Gadolinium at Low Concentration Suppresses both Osteoclastic and Osteoblastic Activities in the Scales of Goldfish

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Abstract: For determining the effect of environmental pollutants on fish bone metabolism, we have developed an in vitro bioassay system using teleost scales that has osteoclasts, osteoblasts and bone matrix as markers: alkaline phosphatase (ALP) for osteoblasts and tartrate-resistant acid phosphatase (TRAP) for osteoclasts. Using this bioassay, the influence of gadolinium (Gd) on osteoclasts and osteoblasts of goldfish scales was examined in the present study. Gd sensitively inhibited TRAP activity. Even Gd at 10^{-13} M suppressed TRAP activity at 6 hours of incubation. At 18 hours of incubation, this inhibition occurred only at 10^{-7} and 10^{-6} M. After 36 hours of incubation, Gd did not influence TRAP activity. In osteoblasts, ALP activity was also suppressed by Gd in the range of 10^{-10} to 10^{-6} M for 6 to 18 hours of incubation. At 36 and 64 hours of incubation, ALP activity was significantly suppressed by Gd (36 hours: 10^{-9} to 10^{-6} M; 64 hours: 10^{-7} and 10^{-6} M). At 96 hours of incubation, however, Gd did not influence ALP activity. This is the first report to indicate the toxicity of Gd on fish bone metabolism using TRAP and ALP enzyme activities. The toxicity of Gd to osteoblasts is comparable to that of tributyltin, an aquatic environmental pollutant used as a biocide in anti-fouling paint. Gd is used in Magnetic Resonance Imaging (MRI) for clinical diagnoses. To avoid the toxicity of Gd ions, chelated forms, known as Gd-based contrast agents, are used for MRI diagnosis. Without a specific recycling process, these compounds are quickly released by urinary excretion and released into environmental waters. Therefore, it is possible that anthropogenic Gd influences aquatic animals. Considering our present data together with that of anthropogenic Gd pollution, we should conduct a Gd risk assessment to protect the ecosystem in the aquatic environment.

Keywords: Gadolinium, Osteoclasts, Osteoblasts, Fish Scales, Goldfish

Introduction

Gadolinium (Gd) is a ductile rare-earth metal. Gd^{3+} is currently used in magnetic resonance imaging (MRI) for clinical diagnoses because Gd^{3+} has paramagnetic properties (Möller et al., 2002; Birka et al., 2016). To avoid the toxicity of Gd^{3+}, chelated forms, known as Gd-based contrast agents (Gd-CAs), have been used (Möller et al., 2002; Telgmann et al., 2013). In general, Gd-CAs are stable complexes. The agents are
rapidly eliminated from a patient’s body. After excretion, they enter the public sewer and, subsequently, the wastewater treatment plant. Because of their polar or anionic nature, however, the Gd complexes most likely are neither adsorbed onto surfaces nor by particulate organic matter (Knappe et al., 2005) but are released into environmental water without a specific recycling process (Telgmann et al., 2013; Braun et al., 2018). Therefore, a significant amount of anthropogenic Gd-concentration in surface waters has been reported worldwide (Möller et al., 2002; Telgmann et al., 2013; Birka et al., 2016; Braun et al., 2018). It is possible that the anthropogenic Gd impacts aquatic animals. Gd appears toxic in animals because Gd functions as a blocker of Ca channels, causing its ionic radius to be nearly equal to that of Ca (Sherry et al., 2009). Actually, Gd influences calcified tissue such as sea urchin spicules (Saitoh et al., 2010; Martino et al., 2017; 2018). As Gd affects the skeletal formation of sea urchins, we presumed that Gd affects bone metabolism in fish.

We have developed an original in vitro bioassay system using goldfish scales that has osteoclasts, osteoblasts and bone matrix as markers: alkaline phosphatase (ALP) for osteoblasts and tartrate-resistant acid phosphatase (TRAP) for osteoclasts (Suzuki et al., 2000; Suzuki and Hattori, 2002; 2003; Suzuki et al., 2004). Using this in vitro bioassay, we have reported the toxicity of heavy metals such as cadmium (Cd) and mercury (Hg) on fish bone metabolism. We found that inorganic mercury (InHg) (10^{-5} to 10^{-3} M) (Suzuki et al., 2011) and methylmercury (MeHg) (10^{-9} to 10^{-6} M) (Suzuki et al., 2004) significantly inhibited the osteoclastic activity of goldfish scales. Cd responded very sensitively to osteoclasts. We demonstrate that even at 10^{-3} M, Cd suppressed osteoclastic activity in goldfish scales at 6 hours of incubation (Suzuki et al., 2004). Thus, in the present study, we examined the effect of Gd on osteoclastic and osteoblastic activities with this goldfish scale in vitro bioassay.

Materials and Methods

Animals

In goldfish (Carassius auratus auratus), we have reported that sensitivity of osteoblastic and osteoclastic activities of scales to calcemic hormones (estrogen and calcitonin) was higher in mature females than in mature males (Suzuki et al., 2000; Yoshikubo et al., 2005). Therefore, female goldfish (n = 9, bw 30.3±1.71 g) were purchased from a commercial source (Higashikawa Fish Farm, Yamatokoriyama, Japan) and used in the scale in vitro bioassay. In addition, all experimental procedures were conducted in accordance with the Guide for the Care and Use of Laboratory Animals of Kanazawa University.

Effects of Gd on Osteoclastic Activity in the Cultured Scales of Goldfish at 6 hours of Incubation

The culture medium was prepared. First, we added 1% penicillin-streptomycin mixture (ICN Biomedicals Inc., Aurora, OH, USA) and HEPES (Research Organics, Inc., Cleveland, OH, USA) (20 mM) to Earle’s Minimum Essential Medium (MEM; ICN Biomedicals Inc.). After filtration, the MEM was used in this experiment.

After preparation of the culture medium, goldfish were anesthetized with ethyl 3-aminobenzoate, methanesulfonic acid salt (Sigma-Aldrich, Inc., St. Louis, MO, USA) and the scales on both sides of the body were then removed. The collected scales were incubated in MEM supplemented with gadolinium acetate (Gd(OCH3)2·H2O) (Wako Pure Chemicals, Osaka, Japan) (10^{-15} to 10^{-6} M) and compared with Gd-free medium as a control. The incubation time and temperature were 6 hours and 15°C, respectively. We have reported the toxicity of Cd at 15°C at 6 hours of incubation (Suzuki et al., 2004). Therefore, these culture conditions were adopted in the present study. After incubation, scales were fixed in 10% formalin in a 0.05 M cacodylate buffer (pH 7.4) and then rinsed in distilled water. These scales were kept in a 0.05 M cacodylate buffer at 4°C until analysis. We examined the effects of Gd on osteoclasts using TRAP enzyme activity because, in mammals, the effects of hormones and some bioactive substances on osteoclasts have been investigated using TRAP (Vaes, 1988; Suda et al., 1999). Therefore, we used TRAP activity as an indicator of osteoclasts.

TRAP activity was measured as follows. Each scale was transferred to its own well in a 96-well microplate. An aliquot of 200 μL of 10 mM para-nitrophenyl-phosphate and 20 mM tartrate in a 0.1 M sodium acetate buffer (pH 5.3) was added to each well. This plate was then incubated at 20°C for 30 min while being shaken. After incubation, the reaction was stopped by adding 50 μL of 2 N NaOH. The 150 μL of colored solution was transferred to a new plate and the absorbance was measured at 405 nm. The absorbance was converted to the amount of para-nitrophenol (pNP) produced using a standard curve for pNP (Suzuki and Hattori, 2002).

Effects of Gd on Scale Osteoclastic Activity in goldfish Scales after Long-Term Culture

To examine the influence of Gd after long-term incubation, scales extracted from goldfish under anesthesia with ethyl 3-aminobenzoate, methanesulfonic acid salt (Sigma-Aldrich) were incubated in MEM with or without Gd for 18, 36, 64 and 96 h. After incubation, the
scales were fixed in 10% formalin in a 0.05 M cacodylate buffer (pH 7.4) and then rinsed in distilled water. These scales were kept in a 0.05 M cacodylate buffer at 4°C until analysis. Then, TRAP activity was measured as described above.

Effects of Gd on Osteoblastic Activity in the Cultured Scales of Goldfish at 6 Hours of Incubation

Goldfish scales were removed under anesthesia with ethyl 3-aminobenzoate, methanesulfonic acid salt (Sigma-Aldrich). Using these collected scales, we examined the effects of Gd on the osteoblasts with ALP as an indicator of osteoblasts (Dimai et al., 1998; Suda et al., 1999). The removed scales were incubated in MEM with or without Gd for 6 h. After incubation, scales were fixed in 10% formalin in a 0.05 M cacodylate buffer (pH 7.4) and then rinsed in distilled water. These scales were kept in a 0.05 M cacodylate buffer at 4°C until analysis. The ALP activity was measured as follows.

Each scale was transferred to its own well in a 96-well microplate. An aliquot of 200 μL of 10 mM para-nitrophenyl-phosphate in an alkaline buffer (100 mM Tris-HCl, pH 9.5; 1 mM MgCl2) was added to each well. Then, this plate was incubated at 20°C for 30 min while being shaken. After incubation, the reaction was stopped by adding 50 μL of 2 N NaOH. The 150 μL of colored solution was transferred to a new plate and the absorbance was measured at 405 nm. The absorbance was converted to the amount of pNP produced using a standard curve for pNP (Suzuki and Hattori, 2002).

Effects of Gd on Scale Osteoblastic Activity in goldfish Scales after Long-Term Culture

Scales were extracted from goldfish under anesthesia with ethyl 3-aminobenzoate, methanesulfonic acid salt (Sigma-Aldrich). Using these scales, we examined the effect of Gd during long-term incubation. The extracted scales were incubated in MEM with or without Gd for 18, 36, 64, and 96 hours. After incubation, the incubated scales were fixed in 10% formalin in a 0.05 M cacodylate buffer (pH 7.4) and then rinsed with distilled water. These scales were kept in a 0.05 M cacodylate buffer at 4°C until analysis. Then, ALP activity was measured as above described.

Statistical Analyses

All results are expressed as the means ± SE. The statistical significance between the control and experimental groups was assessed with one-way analysis of variance followed by Bonferroni’s test. In all cases, the selected significance level was p<0.05.

Results

Effect of Gd on Osteoclastic Activity as Seen in the Cultured Scales of Goldfish at 6 Hours of Incubation

Gd inhibited TRAP activity at 6 hours of incubation. Gd significantly suppressed TRAP activity. In 3 goldfish used in the present study, the detection limit of Gd was 10⁻¹³ (Fig. 1a), 10⁻¹¹ (Fig. 1b) and 10⁻¹⁰ M (Fig. 1c).

![Fig. 1: Effects of Gd on osteoclastic activity in the cultured scales of goldfish at 6 h of incubation](image-url)

Results are shown for 3 individual goldfish. * and ** indicate statistically significant differences at p<0.05 and p<0.01, respectively, from the values in the control scales.
Although the Gd sensitivity was lower, the influence of Gd on osteoclastic activity (Fig. 2b) and osteoblastic activity in the cultured scales of goldfish at 6 hours of incubation was shown in Fig. 3a and b. Results are shown for 2 individual goldfish. *, ** and *** indicate statistically significant differences at p<0.05, p<0.01 and p<0.001, respectively, from the values in the control scales.

**Effect of Gd on Osteoclastic Activity in the Long-Term Culture of Goldfish Scales**

At 18 hours of incubation, TRAP activity was significantly inhibited only at $10^{-7}$ and $10^{-6}$ M (Fig. 2a). After 36, 64 and 96 hours of incubation, Gd did not influence TRAP activity (Fig. 2b–d).

**Effect of Gd on Osteoblastic Activity as Seen in the Cultured Scales of Goldfish at 6 Hours of Incubation**

ALP activity was significantly suppressed by Gd (Fig. 3a and b), although the Gd sensitivity was lower than in TRAP. In the 2 goldfish used in the present study, the detection limit of Gd was $10^{-9}$ M (Fig. 3a) and $10^{-10}$ M (Fig. 3b).
**Effect of Gd on Osteoblastic Activity in the Long-Term Culture of Goldfish Scales**

At 18 hours of incubation, Gd (10^{-10} to 10^{-6} M) significantly inhibited ALP activity (Fig. 4a). At 36 hours of incubation, ALP activity was significantly suppressed by Gd (10^{-9} to 10^{-6} M) (Fig. 4b). This inhibition was maintained at 64 hours of incubation. Gd (10^{-7} and 10^{-6} M) significantly suppressed ALP activity at 64 hours of incubation (Fig. 4c). However, at 96 h of incubation, Gd did not influence ALP activity (Fig. 4d).

**Discussion**

This is the first report to indicate the toxicity of Gd on fish bone metabolism using TRAP and ALP enzyme activities. In scales as well as mammalian bone, bone γ-carboxyglutamic acid protein (Nishimoto et al., 1992), osteocalcin (Lehane et al., 1999) and osteocalcin (Thamamongood et al., 2012) are present. Thus, the scales of some teleosts are a better potential bone model for the analysis of environmental pollutants. Furthermore, we demonstrated that Gd quite sensitively inhibited TRAP activity. Even Gd of 10^{-13} M suppressed TRAP activity at 6 hours of incubation. In the case of the sea urchin, Gd in a range of 10^{-7} to 10^{-5} M influenced skeletogenesis (Saitoh et al., 2010; Martino et al., 2017; 2018). We found that the detection limit of Gd in our bioassay was 10^{-13} M. Therefore, our assay system is quite effective as a bioassay for Gd.

At 6 hours of incubation, very low concentrations of Gd (10^{-10} and 10^{-9} M) influenced osteoblasts and suppressed osteoblastic activity. Therefore, the toxicity of Gd to osteoblasts appears to be higher than that of Cd, MeHg and InHg (Suzuki et al., 2004; Suzuki et al., 2011). Heavy metals such as Cd, MeHg and InHg were resistant to each metal as a result of the production of metallothioneine (MT), which is a metal-binding protein that protects an organism from heavy metals (Suzuki et al., 2004; 2011). Because the mRNA expression of MT in Cd-, MeHg- and InHg-treated goldfish scales was increased, osteoblastic activity did not change at 6 hours of incubation (Suzuki et al., 2004; 2011). This phenomenon is also observed in the scales of nibbler fish, *Girella punctata* (marine fish) (Yachiguchi et al., 2014). ALP activity in the scales of nibbler fish decreased after exposure to InHg (10^{-5} and 10^{-4} M) and MeHg (10^{-6} to 10^{-5} M) for 18 and 36 hours, although ALP activity did not change after 6 hours of incubation (Yachiguchi et al., 2014). Furthermore, we previously analyzed the toxicity
of tributyltin (TBT), an aquatic environmental pollutant used as a biocide in anti-fouling paint (Suzuki et al., 2006). Osteoblastic activity significantly decreased from the control values as a result of TBT treatment (10^{-10} to 10^{-5} M) at 6 hours of incubation (Suzuki et al., 2006). Judging from the comparison of heavy metals (Cd and MeHg) and TBT, the inhibitory effect on osteoblasts at 6 hours of incubation appears to have lower expression of MT mRNA in TBT-treated scales than in Cd- or MeHg-treated scales (Suzuki et al., 2006). Therefore, the toxicity of Gd to osteoblasts may be related to MT expression, as with TBT.

In Table 1, we summarized the comparison of toxicity to osteoclasts and osteoblasts of fish scales. Toxicity of Gd to osteoblasts was higher than those of MeHg and InHg. The toxicity of Gd was comparable to that of Cd. Gd inhibited osteoblastic activity and was toxic to osteoblasts. This inhibition of Gd was almost equal to that of TBT. In addition, the sensitivity of Gd in osteoclasts and osteoblasts was varied among respective goldfish. In the present study, female goldfish were used because sensitivity of osteoblastic and osteoclast activities of scales to calcemic hormones was higher in mature females than in mature males (Suzuki et al., 2000; Yoshikubo et al., 2005). It seems that the sensitivity of Gd is related to the maturation of female goldfish. In the future, we are planning to study the correlation between sex hormones and Gd toxicity.

Gd was present in recycled water in which the stable organic Gd complexes pass through several sewage treatment plants without being significantly decomposed (Knappe et al., 2005). Therefore, anomalously high concentrations of Gd in surface waters are of anthropogenic origin (Rogowska et al., 2018). Specifically, anthropogenic Gd was detected in surface waters (up to 1,100 ng/L) and sediments (up to 90.5 μg/g) (Rogowska et al., 2018). Therefore, aquatic plants, fungi, small planktonic crustaceans, and freshwater fish (Cyprinus carpio) were able to take up anthropogenic Gd from the polluted water and it accumulated in their bodies (Rogowska et al., 2018). Furthermore, in the present study, we demonstrated that a level of Gd that is quite low (10^{-13} to 10^{-11} M) has toxicity for bone metabolism in goldfish. Thus, we strongly believe that anthropogenic Gd has toxicity for aquatic animals and we must consider a Gd risk assessment to protect the polluted aquatic environment.

### Conclusion

We are the first to indicate the toxicity of Gd on fish bone metabolism using TRAP and ALP enzyme activities. We found that the detection limit of Gd in our bioassay was 10^{-13} M. Therefore, our assay system is quite effective as a biosensor of Gd. In addition, Gd toxicity to osteoblasts appears to be higher than that to Cd, MeHg and InHg and equal to TBT. The toxicity of Gd in osteoclasts was comparable to that of Cd. Gd used for clinical diagnoses in MRI is released into environmental waters without a specific recycling process. Gd was found in tap water samples in the area of Berlin, Germany. Up to 18 ng/L of anthropogenic Gd on top of the geogenic background of 0.54 ng/L could be determined (Kulaksiz and Bau, 2011). Recently, the need for Gd risk assessments for human health has been emphasized (Fraum et al., 2017; Gwenzi et al., 2018). In addition to the risk to human, we should also emphasize Gd risk assessment to protect the ecosystem in the aquatic environment.

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Authors’ Contributions

N. Suzuki and A. Hattori: Designed this study.
N. Suzuki, K. Watanabe, A. Sekimoto, M.I. Zanaty, T. Sekiguchi, Y. Kitani, H. Matsubara and M. Urata: Analyzed the data and wrote the paper including graph and table preparation.
A. Hattori and A.K. Srivastav: Supervised this work.

Conflict of Interest

The authors have no conflicts of interest to declare.

Ethics

All experimental procedures were conducted in accordance with the Guide for the Care and Use of Laboratory Animals of Kanazawa University.

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