δ4, Δ5 and Δ8 [12, 21–25, 29]. Prior to the current study, the only documented and known fads2 gene encoding a discrete monofunctional Δ5 desaturase protein in a teleost fish was that of Atlantic salmon [21]. The presence of a Fads-like enzyme with Δ5 desaturase activity in rainbow trout had been indicated indirectly by in vivo trials [46], but the protein had not been isolated or characterised. In the present study, a fads2 gene that encodes a Δ5 desaturase has been isolated and functionally characterised in rainbow trout for the first time. Thus, rainbow trout follow the same pattern previously reported in Atlantic salmon and have the capacity to synthesise EPA and ARA from ALA and LA, respectively, through separate fads2 genes that encode proteins with Δ6 and Δ5 desaturase activity, respectively. The confirmation of a monofunctional Δ5 desaturase protein in rainbow trout is important considering the commercial value of this species, the issues surrounding the provision of preformed dietary n-3 LC-PUFA (i.e. fish oil) in commercially aquaculture species, and in consideration of our understanding of vertebrate fatty acid metabolism and its evolution.

As expected, the phylogenetic analysis of vertebrate Fads protein grouped the deduced rainbow trout Fads2b protein with other salmonid Fads2 proteins. Interestingly, the two salmonid Fads2 proteins that show Δ5 desaturase activity are no more similar to each other than to the other salmonid Δ6 desaturase proteins. The evolution of the fads genes in vertebrates has recently been investigated [15]. It was proposed that the ancestral gnathostome possessed fads1 and fads2 genes, as they are both found in chondrichthyans and have been characterised as Δ5 and Δ6 desaturases, respectively, in catshark [15]; both fads1 and fads2 genes are also found in the coelacanth genome. As all teleost fish species examined to date only possess the fads2 gene, Castro and colleagues [15] proposed that the fads1 gene must have been lost in the
Fig 6. Functional characterisation of the newly cloned rainbow trout Fads2b in yeast (Saccharomyces cerevisiae). The fatty acid profiles of yeast transformed with pYES2 containing the coding sequence of the rainbow trout fads2b as an insert, were determined after the yeast was grown in the presence of one of the exogenously added substrates 18:3n-3 (A), 20:3n-3 (B), 20:4n-3 (C) and 22:5n3 (D). Peaks 1–4 in panels A-D are the main endogenous fatty acids of S. cerevisiae, namely 16:0 (1), 16:1 isomers (2), 18:0 (3) and
actinopterygian lineage that gave rise to teleost fishes. However, analysis of the annotated genome of the non-teleost actinopterygian, the spotted gar fish, *Lepisosteus oculatus*, reveals *fads* genes that encodes proteins with homology to *Fads1*; the functional characterisation of spotted gar Fads proteins would be of interest.

Rainbow trout *fads2b* mRNA was more highly expressed in the liver, intestine including pyloric caeca, and brain compared to other tissues, which was consistent with previous studies that demonstrated these tissues are important sites of LC-PUFA biosynthesis in salmonid fish [47–49]. A high expression of *fads2b* mRNA in the brain of rainbow trout is consistent with the expression pattern of *fads2* (Δ6) in rainbow trout [50], and *fads2* (Δ5) [23] and the three *fads2* (Δ6) genes in Atlantic salmon [12]. Furthermore, many other studies have shown that teleost brain expresses genes encoding the LC-PUFA biosynthesis enzymes including Fads and elongation of very long-chain fatty acid proteins (Elov; see [3,16, 27, 49–53]). Interestingly, it appears that the expression of *fads* genes is higher in the brain of marine species compared with freshwater species [54]. However, this pattern is not found in euryhaline species such as rabbitfish [54], and the marine Senegalese sole [55] in which the *fads* mRNA expression was higher in the liver compared to the brain. The high expression of *fads2* genes in the brain of teleosts could relate to the significance of LC-PUFA in the functionality of neuronal tissue, which has been reported in mammals [56–58]. In rainbow trout, the high expression of *fads2b* mRNA in the pyloric caeca is again consistent with that of *fads2* (Δ6) in rainbow trout [50] and the salmon *fads* genes [12]. In fact, in Atlantic salmon, the pyloric caeca had the highest mRNA expression of *fads2* (Δ6) and *fads2* (Δ5), which reflects a high LC-PUFA biosynthesis in this tissue [49, 59]. In addition, the pyloric caeca expresses *Elov* mRNA and the transcription factors, liver x receptor (*Lxr*) and sterol regulatory element-binding protein (*Srebp*), the latter being important in the control of lipid and fatty acid metabolism by regulating *fads* mRNA expression [60, 61]. Thus, the pyloric caeca contains the appropriate intracellular machinery for LC-PUFA biosynthesis [12, 52, 60, 62].

Commonly, the conventional pathway for synthesising LC-PUFA involves the activity of Δ6 and Δ5 desaturases. However, in addition to the action of Δ6 and Δ5 in LC-PUFA biosynthetic pathways, an alternative pathway has been identified in fish involving the action of Fads2 as a Δ8 desaturase [27]. The trout Fads2 characterised in the present study did not show any Δ8 desaturase activity, as both eicosadienoic (20:2n-6) and eicosatrienoic (20:3n-3) acids, rather than being Δ8 desaturated to 20:3n-6 and 20:4n-3, respectively, were converted into the NMI

| Substrate | Activity | Product | % Conversion |
|-----------|----------|---------|--------------|
| 18:3n-3   | Δ6       | 18:4n-3 | 0.0          |
| 18:2n-6   | Δ6       | 18:3n-6 | 0.0          |
| 20:3n-3   | Δ5 (not Δ8) | 20:4 (Δ5,11,14,17) | 2.6          |
| 20:2n-6   | Δ5 (not Δ8) | 20:3 (Δ5,11,14) | 1.1          |
| 20:4n-3   | Δ5       | 20:5n-3 | 17.8         |
| 20:3n-6   | Δ5       | 20:4n-6 | 2.1          |
| 22:5n-3   | Δ4       | 22:6n-3 | 0.0          |
| 22:4n-6   | Δ4       | 22:5n-6 | 0.0          |

doi:10.1371/journal.pone.0150770.t002

Table 2. Functional characterisation of the putative rainbow trout Fads2b in yeast.
fatty acids $^{\Delta 5,11,14}$ 20:3 and $^{\Delta 5,11,14,17}$ 20:4, respectively. Nevertheless, it is very unlikely that the biosynthesis of NMI fatty acids observed in the yeast expression systems would occur in vivo, as availability of these substrates is limited and the possible presence of the other Fads2 with $\Delta 8$ activity like the previously characterise desaturase [26] would allow 20:2n-6 and 20:3n-3 to be incorporated into the conventional pathway.

In conclusion, this study provides the first report of a fads2 gene that encodes a protein with monofunctional $\Delta 5$ activity from rainbow trout. Understanding of the role of $\Delta 5$ desaturase in fish provides information regarding the evolutionary biology of lipid metabolism and is also relevant for the advancement of novel aquafeed products in commercially important fish species. Although there has been significant interest in the use of plant-derived ingredients in aquafeeds as an alternative to marine resources, the ability to convert plant-derived C18 PUFA, ALA and LA, to C20/22 LC-PUFA in fish shows considerable variation between species. Further study on fads2b expression in the brain of rainbow trout would provide supplementary evidence regarding the significance of the brain in LC-PUFA biosynthesis. In addition, further elucidation of the biosynthetic pathways regulating lipid metabolism in fish will be required to produce a commercially profitable product containing high levels of n-3 LC-PUFA while also reducing the dependency on wild-caught marine ingredients for feeds.

Supporting Information

S1 Table. List of common names and accession numbers of the vertebrate species used to generate the phylogenetic tree of Fads1 and Fads2 proteins shown in Fig 4. (DOCX)

Author Contributions

Conceived and designed the experiments: JAD GMT DRT. Performed the experiments: NKAH GCA OM. Analyzed the data: NKAH GCA OM JAD. Contributed reagents/materials/analysis tools: JAD GMT DRT. Wrote the paper: NKAH JAD GMT DRT.

References

1. Turchini GM, Torstensen BE, Ng W-K. Fish oil replacement in finfish nutrition. Rev Aquaculture. 2009; 1(1):10–57. doi: 10.1111/j.1753-5131.2008.01001.x
2. Torstensen BE, Tocher DR. The effects of fish oil replacement on lipid metabolism of fish. In: Turchini GM, Ng W-K, Tocher DR, editors. Fish oil replacement and alternative lipid sources in aquaculture feeds. Boca Raton, FL: CRC Press; 2011. p. 405–38.
3. Carmona-Antonanzas G, Tocher DR, Taggart JB, Leaver MJ. An evolutionary perspective on Elovl5 fatty acid elongase: comparison of Northern pike and duplicated paralogs from Atlantic salmon. BMC Evol Biol. 2013; 13. 85 doi: 10.1186/1471-2148-13-85 WOS:000318368500001. PMID: 23597093
4. Monroig O, Tocher DR, Navarro JC. Biosynthesis of polyunsaturated fatty acids in marine invertebrates: Recent advances in molecular mechanisms. Mar Drugs. 2013; 11(10):3998–4018. doi: 10.3390/md11103998 WOS:000328622500023. PMID: 24152561
5. Zheng X, Selliez I, Hastings N, Tocher DR, Panserat S, Dickson CA, et al. Characterization and comparison of fatty acyl Delta 6 desaturase cDNAs from freshwater and marine teleost fish species. Comp Biochem Physiol B Biochem Mol Biol. 2004; 139(2):269–79. doi: 10.1016/j.cbpc.2004.08.003 WOS:000224666300016. PMID: 15465674
6. Tocher DR. Metabolism and functions of lipids and fatty acids in teleost fish. Rev Fish Sci. 2003; 11(2):107–84.
7. Buzzi M, Henderson RJ, Sargent JR. The desaturation and elongation of linolenic acid and eicosapentaenoic acid by hepatocytes and liver microsomes from rainbow trout (Oncorhynchus mykiss) fed diets containing fish oil or olive oil. Biochim Biophys Acta -Lipid Lipid Met. 1996; 1299(2):235–44. doi: 10.1016/0005-2760(95)00211-1 WOS:A1996TR38200011.
8. Buzzi M, Henderson RJ, Sargent JR. Biosynthesis of docosahexaenoic acid in trout hepatocytes proceeds via 24-carbon intermediates. Comp Biochem Physiol B Biochem Mol Biol. 1997; 116(2):263–7. doi: 10.1006/psbp.1997.1270

9. Morais S, Monroig O, Zheng XZ, Leaver MJ, Tocher DR. Highly Unsaturated Fatty Acid Synthesis in Atlantic Salmon: Characterization of Elovl5-and Elovl2-like Enolases. Mar Biotechnol. 2009; 11(5):627–39. doi: 10.1007/s11030-009-9179-0 WOS:000268547600009. PMID: 19184219

10. Wijekoon MPA, Parrish CC, Mansour A. Effect of dietary substitution of fish oil with flaxseed or sunflower oil on muscle fatty acid composition in juvenile steelhead trout (Onchorhynchus mykiss) reared at varying temperatures. Aquaculture. 2014; 433(0):74–81. doi: 10.1016/j.aquaculture.2014.05.028

11. Hixson SM, Parrish CC, Anderson DM. Changes in tissue lipid and fatty acid composition of farmed rainbow trout in response to dietary camellina oil as a replacement of fish lipids. Lipids. 2014; 49(1):97–111. doi: 10.1007/s11745-013-3862-7 WOS:000329241600009. PMID: 24264359

12. Monroig O, Zheng X, Morais S, Leaver MJ, Taggart JB, Tocher DR. Multiple genes for functional 6 fatty acyl desaturases (Fad) in Atlantic salmon (Salmo salar L.): gene and cDNA characterization, functional expression, tissue distribution and nutritional regulation. Biochim Biophys Acta. 2010; 1801(9):1072–81. doi: 10.1016/j.bbabio.2010.04.007 PMID: 20403458.

13. Sprecher H. Metabolism of highly unsaturated n-3 and n-6 fatty acids. Biochim Biophys Acta. 2000; 1486(2–3):219–31. doi: 10.1016/S0305-0491(99)00210-6 WOS:A1997WQ11600017. PMID: 9159889

14. Hasting N, Agaba MK, Tocher DR, Leaver MJ, Dick JR, et al. A vertebrate fatty acid desaturase with Delta 5 and Delta 6 activities. Proc Natl Acad Sci U S A. 2011; 108(26):1073/pnas.251516598 WOS:000172576900024. PMID: 11724940

15. Li Y, Monroig O, Zhang L, Wang S, Zheng X, Dick JR, et al. Long chain polyunsaturated fatty acid synthesis in a marine vertebrate: Ontogenetic and nutritional regulation of a fatty acyl desaturase with Delta 5 and Delta 6 activities. Proc Natl Acad Sci U S A. 2009; 106(21):8734–8. doi: 10.1073/pnas.0905508106 WOS:000265705900017.

16. Santigosa E, Geay F, Tonon T, Le Delliou H, Kuhl H, Reinhardt R, et al. Cloning, tissue expression, and functional characterization of two delta 6-desaturase variants of sea bass (Dicentrarchus labrax L.). Aquaculture. 2011; 325(1–2):90–100. doi: 10.1016/j.aquaculture.2011.01.008 WOS:000272859100013.

17. Gonzalez-Rovira A, Mourente G, Zheng X, Tocher DR, Pendon C. Molecular and functional characterization and expression analysis of a Delta 6 fatty acyl desaturase cDNA of European Sea Bass (Dicentrarchus labrax L.). Aquaculture. 2009; 298(1–2):122–31. doi: 10.1016/j.aquaculture.2009.02.010 WOS:0002685705900017.

18. Santigosa E, Geay F, Tonon T, Le Delliou H, Kuhl H, Reinhard R, et al. Cloning, tissue expression analysis, and functional characterization of two delta 6-desaturase variants of sea bass (Dicentrarchus labrax L.). Mar Biotechnol. 2011; 13(1):22–31. doi: 10.1007/s11265-010-9264-4 WOS:000286022600003. PMID: 20333428

19. Tocher DR, Zheng X, Schlechtriem C, Hastings N, Dick JR, Teale AJ. Highly unsaturated fatty acid synthesis in marine fish: Cloning, functional characterization, and nutritional regulation of fatty acyl Delta 6 desaturase of Atlantic cod (Gadus morhua L.). Lipids. 2006; 41(11):1003–16. doi: 10.1007/s11745-006-5051-4 WOS:000243184600003. PMID: 17263300

20. Tanomman S, Ketudat-Cairns M, Janprai A, Boonanuntanasarn S. Characterization of fatty acid delta-6 desaturase gene in Nile tilapia and heterogenous expression in Saccharomyces cerevisiae. Comp Biochem Physiol B Biochem Mol Biol. 2013; 166(2):148–56. doi: 10.1016/j.cbpb.2013.07.011 PMID: 23939229

21. Hastings N, Agaba M, Tocher DR, Leaver MJ, Dick JR, Sargent JR, et al. Vertebrate fatty acid desaturase with delta 5 and delta 6 activities. Proc Natl Acad Sci U S A. 2001; 98(25):14304–9. doi: 10.1073/pnas.251516598 WOS:000125769000024. PMID: 11724940

22. Hastings N, Agaba MK, Tocher DR, Zheng XZ, Dickson CA, Dick JR, et al. Molecular cloning and functional characterization of fatty acyl desaturase and elongase cDNAs involved in the production of eicosapentaenoic and docosahexaenoic acids from alpha-linolenic acid in Atlantic salmon (Salmo salar). Mar Biotechnol (N Y). 2004; 6(5):463–74. doi: 10.1016/S1388-1981(00)00077-9 PMID: 10903473

23. Zheng X, Tocher DR, Dickson CA, Bell JG, Teale AJ. Highly unsaturated fatty acid synthesis in vertebrates: New insights with the cloning and characterization of a delta 6 desaturase of Atlantic salmon: Characterization of ELOVL5-and ELOVL2-like Elongases. Mar Biotechnol. 2009; 11(3):627–39. doi: 10.1016/j.mabi.2009.01.005 WOS:0002685705900017.

24. Li Y, Monroig O, Zhang L, Wang S, Zheng X, Dick JR, et al. Vertebrate fatty acyl desaturase with Δ4 activity. Proc Natl Acad Sci USA. 2010; 107(39):16840–5. doi: 10.1073/pnas.1008429107 PMID: 20826444

25. Morais S, Castanheira F, Martínez-Rubio L, Concepción LEC, Tocher DR. Highly Unsaturated Fatty Acid Synthesis in a Marine Vertebrate: Ontogenetic and nutritional regulation of a fatty acyl desaturase with Delta 5 and Delta 6 activities. Proc Natl Acad Sci U S A. 2001; 98(25):14304–9. doi: 10.1073/pnas.251516598 WOS:000125769000024. PMID: 11724940
desaturase with Δ4 activity, Biochim Biophys Acta. 2012; 1821(4):660–71. doi: 10.1016/j.bbabio.2011.12.011 PMID: 22245719

26. Fonseca-Madrigal J, Navarro JC, Hontoria F, Tocher DR, Martinez-Palacios CA, Monroig O. Diversification of substrate specificities in teleost Fads2: characterization of Delta 4 and Delta 6 Delta 5 desaturases of Chirostoma estor. J Lipid Res. 2014; 55(7):1408–19. doi: 10.1194/jlr.M049791 WOS:000380174000020. PMID: 24792929

27. Monroig Ó, Li Y, Tocher DR. Delta-8 desaturation activity varies among fatty acyl desaturases of teleost fish: High activity in delta-6 desaturases of marine species. Comp Biochem Physiol B Biochem Mol Biol. 2011; 159(4):206–13. doi: 10.1016/j.cbpb.2011.04.007 PMID: 21571087

28. Wang S, Monroig Ó, Tang G, Zhang L, You C, Tocher DR, et al. Investigating long-chain polyunsaturated fatty acid biosynthesis in teleost fish: Functional characterization of fatty acyl desaturase (Fads2) and Elovl5 elongase in the catadromous species, Japanese eel Anguilla japonica. Aquaculture. 2014; 434(0):57–65. doi: 10.1016/j.aquaculture.2014.07.016

29. Tu W-C, Cook-Johnson RJ, James MJ, Muehlhaeusler BS, Stone DAJ, Gibson RA, et al. Investigating long-chain polyunsaturated fatty acid biosynthesis in teleost fish: High activity in delta-6 desaturases of marine species. Comp Biochem Physiol B Biochem Mol Biol. 2011; 159(4):206–13. doi: 10.1016/j.cbpb.2011.04.007 PMID: 21571087

30. Manson JE, Bassuk SS, Lee IM, Cook NR, Albert MA, Gordon D, et al. The VITamin D and OmegA-3 TRIaL (VITAL): Rationale and design of a large randomized controlled trial of vitamin D and marine omega-3 fatty acid supplements for the primary prevention of cancer and cardiovascular disease. Contemp Clin Trials. 2012; 33(1):59–71. doi: 10.1016/j.cct.2011.09.009 PMID: 21868389

31. Hirasa Gesawa A, Tsumaya K, Awaji T, Katsuma S, Adachi T, Yamada M, et al. Free fatty acids regulate gut incretin glucagon-like peptide-1 secretion through GPR120. Nat Med. 2005; 11(1):90–4. PMID: 15619630

32. Simopoulos A. Evolutionary Aspects of Diet: The Omega-6/Omega-3 Ratio and the Brain. Mol Neurobiol. 2011; 44(2):203–15. doi: 10.1007/s12035-010-8162-0 PMID: 21279554

33. Glencross B, Tocher DR, Matthew C, Gordon Bell J. Interactions between dietary docosahexaenoic acid and other long-chain polyunsaturated fatty acids on performance and fatty acid retention in post-smolt Atlantic salmon (Salmo salar). Fish Physiol Biochem. 2014; 40(4):1213–27. doi: 10.1007/s12035-014-9917-8 PMID: 24515629

34. Francis DS, Thanauthong T, Senadheera SP, Paolucci M, Coccia E, De Silva SS, et al. n-3 LC-PUFA deposition efficiency and appetite-regulating hormones are modulated by the dietary lipid source during rainbow trout grow-out and finishing periods. Fish Physiol Biochem. 2014; 40(2):577–93. doi: 10.1007/s12035-013-9868-5 PMID: 24078221

35. Turchini GM, Francis DS, Turchini GM. Fatty acid metabolism (desaturation, elongation and beta-oxidation) in rainbow trout fed fish oil- or linseed oil-based diets. Br J Nutr. 2009; 102(1):69–86. doi: 10.1017/S0007114508137874 WOS:000268311400008. PMID:19123959

36. Cleveland BJ, Francis DS, Turchini GM. Echium Oil Provides No Benefit over Linseed Oil for (n-3) Long-Chain PUFA Biosynthesis in Rainbow Trout. J Nutr. 2012; 142(8):1449–55. doi: 10.3945/jn.112.161487 WOS:000306865200006. PMID: 22739372

37. Altschul SF, Gish W, Miller W, Myers EW, Lipman DJ. Basic local alignment search tool. J Mol Biol. 1990; 215(3):403–10. PMID: 2231712
