Characterization of Carp (Cyprinus carpio L.) Immunoglobulin Structure

Sang-Hoon Choi*, Kwan-Ha Park and Jong-Man Yoon
Department of Marine Biomedical Science, Kunsan National University, Kunsan 573-400, Korea

ABSTRACT: Serum immunoglobulins (Igs) from Israeli carp were purified using affinity chromatography. Fish were immunized with purified mouse IgG, and the specific fish antibodies were purified from the immune serum on a mouse IgG-immobilized agarose gel. Rabbit anti-Israeli carp Igs (R α I. carp Igs) antibodies were produced following hyperimmunization with mouse IgG specific carp antibodies. SDS-PAGE analysis under reducing condition showed that Israeli carp Igs were composed of two μ-like heavy chains with about 82 and 50 kd, respectively, and one light chain with about 25 kd. On immunoblotting analysis, however, R α I. carp Igs failed to react with the light chain. When both protein A and protein G-purified normal carp Ig were compared with mouse IgG-specific Israeli carp Ig, no significant structural differences among them were observed. To investigate if there is any homology between other fish Ig molecules, cross-reactivity of R α carp Ig, no significant structural differences among them were observed. To investigate if there is any homology between other fish Ig molecules, cross-reactivity of R α I. carp Igs against Ig molecules from 6 different fish sera and mouse control serum was checked on immunoblotting analysis. As a result, R α I. carp Igs responded to Israeli carp, common carp, and tilapia Ig molecules. In flow cytometry study, however, R α I. carp Igs appeared to recognize 42.0%, 35.8% and <5% of Israeli carp, common carp and tilapia Ig' head kidney cells, respectively. The result suggests the heterogeneity between receptor Igs on B-like lymphocytes and soluble Igs in serum. It is crucial to obtain pure fish Igs to produce reagent antibodies as tools for the study on their specific immune responses.

KEY WORDS: Affinity Chromatography, Flow Cytometry, Carp Ig, Tilapia

INTRODUCTION

Fish are a heterogeneous group of vertebrates that include hagfish, lampreys, cartilaginous fish, and bony fish; all of which are capable of mounting antibody responses (Warr and Marchalonis, 1982). In past years, much has been learned about the antibodies and the genes encoding them in the elasmobranchs and the teleosts. Information in the case of the hagfish and lampreys is still rather incomplete and difficult to interpret, in that the definitive characterization of the molecules in these species, described as antibodies or immunoglobulins (Igs) (Marchalonis and Edelman, 1968; Raison et al., 1978; Hanley et al., 1990; Varner et al., 1991) remains to be completed. The predominant Ig in the blood of teleosts and most sharks is an IgM-like molecule. It consists of equimolar amounts of heavy (μ) and light (L) chains arranged in a basic unit containing 2 μ and 2 L chains. IgM exists either in polymeric forms, a tetramer (μ2L2)4 in teleosts, and pentamer (μ3L)5 in sharks, or in monomeric forms (μL2) in sharks and some teleosts (Warr and Marchalonis, 1982). In the teleosts, where the antibody response has been studied quite thoroughly, there is no reason to think that these low molecular weight Igs are either the structural or functional equivalents of mammalian IgG.

The structure and function of fish IgM is of special interest, this being the first Ig to appear in evolution and the only Ig class of lower vertebrates. It has been demonstrated that there is a significant homology between the amino acid sequence of IgMμ chain from very diverse species (Bengten et al., 1991; Andersson and Matsunaga, 1993; Lee et al., 1993). Bourmaud et al. (1995) reported the purification of an IgM-like Ig from sea bass, but no characterization of the molecule was provided except its native molecular weight. As for the family Sparidae, a few complete studies are available in the literature (Lobb and Clem, 1981). Thus far, most teleostean serum Igs have been characterized as tetrameric IgM-like macroglobulins with molecular weights between 600 kd and 800 kd (Acton et al., 1971; Litman, 1976; Dorson, 1981). However, heterogeneity has been reported for the heavy and light chains from some fish species (Kobayashi et al., 1982; Lobb et al., 1984; Lobb and Olson, 1988; Sanchez et al., 1989) as well as the presence of different covalently linked IgM forms (Glynn and Pulsford, 1990; Clem and McLean, 1975). In addition, low molecular weight Igs have been described (Clem and McLean, 1975; Warr, 1983). Affinity chromatography techniques have previously been used for the purification of fish antibodies. Among them, variable results have been obtained with protein A-based methods depending on the particular fish species (Suzuki et al., 1990; Estevez et al., 1993; Estevez et al., 1993b). These techniques are improved when a specific interaction of antigen-antibody molecules is involved. The molecule attached to the insoluble support matrix may be an antibody or an antigen against which the fish antibody has been produced (Kofod et al., 1994). In the present study, carp antibodies were produced...
against mouse IgG and purified by mouse IgG-coupled Sepharose 4B, protein-A or G affinity column chromatography. The structural properties of carp Igs were investigated on the basis of electrophoretic analysis. Furthermore, to compare structural homologies between Igs in carp serum and those in other different fish species sera, we used rabbit antibodies against carp Igs. In addition, a flow cytometry analysis was performed to study whether B-like lymphocytes with surface Ig receptors are present in head kidneys from various kinds of fishes as well as carp.

The purpose of the present work was to characterize serum Igs of Israeli carp for the study of their specific immune response.

**MATERIALS AND METHODS**

**Production of fish immune sera**

Five adult two-year-old *Cyprinus carpio* L. (mean weight 500-600 g) were maintained in tanks under controlled temperature (18-20°C). Fish were fed a standard commercial diet and were acclimatized to experimental conditions for at least two weeks before immunization. Fish were injected intraperitoneally on day zero with 200 µg of purified mouse IgG (Sigma, U.S.A.) per fish, in 0.2 ml of a 1:1 emulsion in Freund's complete adjuvant (FCA). Boosters were injected on days 7, 14 and 21 with the same doses of mouse IgG in Freund's incomplete adjuvant (FIA). Final booster was challenged on days 28 with the same doses of mouse IgG in 0.2 ml of sterile Hank's balanced salt solution (HBSS). Following each boosting injection, serum samples were harvested for their serological study. Control fish received 0.2 ml of HBSS in each injection. Both immunized and control fish were anaesthetized with MS-222 (Sigma) on day 40, and bled to death from the caudal vein, using non-heparinized syringes. The blood was allowed to clot at 20°C and then at 4°C.

**Purification of fish Ig**

Fish anti-mouse IgG antibodies were purified by affinity chromatography as described by Smith et al. (1993). Briefly, 2 ml each of mouse IgG, protein A, or protein G-coupled agarose-beads (Sigma) were gravity-packed on a 10×0.5 cm syringe column, respectively, washed with 200 ml of 0.01 M phosphate buffered saline, pH 7.2 (PBS) containing 0.5 M sodium chloride (equilibration buffer) and then stripped with 20 ml of 0.1 M glycine-NaOH, pH 11 (elution buffer). After re-equilibrating the column, 2 ml of pooled immune fish sera were diluted 1:1 with equilibration buffer, 0.22 µm-filtered and applied to the column. The column was washed again with equilibration buffer, until the baseline was restored. Bound proteins were then eluted with 5-10 ml of elution buffer, and collected in one fraction over 1 ml of 0.1 M Tris-HCl, pH 7.2 (neutralization buffer). The proteins were concentrated and changed to a physiological environment (20 mM Tris-HCl, pH 7.2, 0.15 M NaCl, 0.01% thimerosal) by diafiltration (Centriprep-100 concentrators, Amicon, Beverly, MA, U.S.A.) following manufacturer instructions. Protein content of the concentrates was determined by the method of Bradford (1976) (Protein Assay kit, BioRad), sterile-filtered and stored at 4°C until used.

**Rabbit antiseras preparation**

New Zealand rabbits were subcutaneously injected on day zero with 250-300 µg of affinity-purified fish Igs emulsified 1:1 in FCA, in a total volume of 1 ml per rabbit. Animals were boosted in the same way on days 14 and 34 with the antigens prepared in FIA, and on day 45 without adjuvant. Blood samples were taken on days zero (preimmune serum), 41 and 52 by ear vein puncture, and the sera prepared as described above. The titer was determined by ELISA according to the method of Palenzuela et al. (1996).

**SDS-PAGE**

To identify whether fish Igs were efficiently purified by affinity chromatography, 10% denatured polyacrylamide gel electrophoresis was performed according to the Laemmli (1970) method.

**Immunoblot analysis**

The structural properties of fish Igs were investigated by immunoblot analysis. Total fish serum proteins and affinity-purified Igs were reduced and denatured by 5-6 min boiling in loading buffer (62 mM Tris-HCl, pH 6.8, containing 2% [w/v] SDS, 10% [v/v] glycerol, 0.05% [w/v] bromophenol blue and 0.1 M dithiothreitol) and electrophoresed on preparative 10% polyacrylamide gels, and electrotransferred to 0.45 µm nitrocellulose membranes (BioRad) for 1 h at 250 mA. Membranes were blocked for 1 h at room temperature (RT) in Tris-buffered saline (TBS) containing 5% skimmed milk, washed in TBS and mounted in a screening device (Miniprotein II multiscreen apparatus, BioRad). Serial twofold dilutions in TBS of the different rabbit antisera were applied to the channels and incubated for 3 h at RT. After washing, goat anti-rabbit IgG-AP conjugate diluted 1/3000 in TBS, pH 7.5, containing 0.05% (v/v) Tween-20 and 3% skimmed milk (S-TTBS) was delivered to the channels, incubated for 2 h at RT and washed. The membranes were rinsed again in TBS, and the presence of immune complexes detected by incubation in substrate (NBT&BCIP) (Promega, Madison, WI) for 15 min.

**Flow cytometry analysis**

In order to study whether Raf carp Igs recognize
surface Ig receptor on fish B-like cells, flow cytometry analysis was performed with fish head kidney and spleen cells. Aliquots of $5 \times 10^5$ cells were labelled for 30 min on ice with RαI, carp Igs. After washing, cells were incubated for 30 min on ice with fluorescein-conjugated goat anti-rabbit IgG. The fluorescence of $10^4$ viable cells was measured by flow cytometry (FACScan; Becton Dickinson Immunocytometry Systems, Mountain View, CA).

RESULTS

Two heavy chains of Israeli carp Igs

Israeli carp Igs purified by mouse IgG-, protein A-, or protein G-agarose affinity chromatography were electrophoresed. Israeli carp Igs were identified to be composed of two heavy chains (82 and 50 kd) and one light chain (25 kd) (figures 1 and 2A). The band pattern of Protein A-purified Igs was somewhat different from that of protein G-purified Igs, i.e., 50 kd band was clearly observed in the sample of protein G-purified Igs, but not in that of protein A-purified Igs (figure 2A). However, in the immunoblot analysis, 50 kd heavy chain band was identified (figure 2B), suggesting a possibility that protein A and G can recognize different fish Ig molecules, respectively. Figure 3 shows the result of immunoblot analysis for affinity-purified Israeli carp Igs. Two non-identical heavy chains (82 and 50 kd) were detected, whereas no light chains were observed in any three different samples. RαI, carp Igs did not cross-react with purified mouse IgG or catfish Igs.

Figure 1. SDS-PAGE for carp Igs purified by mouse IgG-agarose affinity chromatography. Lane 1, protein marker; 2, purified mouse IgG for control; 3, mouse IgG-specific carp Igs. Protein bands were silver stained.

Figure 2. SDS-PAGE (A) and Immunoblot analysis (B) for affinity chromatography-purified carp Igs. Panel A, proteins bands stained with Coomasie blue; Panel B, goat anti-rabbit IgG-alkaline phosphatase-stained same protein samples used in the panel A. Lane 1, mouse IgG; 2, protein G-purified carp Igs; 3, protein A-purified carp Igs.

Figure 3. Immunoblot analysis for affinity chromatography-purified carp and catfish Igs, and their sera. Lane 1, mouse IgG; 2, carp serum; 3, catfish serum; 4, protein G-purified carp Igs; 5, mouse IgG-agarose-purified carp Igs; 6, protein G-purified catfish Igs.

mouse IgG or catfish Igs. In order to investigate whether the purified fish Igs were contaminated with other protein molecules or composed of two different intra-heavy chains,
non-denatured SDS-PAGE was performed. As shown in figure 4, only one band appeared at over 220 kd, suggesting that purified fish Igs were not contaminated but constructed of two non-identical heavy chains. However, the possibility of the presence of two different Ig molecules in fish serum was not excluded.

**Homology between tilapia Igs and Israeli carp Igs**
To investigate structural homologies among fish Igs, six different fish sera were electrophoresed followed by immunoblotting with RαI carp Igs. As shown in figure 5A, serum proteins of Israeli carp and tilapia appeared similar to those of common carp. In immunoblot analysis, two heavy chains (82 and 50 kd) from Israeli carp, common carp and tilapia Igs were detected, but not from mouse Igs as well as other fish Igs (figure 5B). No light chains from the three fish Igs were observed.

**Alteration in Ig structure following the time-based immunization**
Two carp were periodically immunized with purified mouse IgG. Fish blood samples were collected following each time of antigen immunization. To identify how isotypes and protein concentration of carp Igs were altered after immunization of antigen, electrophoresis and immunoblot analysis were performed. As shown in figure 6A, the band patterns of serum proteins were observed with a slight difference, especially in lane 4, 4’ and 5’. Figure 6B shows the result of immunoblot analysis on the same samples used in figure 6A. Unexpectedly, no change of Ig isotype or concentration was detected following incubation of RαI carp Igs with serum samples.

**Flow cytometry analysis**
In order to investigate whether serum Igs in fish are also expressed on fish B-like cell surfaces like mammalian, we labeled carp and other fish head kidney cells with RαI carp Igs. Both common and Israeli carp kidney cells appeared Ig receptor positive, whereas rabbit antibodies failed to react with tilapia cells, suggesting a structural disparity of epitopes present on serum Igs and cell surface Ig receptor (table 1). As expected, no cross-reaction of rabbit antibodies was observed against other fish B-like cells (table 1).

**DISCUSSION**
The structure and function of IgM is of special interest, this being the first Ig to appear in evolution and the only Ig class of lower vertebrates. It is generally accepted that the major serum IgM of teleosts has a tetrameric form with a molecular weight (MW) between 600 and 900 Kd (Rombout et al., 1993; Navarro et al., 1993; Koumans-van Diepen et al., 1995; van der Heijden et al., 1995). The major plasma Ig found in fish is a molecule that is generally called
IgM. It consists of $\approx 70,000$ relative molecular mass (Mr) heavy chains ($\mu$) and $\approx 22,000$--25,000 Mr light chains (L) in equimolar amounts. IgM has been isolated (and at least partially characterized) from many species of fish, both chondrichthyan and osteichthyan, and much of the earlier work is summarized and referenced (Sigel et al., 1972). In the present study, we developed polyclonal rabbit antibodies against carp Igs which were purified by protein A affinity chromatography and characterized structural properties of fish Igs on a reduced SDS-PAGE. Differently as stated in references above, two heavy chains (82 and 50 kd) and one light chain (25 kd) were observed in carp Igs. The result suggests that carp Igs are composed of two different heavy chains and one light chain. Antibodies are among the most structurally complex of biological molecules. This complexity transcends their final protein form and includes the intricate genetic mechanism required to produce the wide repertoire of antibodies. The need for such complexity is obvious, for within their structures must lie the ability to bind a virtual universe of pathogens and ensure their destruction and removal. The construction and function of such large (-1,000 kd) and complex molecules have yet to be fully delineated even for the well-studied murine and human systems. Therefore, more works should be performed to identify whether two different heavy chains are formed by inter-disulfide bonds in one Ig molecule or two non-identical isotypes of Ig are present in Israeli carp serum. In a native SDS-PAGE analysis, only one protein band was detected, indicating that the purified fish Igs were not contaminated by some other proteins but are internally constructed with two different heavy chains. Nonetheless, we still cannot exclude the possibilities of existence of two non-identical heavy chains in one Ig molecule or different Ig isotypes because native electrophoresis itself is not good enough to prove monospecific protein molecules in one band on the gel. To ascertain the exact structural properties of fish Igs, two-dimensional electrophoresis is being conducted in our laboratory.

On the immunoblot analysis, two heavy chains were clearly observed, whereas a light chain was not done by rabbit anti-carp Igs, suggesting a possibility that fish light chains might not contain immunodominant epitopes to elicit a humoral immune reaction against rabbit. Moreover, unlike mammalian, fish light chains did not appear to be clearly stained with Coomassie blue on the gel, indicating that light chains might contain a large amount of carbohydrate or other molecules. It is, therefore, likely that the prothetic

---

**Table 1.** Flow cytometry analysis for binding of rabbit anti-Israeli carp IgG to surface Ig receptors on fish B-like cells

| Fishes  | Cells | Rel. clgs (%)* |
|---------|-------|---------------|
| I. Carp | K     | 42.0          |
|         | S     | 35.4          |
| Carp    | K     | 35.8          |
|         | S     | 26.4          |
| Rainbow trout | K | 0.5 |
|         | S     | 0            |
| Catfish | K     | 1.0          |
|         | S     | 0.5          |
| Tilapia | K     | 4.3          |
|         | S     | 4.8          |
| Flounder| K     | 0            |
|         | S     | 1.3          |

* Normal rabbit IgG was used as a negative control. The number of cells applied in the reaction was $5 \times 10^5$. GoatIgG-FITC was used for identifying Ig receptor positive cell population. K, kidney cells; S, spleen cells.

The results are representative of three experiments.
groups such as carbohydrate or lipid around protein epitopes hinder an induction of immune reaction.

Although tilapia, Oreochromis niloticus has been developed quite differently from carp, Cyprinus carpio, the electrophoretic patterns of serum proteins from each fish were nearly identical. Furthermore, rabbit antibodies against carp Ig recognized tilapia Ig as well as Israeli carp Ig with a same degree. The result suggests that electrophoretic band patterns of fish serum proteins can be a good tool of classifying fish species. Although specific features of the immune response may vary widely between piscine species, the humoral immune response does share some basic features in form and function with that of mammals. These similarities include basic Ig structure, the cellular requisites for the induction of antibodies, and the role played by these antibodies in such activities as neutralization, complement fixation and opsonization. Many teleosts have been reported to possess only high molecular weight IgM which has a molecular weight of about 700 kd (Amemiya and Litman, 1990; Pilstrom and Petersson, 1991), and a molecular weight shift during the immune response has not been reported. However, some teleosts possess low molecular weight Igs which are found to be either a monomeric form of high molecular weight Ig or to be a physicochemical form distinct from high molecular weight Ig (Clem and McLean, 1975; Warr, 1983). In the present study, we investigated if a molecular weight shift during the immune response occurs on carp Ig structure. While, as time elapses following antigen challenge, the amount of some serum proteins were changed and other protein bands appeared, no molecular weight shift of carp Ig was observed on immunoblot analysis. The result suggests that carp Ig is not switched into other kinds of Ig isotypes.

In flow cytometry analysis, rabbit antibodies which reacted with tilapia serum Igs did not recognize tilapia cells, indicating that immunodominant epitopes present on serum Igs and cell surface Ig receptors are not identical. Expectedly, the rabbit antibodies recognized common carp mononuclear cells other than Israeli carp cells, suggesting that both fishes share same Ig structural properties irrespective of serum Igs or cell surface Ig receptors.

In conclusion, structural properties of carp serum Igs were characterized on the basis of an electrophoretic mobility and a flow cytometry analysis. It is crucial to obtain and characterize pure fish Igs to produce reagent antibodies as tools for the study of their specific immune responses.

ACKNOWLEDGEMENT

This work was financially supported by Korea Sea Grant Program (KSGP) from Ministry of Maritime Affairs and Fisheries.

REFERENCES

Acton, R. T., P. F. Weinheimer, S. J. Hall, W. Niedermeier, E. Shelton and J. C. Bennet. 1971. Tetrameric immune macroglobulins in three orders of bony fishes. Proc. Natl. Acad. Sci. U. S. A. 68:107-111.

Amemiya, C. T. and G. W. Litman. 1990. Complete nucleotide sequence of an immunoglobulin heavy-chain gene and analysis of immunoglobulin gene organization in a primitive teleost species. Proc. Natl. Acad. Sci. USA. 87:811-815.

Andersson, E. and T. Matsunaga. 1993. Complete cDNA sequence of a rainbow trout IgM gene and evolution of vertebrate IgM constant domains. Immunogenetics 38:243-250.

Bengten, E. T., Leanderson and L. Pilstrom. 1991. Immunoglobulin heavy chain cDNA from the teleost Atlantic cod (Gadus morhua L.): nucleotide sequences of secretory and membrane form show an unusual splicing pattern. Eur. J. Immunol. 21:3027-3033.

Bourmaud, C. A., F. Remostand and G. Bouix. 1995. Isolation and partial characterization of IgM-like seabass (Dicentrarchus labrax L. 1758) immunoglobulins. Aquaculture 132:53-58.

Bradford, M. M. A. 1976. Rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Analytical Biochemistry 72: 248-254.

Clem, L. W. and W. E. McLean. 1975. Phylogeny of immunoglobulin structure and function. VII. Monomeric and tetrameric immunoglobulins of the margate, a marine teleost fish. Immunology 29:791-799.

Dorson, M. 1981. Role and characterization of fish antibody. Dev. in Bio. Stand. 49:307-319.

Estevez, F., C. Sanchez, J. Dominguez, J. Leiro, M. L. Sanmartin and F. M. Ubeira. 1993b. Isolation and partial characterization of turbot (Scophthalmus maximus) immunoglobulins. Comp. Biochem. Physiol. 105A:275-281.

Glynn, P. J. and A. L. Pulsford. 1990. Isolation and partial characterisation of the serum immunoglobulin of the flounder, Platichthys flesus. J. Marine Bio. Association U. K. 70:429-440.

Hanley, P. J., I. M. Seppelt, A. A. Gooley, J. W. Hook and R. L. Raison. 1990. Distinct IgH chains in a primitive vertebrate, Eptatretus stouti. J. Immunol. 145:3823-3828.

Kobayashi, K., A. Hara, K. Takan and H. Hirai. 1982. Studies on subunit components of immunoglobulin M from a bony fish, the chum salmon (Oncorhynchus keta). Mol. Immunol. 19:95-103.

Kofod, H., J. L. Larsen and K. Buchmann. 1994. Purification and characterization of IgM-like immunoglobulin from turbot (Scophthalmus maximus L.) Acta. Veter. Scand. 35:1-10.

Koumans-van Diepen, J. C. E., E. Egberts, B. R. Peixoto, N. Taverner and J. H. W. M. Rombout. 1995. B cell and immunoglobulin heterogeneity in carp (Cyprinus carpio L.); an immune(chemical) study. Dev. and Comp. Immunol. 19:97-108.
Laemmli, V. H. 1970. Cleavage of structural proteins during the assembly of the head of bacteriophage T4. Nature (London). 227:680-682.

Lee, M. A., E. Bengten, A. Daggfeldt, A. S. Rytting and L. Pilstrom. 1993. Characterization of rainbow trout cDNAs encoding a secreted and membrane-bound Ig heavy chain and the genomic intron upstream of the first constant exon. Mol. Immunol. 30:641-648.

Litman, G. W. 1976. Physical properties of immunoglobulins of lower species: a comparison with immunoglobulins of mammals. In: Comparative Immunology (Ed. J. J. Marchalonis). Oxford: Blackwell Scientific Publications. pp. 239-275.

Lobb, D. J. and L. W. Clem. 1981. Phylogeny of immunoglobulin structure and function. X. Humoral immunoglobulins of the sheepshead, Archosargus probatocephalus. Dev. Comp. Immunol. 5:271-282.

Lobb, D. J. and M. O. Olson. 1988. Immunoglobulin heavy H chain isotopes in a teleost fish. J. Immunol. 141:1236-1245.

Lobb, D. J., M. O. Olson and L. W. Clem. 1984. Immunoglobulin light chain classes in a teleost fish. J. Immunol. 132:1917-1923.

Marchalonis J. J. and G. M. Edelman. 1968. Phylogenetic origins of antibody structure. III. Antibodies in the primary immune response of the sea lamprey, Petromyzon marinus. J. Exp. Med. 127:891-914.

Navarro, V., J. A. Quesada, M. E. Abad, N. Taverne and J. H. W. M. Rombout. 1993. Immuno(cyto)chemical characterisation of monoclonal antibodies to gilthead seabream (Sparus aurata) immunoglobulin. Fish & Shellfish Immunol. 3:167-177.

Palenzuela, O., A. Sitja-Bobadilla and P. Alvarez-Pellitero. 1996. Isolation and partial characterization of serum immunoglobulins from sea bass (Dicentrarchus labrax L.) and gilthead seabream (Sparus aurata L.). Fish and Shellfish Immunol. 6:81-94.

Pilstrom, L. and A. Peterson. 1991. Isolation and partial characterization of immunoglobulin from cod (Gadus morhua L.). Dev. Comp. Immunol. 15:143-152.

Raison, R. L., C. J. Hull and W. H. Hildemann. 1978. Characterization of immunoglobulin from the Pacific hagfish, a primitive vertebrate. Proc. Natl. Acad. Sci. U. S. A. 75:5679-5682.

Rombout, J. H. W. M., N. Taverne, M. van de Kamp and A. J. Taverne-Thiele. 1993. Differences in mucus and serum immunoglobulin of carp (Cyprinus carpio L.). Dev. Comp. Immunol. 17:309-317.

Sanchez, C., J. Dominguez and J. Coll. 1989. Immunoglobulin heterogeneity in the rainbow trout, Salmo gairdneri Richardson. J. Fish Dis. 12:459-465.

Sigel, M. M., E. W. Voss Jr and S. Rudikoff. 1972. Binding properties of shark immunoglobulins. Comp. Biochem. Physiol. 42A:249-259.

Smith, S. A., D. H. Gebhard, J. M. Housman, M. G. Levy and E. J. Noga 1993. Isolation, purification, and molecular-weight determination of serum immunoglobulin from Oreochromis aureus. J. Aquat. Anim. Health 5:23-35.

Suzuki, Y., M. Tanaka, K. Aida and I. Hanyu. 1990. Affinity of hish immunoglobulin to protein A. Nippon Suisan Gakkaishi 56:831-837.

van der Heijden, M. H. T., J. B. M. A. Rooijakkers, G. H. R. Booms, J. H. W. M. Rombout and J. H. Boon. 1995. Production, characterisation and applicability of monoclonal antibodies to European eel (Anguilla anguilla L., 1758) immunoglobulin, Vet. Imm. and Immunopath. 45:151-164.

Varner, J., P. Neame and G. W. Litman. 1991. A serum heterodimer from hagfish (Eptatretus stouti) exhibits structural similarity and partial sequence identity with immunoglobulin. Proc. Natl. Acad. Sci. U. S. A. 88:1746-1750.

Warr, G. W. 1983. Immunoglobulin of the toadfish Spheroides glaber. Com. Biochem. Physiol. 76B:507-514.

Warr, G. W. and J. J. Marchalonis. 1982. Molecular basis of self/non-self discrimination in the ectothermic vertebrates. In: The Recticuloendothelial System: A Comprehensive Treatise. 3. (Ed. N. Cohen, M. M. Sigel). Plenum, New York, pp. 541-567.