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Diversity, Molecular Characterization and Expression of T Cell Receptor γ in a Teleost Fish, the Sea Bass (*Dicentrarchus labrax*, L)

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Abstract

Two lineages of T cells, expressing either the $\alpha\beta$ T cell receptor (TR) or the $\gamma\delta$ TR, exist in Gnathostomes. The latter type of T cells account for 1–10 % of T cells in blood and up to 30 % in the small intestine. They may recognize unconventional antigens (phosphorylated microbial metabolites, lipid antigens) without the need of major histocompatibility class I (MH1) or class II (MH2) presentation. In this work we have described cloning and structural characterization of TR γ -chain (TRG) from the teleost *Dicentrarchus labrax*. Further, by means of quantitative PCR analysis, we analyzed TRG expression levels both in poly I:C stimulated leukocytes *in vitro*, and following infection with betanodavirus *in vivo*. Two full length cDNAs relative to TRG, with the highest peptide and nucleotide identity with Japanese flounder, were identified. A multiple alignment analysis showed the conservation of peptides fundamental for TRG biological functions, and of the FGXG motif in the FR4 region, typical of most TR and immunoglobulin light chains. A 3D structure consisting of two domains mainly folded as beta strands with a sandwich architecture for each domain was also reported. TRG CDR3 of 8–18 AA in length and diversity in the TRG rearrangements expressed in thymus and intestine for a given V/C combination were evidenced by junction length spectratyping. TRG mRNA expression levels were high in basal conditions both in thymus and intestine, while in kidney and gut leukocytes they were up-regulated after *in vitro* stimulation by poly I:C. Finally, in juveniles the TRG expression levels were up-regulated in the head kidney and down-regulated in intestine after *in vivo* infection with betanodavirus. Overall, in this study the involvement of TRG-bearing T cells during viral stimulation was described for the first time, leading to new insights for the identification of T cell subsets in fish.

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Introduction

In vertebrates, T cells are fundamental players of the specific immune response. T cells identify the antigens through a CD3-associated, antigen (Ag)-specific and heterodimeric T cell receptor (TR) expressed on the cell surface. The majority of mature T cells display an $\alpha\beta$ TR which recognizes peptides presented on the surface of antigen-presenting cells (APC) and reside primarily in secondary lymphoid organs. Another lineage of T cells carries a different TR composed of γ and δ TR chains. Many $\gamma\delta$ T cells reside in epithelial layers of mucosal tissues, such as skin, intestinal epithelium, lung and tongue, where they function as first line of defense as immunity effector cells [1–3]. The TR γ (TRG) and TR δ (TRD) chain proteins are encoded by genes somatically rearranged through the V-(D)-J recombination process during

intrathymic T cell maturation [4]. In contrast to $\alpha\beta$ T cells, the available repertoire of $\gamma\delta$ T cells can be rather restricted since canonical $\gamma\delta$ TRs are expressed in specific anatomical locations [5]. The $\gamma\delta$ T cells display cytotoxic activity [6], can lyse infected macrophages and, in this way, limit the spread of infectious microorganisms [7]. A peculiar feature of $\gamma\delta$ T cells is that they do not recognize peptides processed from complex protein antigens by APC cells, but rather individuate unconventional antigens such as phosphorylated microbial metabolites and lipid antigens. Moreover, the presentation of these ligands by major histocompatibility class I (MH1) or class II (MH2) proteins is not needed, and this is in agreement with the absence of CD4 or CD8 expression in the majority of $\gamma\delta$ T cells [3,8]. For these reasons, and based on the interpretation that $\gamma\delta$ T cells use their T cell receptor as a pattern recognition receptor, these cells have been

considered, functionally, as a bridge between the innate and adaptive immune systems [9]. However, TRG and TRD genes have all the features of the rearranging genes of the adaptive immune response that characterizes vertebrates with jaws, from fish to humans [4]. An experimental 3D structure of a human $\gamma\delta$ T cell receptor from a T cell clone that is phosphoantigen-reactive was obtained [10] and showed a peculiar orientation of the variable and constant regions in the complex when compared to $\alpha\beta$ TR. The obtained 3D structures permitted putative structural interactions between $\gamma\delta$ TR with CD3 isoforms and other ligands, and have been of great help for the understanding of important mechanisms necessary for receptor assembly, ligand recognition and signaling [11–12]. Typical TRG and TRD sequences were found in Chondrichthyans, suggesting that these genes were present in the common ancestors of all jawed vertebrates [13]. In teleost fish, TRG sequences have been identified in species like the green spotted pufferfish (*Tetraodon nigroviridis*) [14], Japanese flounder (*Paralichthys olivaceus*) [15], rainbow trout (*Oncorhynchus mykiss*) [16], and common carp (*Cyprinus carpio* L.) [17]. Moreover, several Atlantic salmon (*Salmo salar*) TRG sequences have been identified in BAC clones [18] and, recently, a TRG locus has been sequenced in the sandbar shark (*Carcharhinus plumbeus*) showing an organization similar to that found in mammals, with a set of V genes preceding J and C genes [19]. While the biology and implication in immune defense of fish $\alpha\beta$ T cells has been partly unrevealed, the role of $\gamma\delta$ T cells is still unknown.

As a fish of significant importance for farming, the European sea bass (*Dicentrarchus labrax* L.) is one of the best studied teleost fish species, and much information on its immune system is available. To better understand the response to pathogens and to develop vaccination, sea bass systemic and mucosal $\alpha\beta$ T cells have been intensely investigated in recent years. In this work, we extend these efforts to the $\gamma\delta$ T cell immunity. We identified the sea bass TRG chain, and provided a first description of its diversity, and its 3D structure considering the putative interactions with the TRD chain. We also preliminarily investigated the modulation of TRG after *in vitro* stimulation with poly I:C and *in vivo* infection with betanodavirus.

Results

Sea Bass Possess Typical TRG Genes

TRG V and C sequences from human, mouse, Japanese flounder and zebrafish were used to mine sea bass ESTs and genomic resources using tblastn (Kuhl H. and Reinhardt R., personal communications). Several partial sequences were identified (data not shown) and allowed the design of primers for direct or RACE amplification of sea bass TRG from the thymus. These PCR products were cloned and sequenced, and allowed the reconstitution of two full-length cDNAs corresponding to sea bass TRG (EMBL accession numbers FR745889 and FR751038). The amino acid sequences represented as “IMTG Collier de Perles” [20–22] (Figure 1) obtained for the two identified sea bass TRG sequences show that amino acids which are fundamental for the TRG 3D structural configuration are conserved in the two sequences. A slight difference can be noted in the two clones within the first loop of the V-DOMAIN, whereas the C-DOMAIN is well conserved. A putative 20 amino acid signal peptide was predicted in these two full length sequences (names Diclal1 and Diclal2) as well as nine O-glycosylation sites but no potential N-glycosylation. Comparison of the sea bass TRG Diclal1 nucleotide and amino acid sequence to its closest counterparts in other species is shown in Table 1. The highest nucleotide and amino acid identity was with Japanese flounder, followed by channel

catfish, whilst the lowest identity was with chicken. A multiple alignment of full length sea bass TRG amino acid sequences with other known TRG sequences was assembled (Figure 2) to investigate the conservation of characteristic amino acid residues involved in structural domains. Some amino acids are conserved in all considered sequences: C⁴² (1st-CYS 23), W⁵⁴ (CONSERVED-TRP 41), Y⁵⁵, Y¹¹², C¹¹⁴ (2nd-CYS 104), F¹²⁴ (J-PHE 118), G¹²⁷, T¹²⁸, L¹³⁰, V¹³² in the V-DOMAIN, C¹⁶¹ (1st-CYS 23), P¹⁶⁸, W¹⁷⁵ (CONSERVED-TRP-41), C²²¹ (2nd-CYS 104) in the C-DOMAIN, and Y²⁹¹, K²⁹⁷ in the transmembrane region (IMGTunique numbering for V domain [23] and C domain [24] shown between parentheses). The two cysteines that in human TRG are involved in an intra-chain disulfide bond fundamental for the assembly of the V-DOMAIN [10] are conserved in Diclal1 and Diclal2, as well as the di-glycine bulge FGXG in the FR4 region, typical of most TR and IG light chains [23]. The C domain showed the conservation of the two cysteine residues involved in human TRG in the formation of another intrachain disulfide bond [10,24], and the characteristic motif CX6PX6WX45C [17]. This motif corresponds to a BC loop of 8 amino acids long, with the conserved cysteine C23, proline P30, tryptophan W41 and cysteine C104. The connecting region (CO) showed no conserved amino acids, while in the transmembrane region (TM) a lysine K, that is important for the assembly of the complex between TR β chain and CD3 [25], is conserved in sea bass TRG sequences.

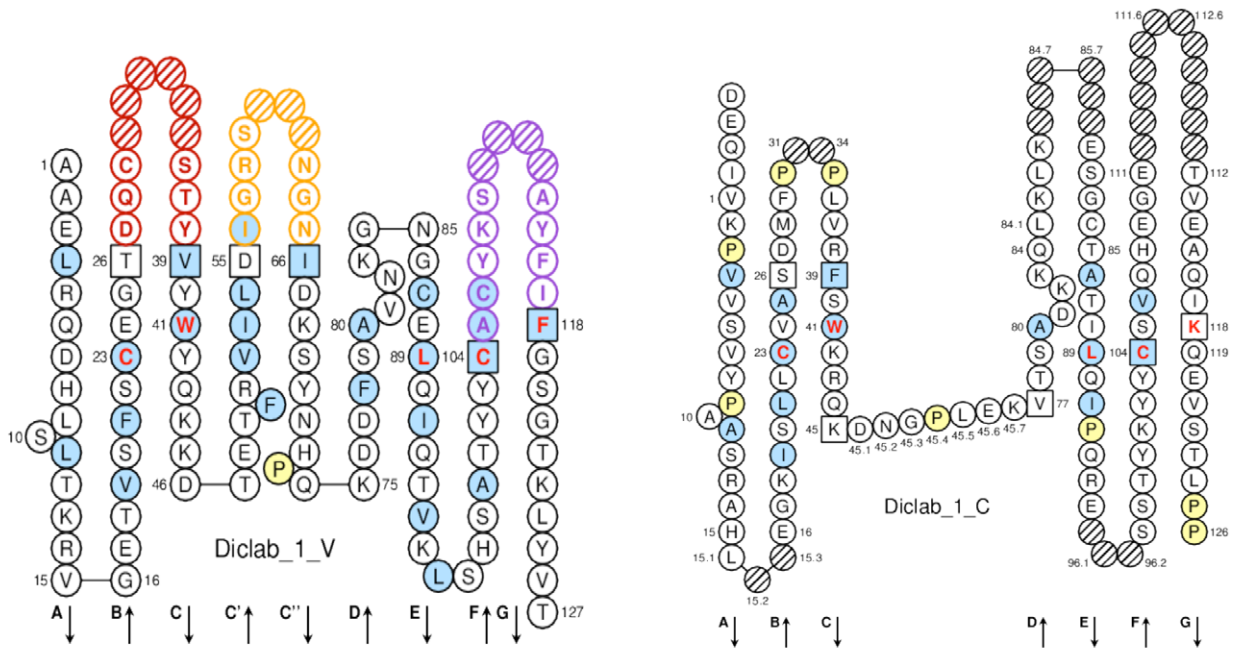
V/C Combinatory Diversity of Sea Bass TRG Chain

In silico mining and RACE-PCR led to the identification of several additional partial TRG sequences (Figure S1). Their comparison defines six V domains belonging to the same subgroup (V γ 1.1–1.6) and five C domains representing most likely different genes (C γ 1–5) (temporary nomenclature). To get insight into the expression and diversity of TRG transcripts combining these V and C genes, we used primers that were specific for V and C subgroups (Table 2) to test all combinations on thymus and gut cDNA from adult healthy bass. Relevant amplification was obtained for only a minority of combinations even in the thymus, suggesting that rearrangements may be restricted to recombination units as classically described for TRG in other species. These PCR products were subjected to a runoff with an internal fluorescent primer common to all C γ sequences and the product size was resolved in a sequencing system, leading to CDR3 length spectratypes for the relevant combinations. Typical results obtained from 3 different fishes are shown in Figure 3. The profiles show a moderate but significant junction size diversity for all the combinations amplified, with two to six main peaks, in both thymus and gut. Interestingly, CDR3 distributions did not appear to be gaussian-like in the thymus for any of the amplified combinations, as typically observed for fish or mammalian TRB. Taken together, these results show that several, but not all, V γ /C γ transcripts are expressed in thymus and gut of adult sea bass, with various junction size distributions suggesting recombination or selection constraints.

3D Structure of Sea Bass TRG Chain

The model of sea bass Diclal1 TRG chain shows the typical fold of immunoglobulin family (Figure 4, panel a). It consists of two domains, and folded mainly as beta strands which form two beta sheets and showing a sandwich architecture for each domain. Few short helices are also observed. Each domain is characterized by the presence of a disulphide bond (see Figure 4, panel a), in particular 1st-CYS 23 - 2nd-CYS 104 in both domains. Four other cysteines are present in Diclal1, while in Diclal2 the last cysteine

a)



b)

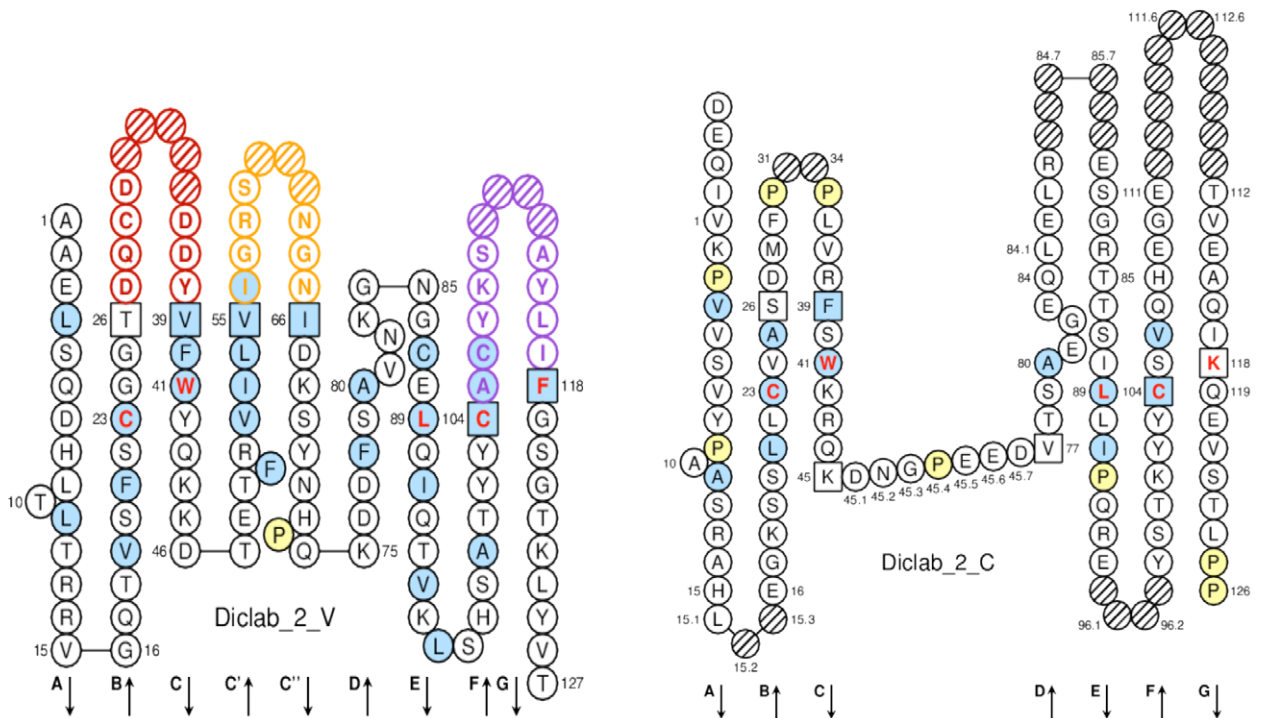


Figure 1. IMGT Colliers de Perles of the two identified sea bass TRG sequences. Panel a) Vdomain (V-GAMMA) and C- domain (C-GAMMA) of Diclab1, Panel b) V- domain (V-GAMMA) and C- domain (C-GAMMA) of Diclab2. Amino acid positions are according to the IMGT unique numbering for V domain and C domain. Anchor positions are shown as squares. In FR-IMGT, the hydrophobic amino acids (hydropathy index with positive value) and tryptophan (W) found at a given position in more than 50% of sequences are displayed with a blue background color. doi:10.1371/journal.pone.0047957.g001

is substituted by an arginine. The conformation of the backbone suggests that they are not suitable to form other intra-chain bridges, but well exposed on the surface of the protein, so their involvement in inter-chain disulphide bridges with the TRD chain cannot be excluded.

Comparing the different TRG sequences found in amplified clones and in genomic contigs, it appeared that the sequence of a TRG V domain showed a large deletion corresponding to the region C'C'' loop (CDR2-IMTG) -C'' strand -D strand (Figure S1). Since this deletion was found both in three different

Table 1. Percentage of nucleotide identity and amino acid identity and similarity of sea bass TR γ Dicl_{ab1} with other known sequences.

	% Nucleotide identity	% Amino acid identity	% Amino acid similarity
<i>Paralichthys olivaceus</i>	69,8	55,6	68,8
<i>Ictalurus punctatus</i>	51,9	36,8	48,9
<i>Danio rerio</i>	50,0	35,7	48,6
<i>Cyprinus carpio</i>	48,3	34,7	48,3
<i>Ginglymostoma cirratum</i>	48,7	27,9	45,5
<i>Homo sapiens</i>	46,0	23,2	41,9
<i>Mus musculus</i>	45,9	23,0	40,1
<i>Oryctolagus cuniculus</i>	46,3	21,6	40,8
<i>Gallus gallus</i>	45,7	21,3	38,9
<i>Xenopus laevis</i>	48,8	25,3	41,6

The highest values have been evidenced in bold (for sequence accession numbers see Figure 2 legend).
doi:10.1371/journal.pone.0047957.t001

transcripts from the gut (data not shown) and from a genomic contig (contig 142010153540001), it could not be explained by a PCR artifact of by a splicing pattern using internal crypting sites as in trout V β 6 or human NKP30 [26–27]. Additionally, CDR3 spectratyping confirmed that this short TRG V domain is expressed in the gut in diverse TRG V1.6/C4 or 5 rearrangements, at least at the transcript level, since a profile with 5 peaks was observed at the expected size. No profile was seen at the size predicted for a rearrangement of a TRG V1.6 sequence without deletion, which would represent a splicing variant as described for trout TR V β 6. No amplification was observed in the thymus for any TRG V1.6/C combination. Another TRG V sequence found in a genomic contig contained a CXCW motif (IMGT position 104–107) that has been found in the mouse functional TRGV5 and TRGV6 genes and in the human TRGV11 (an ORF by absence of splicing of the leader exon) (Figure S1, sequence Part 7) (IMGT Repertoire, <http://www.imgt.org>, IMGT/GENE-DB [28]).

In vitro and *in vivo* TRG Expression Analysis

A basal expression of TRG in all examined tissues of unstimulated sea bass was already described in [29], with the highest levels detected in thymus and intestine.

To investigate whether TRG expression levels could be modulated by the interferon system, leukocytes from head kidney and gut were stimulated *in vitro* with the interferon modulator poly I:C for 6 or 24 hours (Figure 5, Panel a and b). In leukocytes from both tissues, a slight expression decrease was detected after 6 h, whereas a significant increase was evidenced after 24 h of stimulation ($p < 0,0001$).

TRG expression levels were also determined in head kidney and gut from sea bass juveniles infected with betanodavirus [30], compared to non-infected controls. In the head kidney, TRG expression was highly up-regulated (30-fold) 6 hours after the infection, then decreased at 24 and 72 hours post-infection. In the intestine, down-regulation of TRG expression was obtained following viral infection at all tested time points, suggesting a possible migration of $\gamma\delta$ T cells out of this tissue.

Discussion

In mammals, the lymphocytes expressing $\alpha\beta$ TR and $\gamma\delta$ TR receptors display marked differences both in their origin and

function. While $\alpha\beta$ T cells recognize peptides presented by MH proteins, $\gamma\delta$ T cells have a broader range of ligand type and can be cytotoxic independently from antigen presentation. The biology of fish $\gamma\delta$ T cells remains largely unknown, although the presence of typical TRG and TRD genes in fish genomes and a few expression data indicated that they probably have a role in immune defense, especially in mucosal territories. To get insight into the $\gamma\delta$ T cell function through vertebrates, we studied the structure, diversity and expression of the TRG receptor in a teleost fish, the sea bass.

Two full-length sea bass TRG sequences were characterized from this species, which had all the hallmarks of typical TRG sequences and were most similar to TRG genes previously identified in other fish species. The IHWY motif (IMGT positions 39–42) in the FR2 of the V domain, typical of many mammalian TRG chains [13], is changed to VYWY (found in human TRGV9) and VFVY in sea bass, as observed in Japanese flounder, whereas VHMY and IRWY are found in channel catfish and carp, respectively.

CDR3 hypervariable loop confers epitope-specific sensitivity to TR α - and β -chains, whereas CDR1 and CDR2 are mainly in contact with the MH α helices and with the ends of the peptide located in the peptide-binding groove [24,31–33]. For TRG, the CDR3 loop most probably interacts with the ligand as well, although it may be shorter than the loops found in the V domains of the α , β , and δ chains. TRG V domain CDR3 loops in human and mouse are 1–12 and 4–11 amino acid long, respectively. This feature seems to be associated with a low expression of terminal deoxynucleotidyl transferase (TdT) during the TRG V-J rearrangements, and with the presence of short homology regions at the extremities of V and J genes that mediate direct recombination [34–36]. The TRG diversity may be further limited if the locus is organized in cassettes, as in mouse. In those cases TRG rearrangements occur within clusters of TRGV, TRGJ and TRGC genes which represent recombination units, and create mechanistic constraints on the TRGV-TRGJ rearrangements. This may also lead to rearrangements occurring at higher frequency between given TRGV and TRGJ and producing TRG chains with invariant junctions that are expressed even in the absence of the selection [37]. Several of these specific features seems to be retained in fish [15,17] as, for instance, the size of TRGV-TRGJ junction that appears to be shorter in the Japanese flounder, whereas the organization of the TRG locus with several V-J-C clusters is similar to the one observed in mouse [15]. In sea

	L-REGION										V-GAMMA (V-DOMAIN)																																																	
											FR1-IMGT																																																	
											A					B																																												
											(1-15)					(16-26)																																												
											1	10	15	16	23	26																																												
																																																											
Diclab1	MLFLPAALCCFSTALVMM										AALRQDHLSLTKRV	GETVVSFCBEGT																																																
Diclab2	MLFLPAALCCFSTALVMM										AALRQDHLSLTKRV	GQTVSFSBEGT																																																
Paroli	MLLLPAALCCFSTALVMM										AALRQDHLSLTKRV	GGTASFSBEGT																																																
Ictpun	MFIAIYAVLPSLLTEAVL										GVTLRQKDLISMTKEE	GKSVVISCVKT																																																
Gincir	MLVSVACFSCSGL.....										AQSLRQPMLSVSRAR	TKMARFRCLILE																																																
Cypcar	MFLFIAIVLLEMPAVAL										GVTLRQKDLISMTKEE	GKTIPLPCKDT																																																
Danrer	MFAIYIYVLLAEIPAVL..										GVTLNQGKALSKAA	GKTLPLPCKVA																																																
Orycun	MLWTLSSLVAFLPPGSGT.										SSNSEKTMVTVTKPT	GSSVAVTCISIT																																																
Musmus	MLLLRWFSTCCLVVFG...										LGQEQTELSVTRQT	DENVOISCIIVY																																																
Homsap	MRWLVVLLAFLSPASQK.										SSNLEGRKTSVTRQT	GSSAEITCDLT																																																
Xenlae	MQFLPAFVITLFLPKSCSA.										AIWVQQQYISITKVG	SGTARVFCQTT																																																
Galgal	MLALAEAWLHPFSPWRLHWQQQEAVALRTPAGSRLAVLAVFLLLDIGA										QVLLQQRQPSATRER	SKTVTIQCHVE																																																
											(1-26)																																																	
											C'					C''					C'''																																							
											(47-55)					(56-65)					(66-74)																																							
											D					E					F																																							
											(75-84)					(85-96)					(97-104)																																							
																																																											
Diclab1	DQC.....STY VVWYQKDD.....										TETFRVILD	IGRS...NGN					IDKSYNHQP	KDDFSAVNKG					NGELQIQTVKL																																					
Diclab2	DQCD.....DDY VVWYQKDD.....										TETFRVILV	IGRS...NGN					IDKSYNHQP	KDDFSAVNKG					NGELQIQTVKL																																					
Paroli	DQC.....GSY VVWYQKDD.....										TGTFRIILR	VEKS...DGS					IESGYSHPQ	KDDFTAEERP					NNCKLKKIKVKS																																					
Ictpun	GLA.....TTY VVWYQKDD.....										GEALTRILY	VSS...GSK					PVHDTTHPV	AKDFDVLQA					DKFDLKIANKK																																					
Gincir	DVDF.....ASVI VHWYRHTP.....										SQGFRRILY	VTG...AR					PVYDDDLAD	RFTSENVEKE					KSSLDIRINAE																																					
Cypcar	SN.....LDY IHWYVQKQAPSRLLVWVKDQAPSRLLY										ISK.....GG	SVAVDTNNO					EAKDFTVDKK	KLYDLKLSNTQT																																										
Danrer	GLQS.....WNY IHWYQKDD.....										GEAPSRLLY	INE...GG					AVTYDTNNE	QANDETVDR					KLYDLKLGDAQQ																																					
Orycun	QQS.....SY IHWYVQKQ.....										GKAPQRLLY	YVVS...STR					SIVDSGDFD	EKYQAYKSIQ					GSYVNFRLNLR																																					
Musmus	LYPF.....SNTA IHWYRQKT.....										NQQFYLIV	VAT...NYN					ORPLGKHKH	KLEASKDKPKS					STSLINYLKK																																					
Homsap	VTN.....LP IHWYVQKQ.....										GKAPQRLLY	YDVS...TARD					VLESGLSFG	KYTHTP					AR WSWILLRLQNLIE																																					
Xenlae	SMD.....LP IHWYVQKQ.....										SQLEKRLY	YHQ...EK					INVDGFSN	AKFDSKQTE					LGFTLIIQNTNA																																					
Galgal	GIADF.....HNAY IHWYRQKQ.....										AGAPERLLY	VTA...VAQ					VSYSDSDSK	NKYTSKMGK					KICVLSVQDIDG																																					
											V-GAMMA (V-DOMAIN)										C-GAMMA (C-DOMAIN)																																							
											CDR3-IMGT					FR4-IMGT					A					AB					B					BC					C																			
											(105-117)					(118-129)					(1-15)					(16-26)					(27-38)					(39-45)																								
											F					G					(97-104)					(105-117)					(118-129)																													
											(97-104)					(105-117)					(118-129)					(120-130)					(131-141)																													
																																																											
Diclab1	SHSATYCC ACYKS.....AYFI										FGSGTKLIVT..	DEQIVKPVSVVPAASRAHL..					EGKISLLCVAS					DMFP..PLVR					FSWKRQK																																	
Diclab2	SHSATYCC ACYKS.....AYLI										FGSGTKLIVT..	DEQIVKPVSVVPAASRAHL..					EGKSLLCVAS					DMFP..PLVR					FSWKRQK																																	
Paroli	VHSASYCC VCKWST...ERIFI										FGSGTKLIVT..	DTQVKPKVMVMRYRTASRDDL..					DGKSVLLCVAS					NMSF..PLVH					FSWKRQK																																	
Ictpun	SHSAVYCC ASWESDRGYSYKVV										FGSGTRLIVT..	DVKERVKPEQVYVVPVSTPEK..					GEKSFLLCHAR					GMFP..DLVR					FTWQAKD																																	
Gincir	SDAGVYCC AIWDV...GALLQ										FGGTRLIVT..	GYNVREPKIQTFGPNBTELDL..					NRAAIVCLLT					DFEP..EVIR					VQWIGD																																	
Cypcar	SHSAVYCC AYWDT...SDKKI										FGSGTRLIVT..	GPNVTVESPKVSGYLPKSKYSDK..					HKQTMMLCHAS					GTVP..YLVK					FTWAKKS																																	
Danrer	KHTAVYCC AYWDT...SSRRI										FGSGTRLIVT..	EPGKDSVTPKLSGYLNKA..					NEKPAALQAK					DMFP..DLVS					FKWEKKS																																	
Orycun	DDSGVYCC AVWTKQ.NWIKI										FPKGTKLIVT..	DKRLDADSPKPTIFLPSVAETNL..					HKTGTYLCLLE					KEFP..DVIR					VYWEKKN																																	
Musmus	EDEATYCC ADWMSD.SGFHKV										FAEGTKLIVIPS	DKRLDADSPKPTIFLPSVAETNL..					HKTGTYLCLLE					KEFP..DVIR					VYWEKKN																																	
Homsap	NDSGVYCC ATWDRP...RLKLL										FGSGTRLIVT..	DKQLDADSPKPTIFLPSVAETNL..					QKAGTYLCLLE					KEFP..DIIK					IHWQEKK																																	
Xenlae	DDAGTYCC ACWDYD...GWGKV										FGSGTKLIVT..	NTARSAEKFNATILSTSKKVIK..					QGQGIYCLLE					NEFP..DAIQ					VWWRKGN																																	
Galgal	DDKGTYYC AYWESR.GYYKYV										FGSGTKLIVS..	DKGSSAPENYEMQEEHE...KQVYVCLIE										KSYP..EVIR					VKWIDEA																																	
											CD										DE										EF										FG										G									
											(77-84)					(85-96)					(97-104)					(105-117)					(118-126)																													
																																																											
Diclab1	DNGPLEK.VTSADKKQLK...ESGCTATILQIPQRE..										SSTYKYCC					SVQHEGTEVQAQI					KQEVSTLPP																																							
Diclab2	DNGPEED.VTSAAGQQLER...ESGRTSILLIPQRE..										YSTKYCC					SVQHEGTEVQAQI					KQEVSTLPP																																							
Paroli	EGGPLED.LTSAAGQQLERLV...PERTAAIMVVDRA..										SYTYKYRC					NVRHEGGTERTV					PALPAPTEP																																							
Ictpun	QGGNVVD.LRGDERLQRDEV...PEVRI TSMILVGGK...AKNNNFIC										TVKHDSVSKKEL					PIPREEDTS																																												
Gincir	KNAPSQD.VLTDVAVKQEND...AYSVSRLLIITKLE..										WTSQNI SC					RAEHETNPAKVTI					PKIESPGANL																																							
Cypcar	ETEEMTA.VPKEDVQGSYK...DKKIVTSMIVDKNT...AENNSYQC										TVTIDGITENPQI					LEMKREGIK																																												
Danrer	SSGWTE.VSNQIVHESHN...EDPVTSMLVNTP...EDNIYRC										TVTHEGSKDPPQI					EIKKDKDEK																																												
Orycun	GNTLL...DSQEGDILKTKG...TYMFKSWLTVPEE...AMGKEHC										IVKHENKGGADQ					EIEFPPIKK																																												
Musmus	SNTLL...GSQEGTMTKND...TYMFKSWLTVPEE...SLDKHEHC										IVKHENKGGADQ					EIEFPPIKT																																												
Xenlae	KDIPSEQGEIKSEKDKDND...VYSTTSLVSVTKD...DLGNKFTC										HYKHEGLSKQENV					DEVSVVGSK																																												
Galgal	NKEVTQNVKGDVWVSGED...KYSVTSWLSVPLE...SKNKIYSC										TYEHESGGNSLST					QDLFPVPS																																												
											CO (CONNECTING-REGION)																																																	
Diclab1	PTTSPSPSPSPSPSPSPSLIPSPSPSLIPAPPASAPSOYQVKKLLCLMY																																																											
Diclab2	PTTSPSPSPSPSPSPSPSLIPSPSPSLIPAPPASAPSOYQVKKLLCLMY																																																											
Paroli	PSTPPSPSPSPSPSPSPSPSETSPPTWSQHEKLLKLLCLLY																																																											
Ictpun	KSNAGVINTPTQKAEAEVEEIEIMNFGVEHRSRSLYLFVSTY																																																											
Gincir	NISTIVNEGQPLSLKLAFTY																																																											
Cypcar	TAKGPSPTCPDSEETM.OIGSDSEQISSLYVYVYAY																																																											
Danrer	SVIKPSGGDPTCPSTETPTISQESANPEKQSLQLFVYGY																																																											
Orycun	GTVLGAVEKRRKPSLGSNRTVLGTTDMBGKPHLGYAKDVLRLQLTNSVYVY																																																											
Musmus	VATTQWQKNDVLFQFTSAYVY																																																											
Homsap	DVTTVDPKYNYSKDNVDVITMDPKDNWSDANDLTLQLTNTSAYVY																																																											
Xenlae	SSIVVPGGENKVKTCNESSTDNMIYPPNAPASRAVLY																																																											
Galgal	ERSPQEQDCTQSGNSTVNRDHTHKAQLVY																																																											
											TM										CY																																							
Diclab1	TVLMVKSIVYCCGLSCLMI										FRNKGPSNTCTHAD																																																	
Diclab2	TVLMVKSIVYCCGLSCLMI										FRNKGPSNTCTHAD																																																	
Paroli	TVLMVKSIVYCCGLSCLMI										LRNRRPFAAHRTELPPAASTSH																																																	
Ictpun	VLLLVKNVLYFCTVFVLLF										KRNPAAKI																																																	
Gincir	TLLLVKSVVYCGIISI.LF										RLRHDRVKKPL																																																	
Cypcar	GVMIKNGLDVFCVGFIFLL										KKKAGRKKDESS																																																	
Danrer	AVMLKKNVLYFIVVIVLL										KKKAGRKKDESS																																																	
Orycun	LLLLLSSVYLAIVTFSLF										RRTADCSAEKSS																																																	
Musmus	LLLLLSSVYLAIVTFSLF										RRTSVCNGEKKSS																																																	
Homsap	LLLLLSSVYFAIITCCLL										RRTAFCCNGEKS																																																	
Xenlae	LLLLLSSVYFAIITCCLL										RPTKPCF																																																	
Galgal	VLLLVKSMYVIVLFFFF										KYRTATAAKFGSGKKT																																																	

Figure 2. Alignment of the predicted sea bass TR γ chain amino acid sequences with other known TR γ molecules. The position of the framework (FR) and CDR regions for the V-DOMAINS following the IMGT numbering are indicated above the sequences. Conserved amino acid residues are evidenced. Accession numbers: *Dicentrarchus labrax* clone 1 FR745889; *Dicentrarchus labrax* clone 2 FR751038; *Paralichthys olivaceus* AB076073; *Ictalurus punctatus* DQ435303; *Ginglymostoma cirratum* FJ513785; *Cyprinus carpio* ABD04398; *Danio rerio* AY973921; *Oryctolagus cuniculus* RABTCRG; *Mus musculus* MUSTCRGZZX; *Homo sapiens* S01895; *Xenopus laevis* AF440821; *Gallus gallus* GGU22666. doi:10.1371/journal.pone.0047957.g002

bass, the length of TRG CDR3-IMGT found in our sequenced clones varied between 9 and 15 amino acids (see Figure S1) and did not obviously follow the same trend as in mammals. In fact, the junction length spectratyping (Figure 3) showed that sea bass TRG CDR3 lengths are 8–18 AA (mostly 11–15), and TRG CDR3 length distribution is narrow, as already reported in the Japanese flounder and mammals. The conservation of this peculiarity, which has been associated to the direct antigen binding by $\gamma\delta$ T cells (while $\alpha\beta$ T cells are MH restricted [38]), may suggest that fish $\gamma\delta$ T cells recognize their targets as their mammalian counterparts. Additionally, a significant number of CDR3 sequences (9 among 35) were found several times in the Japanese flounder, suggesting that the repertoire of these receptors may be strongly constrained [15].

Our results show that TRG CDR3 length distributions are generally not gaussian-like as usually seen for other Ag-specific receptors in naive individuals. This is reminiscent of what was reported for TRG rearrangements implicating TRVG 3, 5, 8 and 9 genes from human spleen [39, Figure 4C]. Such irregular profiles were even found in the thymus, while a large unbiased diversity is observed in this tissues for example for TRB [40,54]. To our knowledge, TRG CDR3 length distributions have not been characterized from the thymus of other species. Hence, further studies will be necessary to determine if the thymic restriction of TRG repertoire is due to the particular rearrangement constraints of this isotype and represents a feature conserved through vertebrates. In any case, sea bass TRG CDR3 length spectratypes contains several peaks and show that the rearrangements expressed in thymus and gut are not restricted to one or two canonical sequences.

Furthermore, the spectratypes appeared to be different between thymus and gut of the same animal for a given V/C combination, which suggests that different repertoires are expressed in these tissues. To date, there is no evidence in fish for thymus-independent $\gamma\delta$ -T cell differentiation in the gut. At this stage, it is therefore not possible to decide if these odd distributions are due to selection pressures exerted on the $\gamma\delta$ T cells in both thymus and

gut, or if TRG rearrangements are strongly constrained at the recombination level, thus leading to skewed distribution in the thymus and, possibly, to tissue specific invariant TRG chain as observed in mouse skin and vaginal epithelium [37,41].

Regarding cathe interaction with TRD chain, the molecular modeling of sea bass TRG chain and its comparison with human TRG chain suggest whose regions in the V-DOMAIN and in the C-DOMAIN would be involved (1hxm, Contact analysis in IMGT/3Dstructure-DB, <http://www.imgt.org>) [42–43]. Among these regions, the segments located in the V-domain are identical or with conservative peptide changes in the sea bass sequences Diclab1 and Diclab2, whereas regions in the C-Domain of Diclab1 and Diclab 2 show clear differences in the content of charged side chains (see fig. 2 and fig. 4b). In the C domain a high number of basic and acidic amino acids that may interact with other chains in the TR/CD3 complex are present. Overall, these data suggest that the structural features of TRG domains involved in TR $\gamma\delta$ inter-chain interactions are conserved between fish and mammals.

The characterization of sea bass TRG expression in different tissues extends and confirms previous observations in carp and sea bass, [17,29,44]. The receptor appears to be predominantly expressed in thymus, where T cell lymphopoiesis occurs [45], and in mucosa. Investigating possible activities associated with TRG-bearing cells, our results show that in sea bass TRG expression in leukocytes can be modulated by poly I:C and, in turn, induction by poly I:C might indicate that IFN is involved. Indeed, human $\gamma\delta$ T cells express more TLR3 mRNA than $\alpha\beta$ T cells [46], and the TLR3 ligand enhance their *in vitro* activation via the stimulation of type I IFN production [47].

Interestingly, sea bass infection *in vivo* by a natural viral pathogen, the betanodavirus [30], induced significant modifications of the TRG expression in intestine and head kidney. These results are similar to observations reported in macaques after an *in vivo* infection with the simian immunodeficiency virus (SIV). In this model, the SIV infection resulted in a fast decrease of $\gamma\delta$ T cell mRNA levels at mucosal sites, and in an increase at lymphoid sites, suggesting a rapid redistribution of $\gamma\delta$ T cells after the infection [48]. In the same line, our results in sea bass may be interpreted as either a true down regulation and/or a migration of $\gamma\delta$ T cells out of the tissue. Additionally, the TRG up regulation in the head kidney may be partly due to a higher transcription rate of the gene in activated cells. In helping to have new knowledge on this, future experiments the anti- sea bass T cell mAb DLT15 [44] will be employed in for the *in situ* labelling of immunoreactive cells during *in vivo* and *in vitro* stimulations.

In conclusion, the identification of TRG gives the possibility to investigate on the presence and functions of new T cell subsets in sea bass. In particular, our results indicate that sea bass $\gamma\delta$ T cells are affected by the interferon response, and are probably involved in virus-induced immunity. Future studies will address the importance of these cells for the immunity to infections in fish.

Methods

Sea Bass TRG Chain Cloning and Sequence Analysis

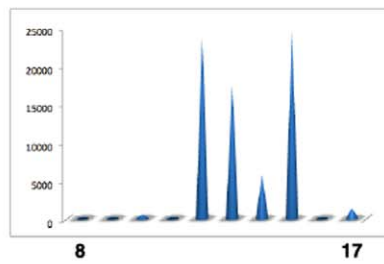
Two primers (TRGF1:5'- GAGGAACTGACCAGTGTAG -3' and TRGR1:5'- AGCAAGAGAGTCCACAGCA -3') corre-

Table 2. Sequence of primers used to study different V and C combinations.

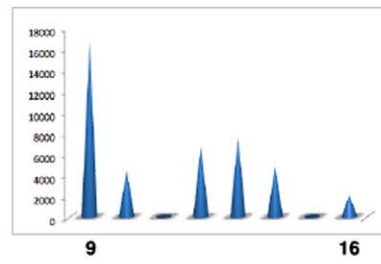
Name	Sequence (5'-3')	Note
VG1.1&2	GWTATTGGTAGGAGTAATG	W = A/T
VG1.3&4	CTTTATTTTAAACAAGACWCYTG	W = A/T, Y = C/T
VG1.5	TGATAAGAGTAATGGTCGAGTTG	
VG1.6 ext	GTGTAGTCTTCTGTAATC	
VG1.6 int	CCAGTACATCGAGTAAGATG	
CGfluo	TATGTAACAGATGAGCAGATAGTG*	
CG1&4&5	TGTACAGCCACCATCTTCGW	W = A/T
CG2&3	CGCACCACTCCATCTTGCT	
CG3	CAGCAGCTCTGCTCCAGAG	
CG5	CGTCTCCAACATCACTTCCA	

doi:10.1371/journal.pone.0047957.t002

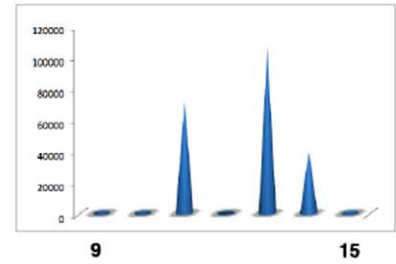
Thymus



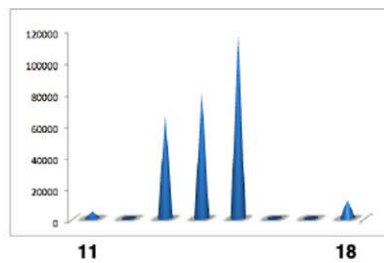
V1/2-C2/3



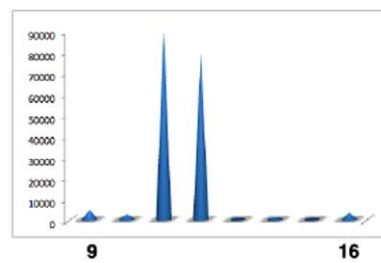
V1/2-C3



V1/2-C5

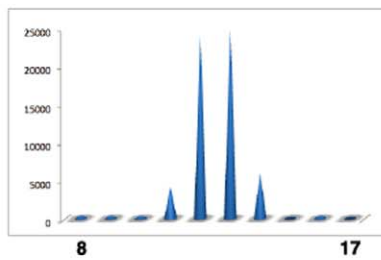


V1.5-C3

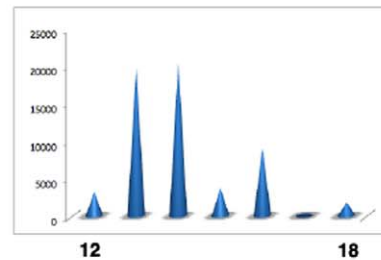


V1.5-C5

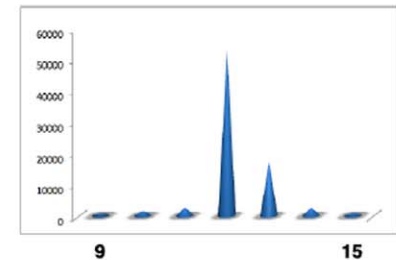
Gut



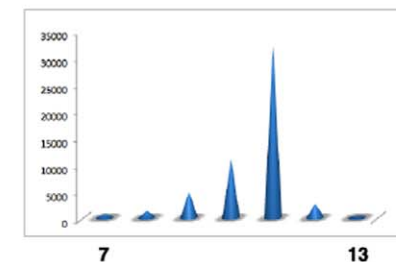
V1/2-C2/3



V1.5-C2/3



V1/2-C5



V1.6-C4/5

Figure 3. Spectratyping analysis of the γ TR diversity in gut and thymus of healthy fish. CDR3 length distribution profiles of γ transcripts for selected $V\gamma-C\gamma$ combinations in naive thymus and gut. Typical results from the same fish are shown. Y-axis: fluorescence arbitrary units, x-axis: CDR3 size, with values indicated for the smallest and longest CDR3 amplified in each profile. doi:10.1371/journal.pone.0047957.g003

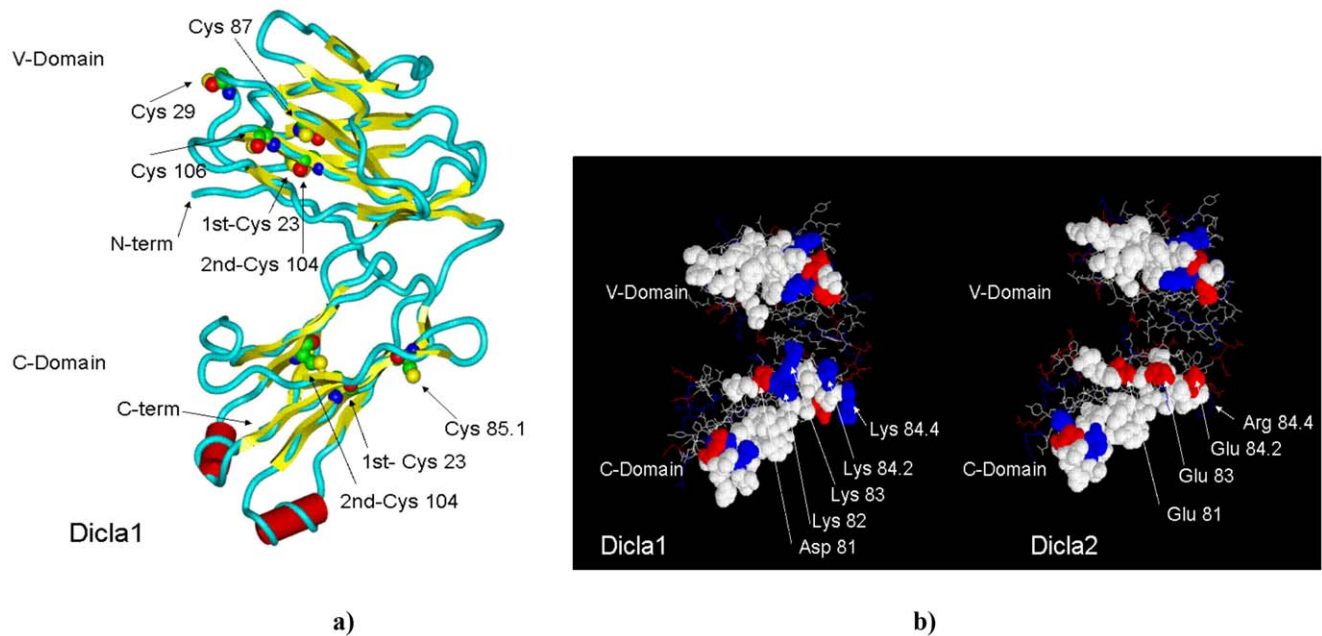


Figure 4. 3D model of sea bass TR γ chain. Panel a). 3D model of sea bass Dicla1. The backbone ribbon and secondary structure topology are shown: yellow arrows represent β -strands and red cylinders represent α -helices. The Cys residue are evidenced along the sequence. Panel b). Amino acid residues putatively involved in the interactions with TR δ chain in both Dicla1 and Dicla2 sea bass TR γ sequences are represented as space-fill balls. The basic and acidic amino acid residues have been indicated in blue and red, respectively. Arrows and labels indicate the charged amino acids of the evidenced areas in the two sea bass TR γ sequences.
doi:10.1371/journal.pone.0047957.g004

sponding to highly conserved regions of known TRG genes were used in RT-PCR on total RNA extracted with Trisure (Bio-line) solution from the thymus of a juvenile sea bass (150 g of weight). The leukocytes from thymus were obtained following procedures already described [49]. RT-PCR was performed using Ready-To-Go RT-PCR Beads (GE Healthcare). For cDNA synthesis, 1 μ g of total RNA and 0.5 μ g of random primers [pd(N)₆] were used in each reverse transcription reaction in a total volume of 50 μ l. Reactions were conducted using the Mastercycler personal (Eppendorf). The cycling protocol was one cycle of 94°C for 5 min, 35 cycles of 94°C for 45 s, 54°C for 45 s, 72°C for 45 s, followed by one cycle of 72°C for 10 min. PCR products (15 μ l) were visualised on 1% (w/v) agarose gels containing Gel Red using hyperladder IV (Bioline) as size marker. Controls for the presence of DNA contamination were performed using the RNA samples as template in the PCR cycle. DNA amplified by PCR was purified using the QIAquick Gel Extraction Kit (QIAGEN), inserted into the pGEM-T Easy vector (Promega) and transfected into competent JM109 *Escherichia coli* cells. Plasmid DNA from at least ten independent clones was purified using the Wizard Plus SV Minipreps DNA Purification System (Promega) and sequenced using MWG DNA Sequencing Services. Sequences generated were analysed for similarity with other known sequences using the BLAST program [50].

A RACE-PCR was performed to obtain the complete TRG chain sequence. cDNA was synthesised from total thymus RNA with the First-strand cDNA Synthesis kit (GE Healthcare) following the manufacturer's instructions. For 3' RACE-PCR, cDNA was transcribed using an oligo-dT adaptor primer (5'-CTCGAGATCGATGCGGCCGCT₁₅-3'). PCR was performed with the TRGF1 primer and the oligo-dT adaptor primer. For 5' RACE-PCR, cDNA was transcribed from total RNA using the oligo-dT primer, treated with *E. coli* RNase H (Promega), purified using a PCR Purification Kit (QIAGEN), and tailed with poly(C) at

the 5' end with terminal deoxynucleotidyl transferase (TdT, Promega). PCR was performed with TRGR1 primer and an Oligo-dG primer (5'-GGGGGGIGGGIIGGGIIG-3'). Sequencing and similarity searches were performed as described above. The expression of these sequences was confirmed by PCR using primers that amplify the complete coding sequence (data not shown).

The obtained TRG cDNA sequences were analysed for the presence of a signal peptide, using SignalP software [51], and of N- (with the NetNGlyc 1.0 Server) and O-linked glycosylation sites [52]. The TRG nucleotide and amino acid sequence were compared with counterparts in other vertebrate species with the EMBOSS Pairwise Alignment tool. Alignment of the sea bass TRG amino acid sequences to other known molecules from other species was carried out using MEGA 4.1 Software [53].

CDR3 Length Spectratyping Analysis

The spectratyping of sea bass TRG CDR3 length was previously adapted for rainbow trout TRB [54]. A first amplification using a forward primer specific for a TRV γ sequence in combination with a reverse primer specific for a TRC γ sequence (see Table I for the primer combinations), was performed as follows: 1 μ l cDNA was used as template for PCR1 using 0.4 mM of each dNTP, 0.4 μ M of each primer (forward: TRG V, reverse: TR γ C), and 0.025 μ l⁻¹ of GoTaq DNA polymerase (Promega) in 1x reaction buffer with 2 mM of MgCl₂ (95°C for 5 min; 40 cycles of 95°C 45 s, 60°C 45 s, 70°C 45 s; 70°C 10 min) (see Table I for primer sequences). This first PCR amplifies sequences for a given TRGV- TRGC combination but with different TRGJ content and diverse CDR3 lengths. In a second step, these PCR products are subjected to run-off reactions using 5' 6-FAM-fluorescent internal, isotype TRGC-specific, reverse primers. Two μ l of product of the first PCR were used as template using 0.4 mM

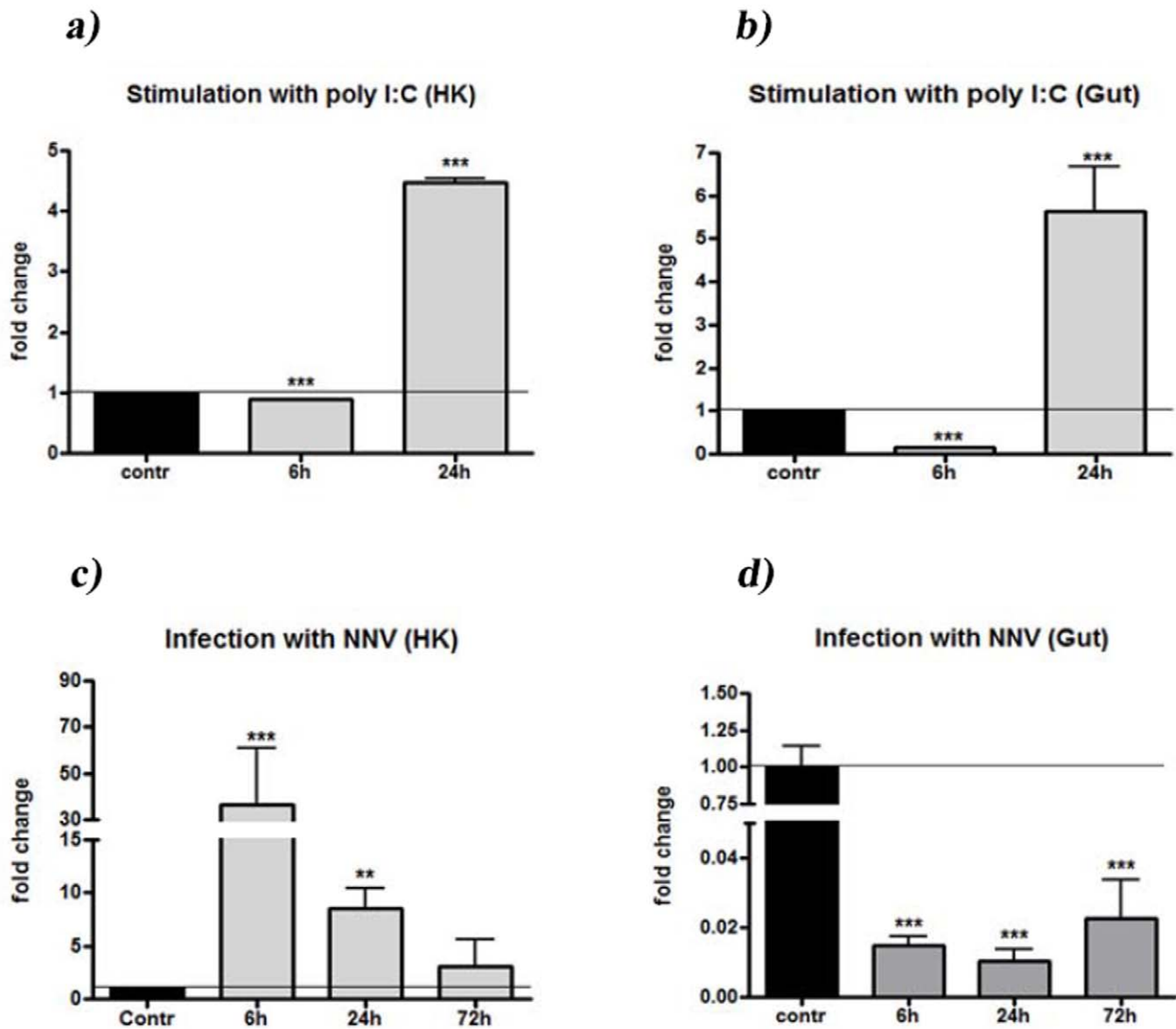


Figure 5. TRG expression analysis. Panel a) and b). Stimulation with poly I:C. TR γ mRNA levels expressed as a ratio relative to rRNA 18 levels in the same samples after real-time PCR analysis of head kidney and gut leukocytes stimulated with PBS (control) and with 20 μ g/ml of poly I:C for 6 and 24 h and normalised against the non-stimulated 0 h control. Data are expressed as the mean \pm SD; one asterisk indicates when $p < 0.05$ with respect to the time 0 control; two asterisks indicate when $p < 0.01$ with respect to the time 0 control and three asterisks indicates when $p < 0.001$ with respect to the time 0 control. Panel c) and d). Infection with betanodavirus. TR γ mRNA levels as a ratio relative to rRNA 18 levels in the same samples after real-time PCR analysis of head kidney and gut leukocytes in control fish and in infected fish at different sampling times. Data are expressed as indicated above for panel a) and b).
doi:10.1371/journal.pone.0047957.g005

of each dNTP, 10 pmoles of the fluorescent reverse primer, and 0.025 μ g/ml of GoTaq DNA polymerase (Promega) in 1x reaction buffer with 2 mM of $MgCl_2$ (95°C for 5 min; 5 cycles of 95°C 1 min, 60°C 1 min, 70°C 2 min; 70°C 10 min). Two μ l of run-off product were mixed with 8 μ l deionized formamide (Applied Biosystems) and 0.5 μ l of the internal standard (GeneScanTM 500XL ROX, size standard, Applied Biosystems). Mix was denatured at 95°C for 5 min and placed on ice before analysis in an ABI 3730HT sequencer (Applied BioSystems) at GeT-PlaGe core facility, Toulouse, France. CDR3 length distributions were analyzed using GeneMapper (Applied BioSystems) and ISEApeaks software [55] extract and analyze spectratype data for each VH-C combinations. Each spectratype or profile is composed of several peaks (typically 4 to 10 for VH-C μ and VH-C δ , and 5 to 13 for

VH-C τ) separated according to their corresponding length of run-off products, spaced by 3 nucleotides as expected for in-frame transcripts.

Three-dimensional Modeling of Sea Bass TRG Chain

Molecular modeling of sea bass TRG chain was performed in agreement with well established procedures, previously described in our works [56–58]. The experimental model from PDB data bank related to the Human V γ 9V δ 2 T cell receptor (code 1HMX, chain B), was chosen as the template for the comparative modeling strategy. The percentage of sequence identity (27%) required special care for the alignment of the sequences, in order to verify its quality before the successive modeling procedures. The alignments obtained by different free available software (BLAST,

EMBOSS Align, ClustalW) were compared and, finally, the alignment with the right position of the cysteine residues involved in the disulphide bridges was chosen. Modeller9v5 (<http://salilab.org/modeller/>) was used to create models of both the identified sea bass TRG chain sequences, after the removal of the 1–19 segment (signal peptide, not present in the template structure). The best model was selected by verifying the quality of the models in terms of stereochemistry, by using PROCHECK software [59] and in terms of energy, by using PROSA-web server [60]. Further analysis of the model was performed with tools for the visualization and evaluation of structural parameters.

In vitro and *in vivo* TRG Expression Analysis

The *in vitro* TRG expression was studied on head kidney (HK) leukocytes obtained from five sea bass juveniles as already described [49]. Fish were purchased from a local fish farm (Civita Ittica Srl, Civitavecchia, Italy), lethally anaesthetised with phenoxyethanol (100 ppm), and organs removed and placed in cold HBSS. Head kidney and gut leukocytes were adjusted to 1×10^5 cells/ml and incubated at 18°C for 6 h and 24 h with 20 µg/ml of poly I:C (Sigma). Leukocytes from kidney and the intestinal tract (whole, excluding stomach) were obtained as previously described [30]. The control was stimulated with PBS only at the same time points. Total RNA was isolated with Trisure (Bio-line) after stimulation periods, resuspended in DEPC-treated water and used for real-time quantitative PCR without pooling the samples coming from the different flasks. Controls for the presence of DNA contamination were performed with RT-PCR using β -actin primers that span an intron (ACTFOR: 5′ –ATG-TACGTTGCCATCC- 3′; ACTRV: 5′-GAGATGC-CACGCTCTC- 3′).

The *in vivo* TRG expression was studied on head kidney (HK) and gut leukocytes obtained from five sea bass juveniles experimentally infected with betanodavirus (nervous necrosis virus, NNV) [30]. Sea bass samples for TRG expression were from *in vivo* experiments previously performed and already described in details [30]. From each individual fish the head kidney and gut were removed after infection with NNV at hours: 0, 6, 24, 72. The tissue was immersed in 1 ml of Trizol, labelled, immediately frozen in liquid nitrogen and stored at –80°C until further use. Total RNA was extracted as described before.

For reverse transcription, the BioScript RNase H minus (Bioline) enzyme was used with the with the protocol described in [56]. The expression level of the target genes was determined with a Mx3000P™ real time PCR system (Stratagene) equipped with version 4.0 software and using the Brilliant SYBR Green Q-PCR Master Mix (Stratagene) following the manufacturer's instructions, with ROX as internal passive reference dye. Specific PCR primers were designed for the amplification of about 200 bp

products from the constant region of sea bass TRG (TRGF2:5′ –CTGCTGTGTGTGGCCTCAGAC- 3′ and TRGR2:5′ –GTGCTGGACGGAGCAGTGGTA- 3′) and sea bass ribosomal RNA 18S (RIBFR: 5′ –CCAACGAGCTGCTGACC- 3′ and RIBRV: 5′ –CCGTTACCCGTGGTCC- 3′), used as a house-keeping gene. Ten ng of cDNA template were used in each PCR reaction. The PCR conditions were 95°C for 10 min, followed by 35 cycles of 95°C for 45 s, 52°C for 45 s and 72°C for 45 s. Triplicate reactions were performed for each template cDNA and the template was replaced with water in all blank control reactions. The analysis was carried out using the endpoints method option of the Mx3000P™ software that causes the collection of the fluorescence data at the end of each extension stage of amplification. A relative quantitation has been performed, comparing the levels of the target transcript to a reference transcript (calibrator: the time 0 control for the stimulations and the not treated specimens for the virus infection). A normalizer target (the ribosomal RNA transcript) is included to correct for differences in total cDNA input between samples. The results are expressed as the mean \pm SD and the differences from the controls have been considered significant if $p < 0.05$ using a statistical analyses performed by the one-way ANOVA followed by the Bonferroni test. The real-time PCR products from the different experiments were examined by agarose gel electrophoresis to investigate their specificity and size.

Ethic Statements

Fish for *in vitro* experiments were purchased from a local fish farm (Civita Ittica Srl, Civitavecchia, Italy), lethally anaesthetised with phenoxyethanol (100 ppm), and organs removed and placed in cold HBSS.

The samples of the *in vivo* work came from experiments described in Scapigliati et al., 2010. Experiments were performed at the research facilities of CIFPA El Toruño, Cadiz, Spain, during the EU funded project “IMAQUANIM”, and were approved by the IMAQUANIM consortium.”

Supporting Information

Figure S1 Multiple alignment of TRG sequences with different V and C sequences from RACE cloning or genomic contigs (noted .Gen).

(TIF)

Author Contributions

Conceived and designed the experiments: GS FB PB. Performed the experiments: FB ER RC AF. Analyzed the data: GS PB FB ER M-PL AS. Wrote the paper: GS FB PB. Supplied genomic resources: HK RR.

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