

Static and dynamic hypergravity responses of osteoblasts and osteoclasts in medaka scales

メタデータ	言語: eng 出版者: 公開日: 2017-10-05 キーワード (Ja): キーワード (En): 作成者: メールアドレス: 所属:
URL	http://hdl.handle.net/2297/34731

Static and Dynamic Hypergravity Responses of Osteoblasts and Osteoclasts in Medaka Scales

Author(s): Sachiko Yano , Kei-ichiro Kitamura , Yusuke Satoh , Masaki Nakano , Atsuhiko Hattori , Toshio Sekiguchi , Mika Ikegame , Hiroshi Nakashima , Katsunori Omori , Kazuichi Hayakawa , Atsuhiko Chiba , Yuichi Sasayama , Sadakazu Ejiri , Yuko Mikuni-Takagaki , Hiroyuki Mishima , Hisayuki Funahashi , Tatsuya Sakamoto and Nobuo Suzuki

Source: Zoological Science, 30(3):217-223. 2013.

Published By: Zoological Society of Japan

DOI: <http://dx.doi.org/10.2108/zsj.30.217>

URL: <http://www.bioone.org/doi/full/10.2108/zsj.30.217>

BioOne (www.bioone.org) is a nonprofit, online aggregation of core research in the biological, ecological, and environmental sciences. BioOne provides a sustainable online platform for over 170 journals and books published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Web site, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/page/terms_of_use.

Usage of BioOne content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

Static and Dynamic Hypergravity Responses of Osteoblasts and Osteoclasts in Medaka Scales

Sachiko Yano^{1,2}, Kei-ichiro Kitamura³, Yusuke Satoh³, Masaki Nakano⁴, Atsuhiko Hattori⁴, Toshio Sekiguchi², Mika Ikegame⁵, Hiroshi Nakashima³, Katsunori Omori⁶, Kazuichi Hayakawa⁷, Atsuhiko Chiba⁸, Yuichi Sasayama², Sadakazu Ejiri⁹, Yuko Mikuni-Takagaki¹⁰, Hiroyuki Mishima¹¹, Hisayuki Funahashi¹², Tatsuya Sakamoto¹³, and Nobuo Suzuki^{2*}

¹Japan Aerospace Exploration Agency, Tsukuba, Ibaraki 305-8505, Japan

²Noto Marine Laboratory, Institute of Nature and Environmental Technology, Kanazawa University, Housu-gun, Ishikawa 927-0553, Japan

³Institute of Health Sciences, College of Medical, Pharmaceutical and Health Sciences, Kanazawa University, Kanazawa, Ishikawa 920-0942, Japan

⁴Department of Biology, College of Liberal Arts and Sciences, Tokyo Medical and Dental University, Ichikawa, Chiba 272-0827, Japan

⁵Department of Oral Morphology, Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama University, Okayama, Okayama 700-8525, Japan

⁶Faculty of Economics, Asia University, Musashino, Tokyo 180-8629, Japan

⁷Institute of Pharmaceutical Sciences, College of Medical, Pharmaceutical and Health Sciences, Kanazawa University, Kanazawa, Ishikawa 920-1192, Japan

⁸Department of Materials and Life Sciences, Sophia University, Tokyo 102-8554, Japan

⁹Department of Oral Anatomy, Division of Oral Structure, Function and Development, Asahi University School of Dentistry, Hozumi, Gifu 501-0296, Japan

¹⁰Department of Functional Biology, Kanagawa Dental College, Yokosuka, Kanagawa 238-8580, Japan

¹¹Department of Human Life Sciences, Kochi Gakuen College, Kochi 780-0955, Japan

¹²Department of Anatomy, Showa University School of Medicine, Shinagawa-ku, Tokyo 142-8555, Japan

¹³Ushimado Marine Institute, Okayama University, Ushimado, Okayama 701-4303, Japan

Fish scales are a form of calcified tissue similar to that found in human bone. In medaka scales, we detected both osteoblasts and osteoclasts and subsequently developed a new scale assay system. Using this system, we analyzed the osteoblastic and osteoclastic responses under 2-, 3-, and 4-gravity (G) loading by both centrifugation and vibration. After loading for 10 min, the scales from centrifugal and vibration loading were incubated for 6 and 24 hrs, respectively, after which the osteoblastic and osteoclastic activities were measured. Osteoblastic activity significantly increased under 2- to 4-G loading by both centrifugation and vibration. In contrast, we found that osteoclastic activity significantly decreased under 2- and 3-G loading in response to both centrifugation and vibration. Under 4-G loading, osteoclastic activity also decreased on centrifugation, but significantly increased under 4-G loading by vibration, concomitant with markedly increased osteoblastic activity. Expression of the receptor activator of the NF- κ B ligand (RANKL), an activation factor of osteoclasts expressed in osteoblasts, increased significantly under 4-G loading by vibration but was unchanged by centrifugal loading. A protein sequence similar to osteoprotegerin (OPG), which is known as an osteoclastogenesis inhibitory factor, was found in medaka using our sequence analysis. The ratio of RANKL/OPG-like mRNAs in the vibration-loaded scales was significantly higher than that in the control scales, although there was no difference between centrifugal loaded scales and the control scales. Accordingly, medaka scales provide a useful model by which to analyze bone metabolism in response to physical strain.

Key words: osteoblast, osteoclast, scale, medaka, gravity response, RANKL, OPG

INTRODUCTION

Various in vitro models have been developed elucidate the effect of physical strain, including the response of bone

metabolism to different gravitational loads, (Tjandrawinata et al., 1997; Tanaka et al., 2003; Peng et al., 2011). Most studies using in vitro models noted osteoblastic responses to physical strain as the determinant in bone (Tjandrawinata et al., 1997; Tanaka et al., 2003). Bone consists of osteoblasts, osteoclasts, and the bone matrix, and both cell-to-cell and cell-to-matrix interactions are critical for cell response to physical stress (Harter et al., 1995; Owan et al., 1997; Hoffler et al., 2006). It was recently reported that mechanical

* Corresponding author. Tel. : +81-768-74-1151;
Fax : +81-768-74-1644;
E-mail: nobuos@staff.kanazawa-u.ac.jp
doi:10.2108/zsj.30.217

stretch-induced calcium efflux from bone matrix and stimulated osteoblasts, suggesting that the bone matrix acts as a reservoir for mechanochemical transducers, which convert mechanical strain into a chemical signal for the onset of calcium efflux (Sun et al., 2012). A co-culture system of osteoblasts and osteoclasts with the matrix is essential to elucidate bone metabolism under gravity (G) loading conditions, indicating the need for the development of such a system.

The teleost scale, a calcified tissue, contains osteoblasts and osteoclasts (Bereiter-Hahn and Zylberberg, 1993; Suzuki et al., 2000; Yoshikubo et al., 2005) that are similar to those found in avian and mammalian membrane bone. Moreover, multinucleated osteoclasts, an active type of osteoclast, have been detected by tartrate-resistant acid phosphatase (TRAP) staining in the scales of goldfish (Suzuki et al., 2000; Azuma et al., 2007; Suzuki et al., 2011), carp (de Vrieze et al., 2010), and rainbow trout (Persson et al., 1999), together with the osteoblasts detected by alkaline phosphatase (ALP) staining (de Vrieze et al., 2010). With such typical components of bone matrix as type I collagen (Zylberberg et al., 1992), bone γ -carboxyglutamic acid protein (Nishimoto et al., 1992), osteonectin (Lehane et al., 1999), and hydroxyapatite (Onozato and Watabe, 1979), a teleost scale is a suitable model for mammalian bone.

Medaka (*Oryzias latipes*), a small teleost, is a particularly suitable model organism, as its entire genome sequence has been mapped, facilitating genetic analysis. Its relatively short life cycle and high productivity (Kasahara et al., 2007; Kawakami, 2007; Takeda, 2008) are also valuable features. Therefore, medaka appears to be a model organism that can be used to analyze various biological processes, including bone metabolism, at the molecular level (Inohaya et al., 2007; Watanabe-Asaka et al., 2010). Medaka were launched into space in 1994 as part of a microgravity experiment (Ijiri, 1995). This experiment included the first observation of the mating behavior, development, and hatching of a vertebrate in space. Using medaka, we can analyze the response of osteoblasts and osteoclasts, not only in a hypergravity environment on the ground but also under microgravity conditions in space.

In the present study, we investigated bone metabolism under G-loading using medaka scales as a bone model. To demonstrate the coexistence of bone cells in medaka scales, we first analyzed the morphological features of both osteoblasts and osteoclasts. Second, we developed a new in vitro assay system using medaka scales. In this system, ALP and TRAP were used as respective markers of osteoblasts and osteoclasts. Third, we examined static (centrifugation) and dynamic (vibration) G-loading using the developed assay system with medaka scales. We demonstrated that osteoblasts and osteoclasts in medaka scales responded with certain degrees of sensitivity to G-loading by both centrifugation and vibration. Using our original system with medaka scales, we measured the difference between static and dynamic G-loading.

MATERIALS AND METHODS

Animals

Medaka were purchased from a commercial source (Higashikawa Fish Farm, Yamatokoriyama, Japan) and used for the in vitro scale

assay. All experimental procedures were conducted in accordance with the Guidelines for the Care and Use of Laboratory Animals of Kanazawa University, Japan.

Morphological study of osteoblasts and osteoclasts in medaka scales

Scales were collected from medaka anesthetized with ethyl 3-aminobenzoate, methanesulfonic acid salt (Sigma-Aldrich, Inc., St. Louis, MO, USA) and fixed using 4% paraformaldehyde solution neutralized with phosphate buffer solution (pH 7.2; Wako, Co., Ltd., Osaka, Japan). Subsequently, osteoblasts were detected by ALP staining using NBT/BCIP Stock Solution (Roche Applied Science, Mannheim, Germany). The scales were TRAP stained using the methods described by Cole and Walters (1987). After staining, the osteoblasts and osteoclasts were observed under a microscope.

Development of an in vitro assay system using medaka scales

Medaka were anesthetized with ethyl 3-aminobenzoate, methanesulfonic acid salt (Sigma-Aldrich, Inc., St. Louis, MO, USA), after which all scales collected from the left side of the animal were placed into a 1.5-mL microtube and all scales collected from the right side of medaka were transferred into a different 1.5-mL microtube. One hundred microliters of distilled water were added to each microtube. After sonication, the tube was centrifuged and the supernatant was used to detect both ALP and TRAP activities. The methods for measuring ALP and TRAP activities were reported by Suzuki et al. (2007). The ALP and TRAP data obtained for the scales from the left and right sides of the medaka were compared.

Effect of osteoblastic and osteoclastic activities under 2-, 3-, and 4-G loading by centrifugation and vibration

Scales were collected from medaka anesthetized with ethyl 3-aminobenzoate, methanesulfonic acid salt. All the left-side scales (loaded experimental scales) and right-side scales (unloaded control scales) from each individual were put into respective microtubes, followed by the addition of a 500- μ L aliquot of Leibovitz's L-15 medium (Invitrogen, Grand Island, NY, USA) containing a 1% penicillin–streptomycin mixture (ICN Biomedicals, Inc., Aurora, OH, USA). To fix the scales, a cotton ball (1 cm in diameter) was placed into each microtube. The microtube containing the scales was loaded to 2-, 3-, and 4-G by centrifugation (LIX-130; Tomy Digital Biology Co., Ltd., Tokyo, Japan) or by vibration with the original apparatus (Suzuki et al., 2007) for 10 min at room temperature. The loaded scales were compared with unloaded (1-G control) scales. The loading times were determined following our previous study using goldfish scales (Suzuki et al., 2007). After loading, the centrifuged and vibrated scales were incubated for 6 and 24 hrs, respectively, at 15°C. We previously reported that calcemic hormones such as calcitonin and estrogen were effective at these incubation times (Suzuki et al., 2000; Yoshikubo et al., 2005); therefore, we used these times in the present study. After incubation, the ALP and TRAP activities in the medaka scales were measured as described above.

Analysis of the interaction between osteoblasts and osteoclasts under 4-G loading by centrifugation and vibration

We analyzed the mRNA expression of both the receptor activator of the NF- κ B ligand (RANKL), an activating factor of osteoclasts expressed in osteoblasts, and osteoprotegerin (OPG), an osteoclastogenesis inhibitory factor in osteoblasts. OPG, a decoy receptor of RANKL, inhibits osteoclastogenesis by binding to RANKL (see the review by Lacey et al., 2012). To analyze the interaction between osteoblasts and osteoclasts, the ratio of the expression of the RANKL/OPG-like mRNA was examined.

After 4-G loading, the scales were incubated for 24 hrs at 15°C and then frozen at -80°C for mRNA analysis. The loaded scales were compared with unloaded (1-G control) scales. Total RNAs

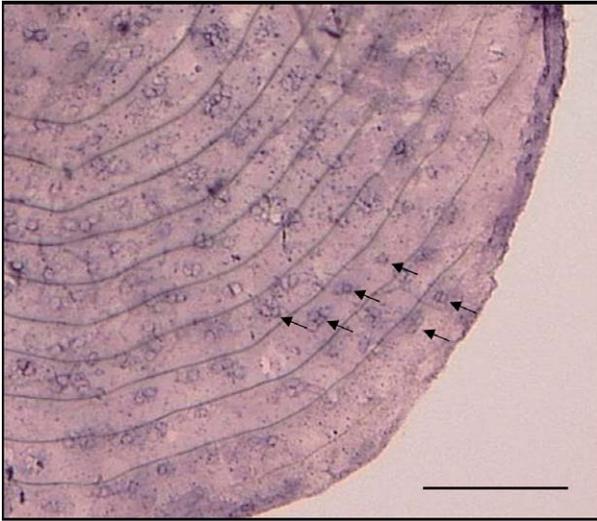


Fig. 1. Microscopic views of medaka scales stained for alkaline phosphatase (ALP). Arrows indicate ALP positive cells. Bar: 100 μm .



Fig. 2. Microscopic views of medaka scales stained for tartrate-resistant acid phosphatase. Arrowheads and arrows indicate mono- and multi-nucleated osteoclastic cells, respectively. Bar: 100 μm .

were prepared from medaka scales using a total RNA isolation kit for fibrous tissue (Qiagen GmbH, Hilden, Germany). Complementary DNA was synthesized using the PrimeScript™ RT reagent kit (Takara Bio Inc., Otsu, Japan). The primer sequences—sense: AGGCAAACGGCAAAGAAAT; anti-sense: CCCAGCTTTATGGCTCCAA—were designed from medaka RANKL (JN119285) (To et al., 2012). The OPG-like sequence in medaka was determined by sequence analysis, as follows. All amino acid sequences of medaka were retrieved from the Genome to Protein Structure and Function database. We analyzed the amino acid sequence of OPG in fugu (ENSTRUP0000023772) as a query to all amino acid sequences of medaka, and selected the best-hit sequence as the candidate for the OPG amino acid sequence of medaka. Thereafter, we used CLUSTAL X2 (Larkin et al., 2007) for multiple sequence alignment of homologous sequences. The primers for the OPG-like sequence in medaka were as follows: sense: 5'-GGATCCGTCCTGGTAAAA-3'; antisense: 5'-GAGCACTCGATTCCACCTC-3'.

β -actin (ENSORLT0000021168) was amplified using the following primers: sense: 5'-TGTGCTACGTGGCTCTTGAC-3'; anti-sense: 5'-GCCAATGAAAGAAGGTTGGA-3'. The PCR amplification was performed using the real-time Mx3000p PCR apparatus (Agilent Technologies, Santa Clara, CA, USA) (Suzuki et al., 2011). The annealing temperature of RANKL, OPG-like, and β -actin fragments was 60°C. The initial reaction condition was 10 s at 95°C, followed by 40 cycles of denaturation at 95°C for 5 s, and annealing/extension at 60°C for 40 s. The RANKL and OPG-like mRNA levels were normalized to the β -actin mRNA level.

Statistical analysis

All results are expressed as means \pm SEM ($n = 10$). The data were assessed using the paired t -test and the significance level chosen was $P < 0.05$.

RESULTS

Osteoblasts and osteoclasts in medaka scales

In the medaka scales, ALP-stained osteoblasts (Fig. 1) and TRAP-stained mono- and multi-nucleated osteoclastic cells were detected (Fig. 2).

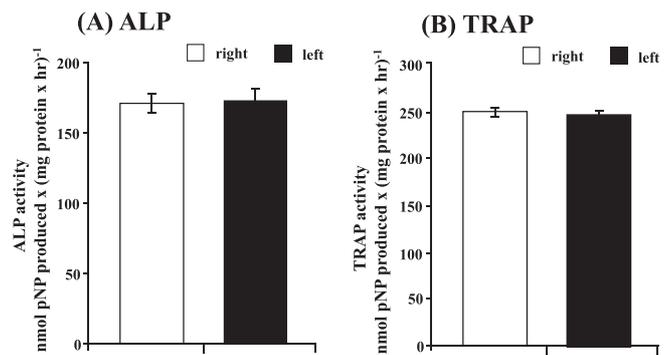


Fig. 3. Comparison of osteoblastic (A) and osteoclastic (B) activity in medaka scales from the right and left sides of the medaka body.

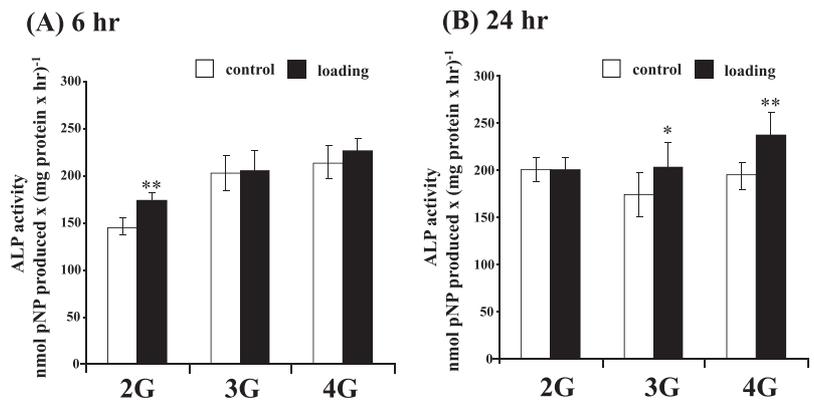


Fig. 4. Effect of osteoblastic activity after incubation for 6 (A) and 24 hrs (B) under 2-gravity (G), 3-G, 4-G loading by centrifugation. * and ** indicate statistically significant differences at $P < 0.05$ and $P < 0.01$, respectively, from the values in the control scales.

Comparison of ALP and TRAP activities between scales from the left and right sides of medaka

ALP activity in scales from the left side of medaka was similar to that in scales from the right side (Fig. 3A) with no significant difference. The TRAP activity in the scales from the left side was nearly equal to that in scales from the right side (Fig. 3B).

Effect of osteoblastic and osteoclastic activities under 2-, 3-, and 4-G loading by centrifugation

The ALP activity significantly increased under 2-G loading by centrifugation after 6 hrs of incubation (Fig. 4A). The ALP activity increased significantly under 3- and 4-G loading by centrifugation after 24 hrs of incubation (Fig. 4B). In contrast, under 2- to 4-G loading by centrifugation, the TRAP activity significantly decreased after both 6 and 24 hrs of incubation (Fig. 5A, B).

Effect of osteoclastic and osteoblastic activity under 2-, 3-, 4-G loading by vibration

The ALP activity increased significantly under 3- and 4-G loading by vibration after 6 hrs of incubation (Fig. 6A). Under 2- to 4-G loading by vibration, the ALP activity significantly increased after 24 hrs of incubation (Fig. 6B). Under 3-G loading by vibration, the TRAP activity significantly decreased after 6 hrs of incubation (Fig. 7A). After 24 hrs of incubation, the TRAP activity significantly decreased under 2-G loading but significantly increased under 4-G loading by vibration (Fig. 7B).

Determination of the OPG-like sequence in medaka

Using our original system, the OPG-like sequence was determined from the medaka database. After analysis using CLUSTAL X2, we found that 18 cysteines are strictly conserved in fish, birds, and mammals (Fig. 8). The amino acid identity of the medaka OPG-like sequence was 69.9% compared to the fugu OPG, 38.3% compared to the chicken OPG, 39.0% compared to the mouse OPG, and 41.2% compared to the human OPG. Furthermore, similarity analysis using the BLOSUM62 matrix confirmed that the medaka OPG-like sequence shows a high similarity to fugu (80.1%) and a relatively high similarity to other vertebrate OPG (chicken, 60.0%; mouse, 58.0%; human, 58.3%).

Analysis of the interaction between osteoblasts and osteoclasts under 4-G loading by centrifugation and vibration

RANKL mRNA expression was increased significantly by vibration loading, but not by

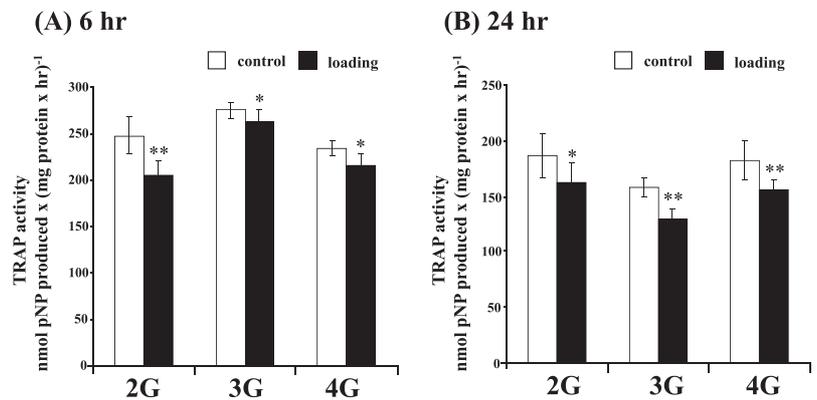


Fig. 5. Effect of osteoclastic activity after incubation for 6 (A) and 24 hrs (B) under 2-gravity (G), 3-G, 4-G loading by centrifugation. * and ** indicate statistically significant differences at $P < 0.05$ and $P < 0.01$, respectively, from the values in the control scales.

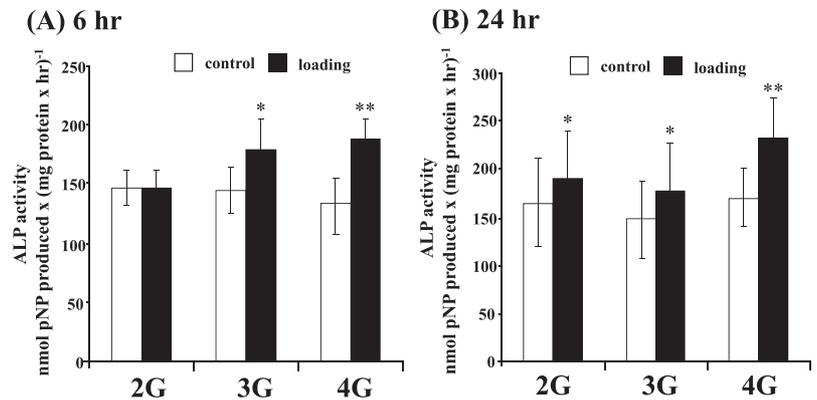


Fig. 6. Effect of osteoblastic activity after incubation for 6 (A) and 24 hrs (B) under 2-gravity (G), 3-G, 4-G loading by vibration. * and ** indicate statistically significant differences at $P < 0.05$ and $P < 0.01$, respectively, from the values in the control scales.

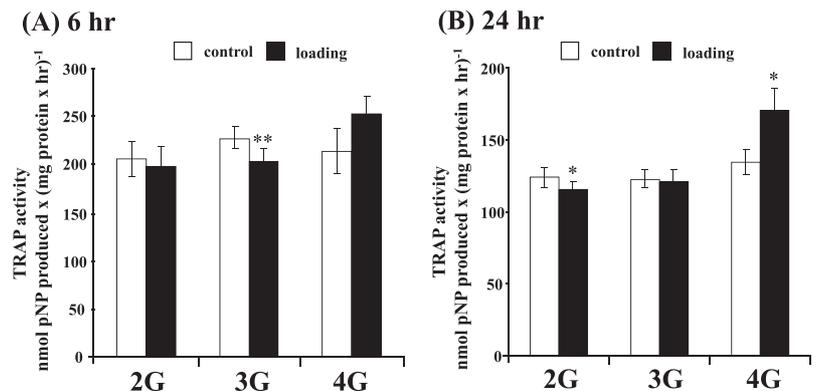


Fig. 7. Effect of osteoclastic activity after incubation for 6 (A) and 24 hrs (B) under 2-gravity (G), 3-G, 4-G loading by vibration. * and ** indicate statistically significant differences at $P < 0.05$ and $P < 0.01$, respectively, from the values in the control scales.

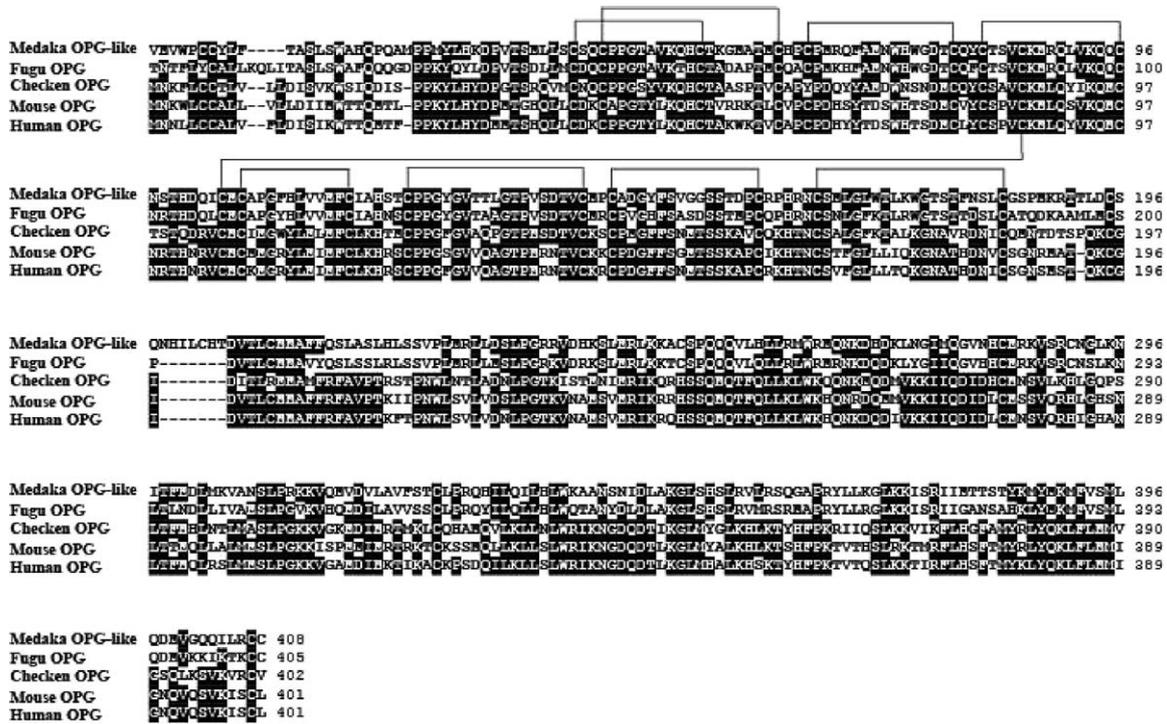


Fig. 8. Multiple protein sequence alignment of osteoprotegerin (OPG) with other animals: fugu OPG (ENSTRUP0000023772), chicken OPG (ENSGALP0000025915), mouse OPG (PRO_0000034588), and human OPG (PRO_0000034587), and concatenated cysteines represent disulfide bonds in OPG sequences. This multiple protein sequence alignment showed that disulfide bonds are highly conserved in the OPG sequences of vertebrates.

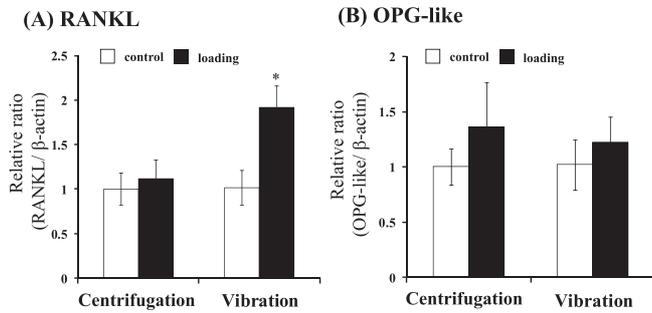


Fig. 9. Changes in expression of the receptor activator of NF- κ B ligand (RANKL) (A) and osteoprotegerin- (OPG-) like mRNA (B) under 4-gravity loading by centrifugation and vibration. * indicates statistically significant difference at $P < 0.05$ from the values in the control scales.

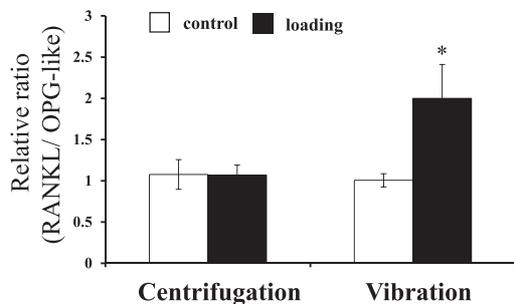


Fig. 10. The ratio of expression of RANKL/OPG-like mRNA in the centrifugal- and vibration-loaded scales. * indicates statistically significant difference at $P < 0.05$ from the values in the control scales.

centrifugal loading (Fig. 9A). The expression of the OPG-like mRNA was not significantly different between centrifugal and vibration loading (4-G) (Fig. 9B). The ratio of the expression of RANKL/OPG-like mRNA in the vibration-loaded scales was significantly higher than that in the control scales (Fig. 10).

DISCUSSION

The present study is the first to demonstrate that medaka scales respond to G-loading by using ALP and TRAP as marker enzymes of osteoblasts and osteoclasts stained by the respective substrates (Figs. 1, 2), supporting the notion that this new assay system can be a useful tool in analyzing the response of these cells to gravitational stress.

Osteoblasts in medaka scales were activated by loading with increasing gravity (2-G, 3-G, and 4-G) for 10 min by centrifugation. Medaka scales responded to G-force < 5 , which is much lower than the 5 to 50 G needed for mammalian osteoblasts to respond (Gebken et al., 1999; Saito et al., 2003; Searby et al., 2005), suggesting that medaka scales are very sensitive to G-loading. In addition, the osteoclastic activity in medaka scales decreased under 2-G, 3-G, and 4-G loading by centrifugation, suggesting a very good response of osteoclasts to low G loading, although the mechanisms have yet to be determined. Moreover, osteoblastic and osteoclastic activities in medaka scales were sensitive not only to dynamic G-loading by vibration with a G-load apparatus, but also to static G-loading by centrifugation. Fish scales contain osteoblasts, osteoclasts, and a matrix similar to that in bone (Bereiter-Hahn and Zylberberg,

1993; Suzuki et al., 2000; Yoshikubo et al., 2005; Azuma et al., 2007). Bone matrix plays an important role in the response to physical stress (Owan et al., 1997; Hoffer et al., 2006); in future studies, we will seek to identify the difference in matrix components, if any, to elucidate the mechanisms underlying the extreme sensitivity of medaka scales to G-loading.

The interaction between osteoblasts and osteoclasts has been reported in mammals, and cytokine from osteoblasts, in particular, is required to produce differentiated osteoclasts (Suda et al., 1999). RANK in osteoclasts binds RANKL, the ligand, resulting in osteoclast activation whereby multinucleated osteoclasts (an active type of osteoclast) are formed (Teitelbaum et al., 2000). OPG, a decoy receptor of RANKL, inhibits osteoclastogenesis by binding to RANKL (see the review by Lacey et al., 2012). We demonstrated that RANKL mRNA expression increases significantly in response to vibration loading, but not centrifugal loading. In addition, the ratio of the expression of RANKL/OPG-like mRNA in the scales loaded by vibration was significantly higher than that in control scales, while there was no difference on centrifugation. Because the RANKL/OPG ratio is an indicator of bone resorption (Lacey et al., 2012), medaka scales provide a good model by which to investigate bone metabolism.

In a study of a widely used hind-limb-elevation (tail suspension) model, the results of bone resorption by osteoclasts were inconsistent (Carmeliet et al., 2001); in this field, most subsequent research has thus been focused on osteoblastic response in bone formation. Recently, in isolated osteoclasts, it was reported that osteoclastic activity increased in those osteoclasts that were cultured in space (Tamma et al., 2009); however, there has been no data relating the interaction between osteoblasts and osteoclasts in space. Although bone mass is reportedly increased by mechanical strain, it has also been reported that mechanical strain on isolated osteoclasts upregulated their bone-resorbing activity (Kurata et al., 2001); therefore, the results obtained from the isolated osteoclast system may differ from that obtained from the *in vivo* system. Moreover, we demonstrated that melatonin, a major hormone secreted from the pineal gland, activated the growth of isolated osteoblasts in culture, although this hormone also suppressed the functions of osteoblasts using an *in vitro* assay system with scales (Suzuki and Hattori, 2002). These results obtained using an *in vitro* assay system resembled those of an *in vivo* study in rats (Ladizesky et al., 2003). Based on these results, we propose that our study using a scale-organ-culture system provides more accurate reproduction of the *in vivo* study.

Medaka has a number of beneficial features as a model organism, and transgenic systems have been developed using this species. For example, fluorescent protein markers of osteoblasts can be observed *in vivo* (Inohaya et al., 2007). Furthermore, the launch of the aquatic animal habitation module (Aquatic Habitat), which is planned for the near future, will enable breeding medaka in the International Space Station (Sakimura et al., 2003; Watanabe-Asaka et al., 2010). We will be able to perform space experiments using the scales of space-bred medaka, both *in vitro* and *in vivo*, in the near future. Together with the present data,

medaka scales provide a promising model system by which to study bone metabolism, and will also be useful in evaluating the physical strain associated with gravity and microgravity in space flight.

ACKNOWLEDGMENTS

This study was supported in part by grants to N.S. (Kurita Water and Environment Foundation; Grant-in-Aid for Space Utilization by the Japan Aerospace Exploration Agency; Grant-in-Aid for Scientific Research [C] Nos. 21500404 and 24620004 by JSPS), to A.H. (Grant-in-Aid for Scientific Research [C] Nos. 21570062 and 24570068 by JSPS), to K.K. (Grant-in-Aid for Scientific Research [C] Nos. 21500681 and 24500848 by JSPS), to T.S. (Grant-in-Aid for Young Scientists [B] Nos. 22770069 and 40378568 by JSPS), to H.M. (Grant-in-Aid for Scientific Research [C] No. 23592727 by JSPS), and to K.H. (the Environment Research and Technology Development Fund [B-0905] sponsored by the Ministry of the Environment, Japan; Health, Labour Sciences Research Grants of the Ministry of Health, Labour and Welfare, Japan; Grant-in-Aid for Scientific Research [B] No. 21390034 and for Exploratory Research No. 24651044 by JSPS).

REFERENCES

- Azuma K, Kobayashi M, Nakamura M, Suzuki N, Yashima S, Iwamura S, et al. (2007) Two osteoclastic markers expressed in multinucleated osteoclasts of goldfish scales. *Biochem Biophys Res Commun* 362: 594–600
- Bereiter-Hahn J, Zylberberg L (1993) Regeneration of teleost fish scale. *Comp Biochem Physiol* 105A: 625–641
- Carmeliet G, Vico L, Bouillon R (2001) Space flight: A challenge for normal bone homeostasis. *Crit Rev Eukaryot Gene Expr* 11: 131–144
- Cole AA, Walters LM (1987) Tartrate-resistant acid phosphatase in bone and cartilage following decalcification and cold-embedding in plastic. *J Histochem Cytochem* 35: 203–206
- de Vrieze E, Mets JR, Von den Hoff JW, Flik G (2010) ALP, TRAcP and cathepsin K in elasmoid scales: A role in mineral metabolism. *J Appl Ichthyol* 26: 210–213
- Gebken J, Lüders B, Notbohm H, Klein HH, Brinckmann J, Müller PK, Bätge B (1999) Hypergravity stimulates collagen synthesis in human osteoblast-like cells: Evidence for the involvement of p44/42 MAP-kinases (ERK 1/2). *J Biochem* 126: 676–682
- Harter LV, Hruska KA, Duncan RL (1995) Human osteoblast-like cells respond to mechanical strain with increased bone matrix protein production independent of hormonal regulation. *Endocrinology* 136: 528–535
- Hoffler CE, Hankenson KD, Miller JD, Bilkhu SK, Goldstein SA (2006) Novel explant model to study mechanotransduction and cell-cell communication. *J Orthop Res* 24: 1687–1698
- Ijiri K (1995) Fish mating experiment in space - What it aimed at and how it was prepared. *Biol Sci Space* 9: 3–16
- Inohaya K, Takano Y, Kudo A (2007) The teleost intervertebral region acts as a growth center of the centrum: *In vivo* visualization of osteoblasts and their progenitors in transgenic fish. *Dev Dyn* 236: 3031–3046
- Kasahara M, Naruse K, Sasaki S, Nakatani Y, Qu W, Ahsan B, et al. (2007) The medaka draft genome and insights into vertebrate genome evolution. *Nature* 447: 714–719
- Kawakami K (2007) Tol2: A versatile gene transfer vector in vertebrates. *Genome Biol* 8 Suppl 1: S7.1–S7.10
- Kurata K, Uemura T, Nemoto A, Tateishi T, Murakami T, Higaki H, et al. (2001) Mechanical strain effect on bone-resorbing activity and messenger RNA expressions of marker enzymes in isolated osteoclast culture. *J Bone Miner Res* 16: 722–730
- Lacey DL, Boyle WJ, Simonet WS, Kostenuik PJ, Dougall WC, Sullivan JK, et al. (2012) Bench to bedside: Elucidation of the

- OPG-RANK-RANKL pathway and the development of denosumab. *Nat Rev Drug Discov* 11: 401–419
- Ladizesky MG, Boggio V, Albornoz LE, Castrillón PO, Mautalen C, Cardinali DP (2003) Melatonin increases oestradiol-induced bone formation in ovariectomized rats. *J Pineal Res* 34: 143–151
- Larkin MA, Blackshields G, Brown NP, Chenna R, McGettigan PA, McWilliam H, et al. (2007) Clustal W and Clustal X version 2.0. *Bioinformatics* 23: 2947–2948
- Lehane DB, Mckie N, Russell RGG, Henderson IW (1999) Cloning of a fragment of the osteonectin gene from goldfish, *Carassius auratus*: Its expression and potential regulation by estrogen. *Gen Comp Endocrinol* 114: 80–87
- Nishimoto SK, Araki N, Robinson FD, Waite JH (1992) Discovery of bone γ -carboxyglutamic acid protein in mineralized scales. *J Biol Chem* 267: 11600–11605
- Onozato H, Watabe N (1979) Studies on fish scale formation and resorption III: Fine structure and calcification of the fibrillary plates of the scales in *Crassius auratus* (Cypriniformes: Cyprinidae). *Cell Tissue Res* 201: 409–422
- Owan I, Burr DB, Turner CH, Qiu J, Tu Y, Onyia JE, Duncan RL (1997) Mechanotransduction in bone: Osteoblasts are more responsive to fluid forces than mechanical strain. *Am J Physiol Cell Physiol* 273: C810–C815
- Peng Q, Wang Y, Qiu J, Zhang B, Sun J, Lv Y, Yang L (2011) A novel mechanical loading model for studying the distributions of strain and mechano-growth factor expression. *Arch Biochem Biophys* 511: 8–13
- Persson P, Björnsson B. Th, Takagi Y (1999) Characterization of morphology and physiological actions of scale osteoclasts in the rainbow trout. *J Fish Biol* 54: 669–684
- Saito M, Soshi S, Fujii K (2003) Effect of hyper- and microgravity on collagen post-translational controls of MC3T3-E1 osteoblasts. *J Bone Miner Res* 18: 1695–1705
- Sakimura T, Uchida S, Kono Y, Ochiai T, Fujimoto N (2003) Developmental status of aquatic animal experiment facility, aquatic habitat (AQH), for International Space Station. *Biol Sci Space* 17: 240–241
- Searby ND, Steele CR, Globus RK (2005) Influence of increased mechanical loading by hypergravity on the microtubule cytoskeleton and prostaglandin E2 release in primary osteoblasts. *Am J Physiol* 289: C148–C158
- Suda T, Takahashi N, Udagawa N, Jimi E, Gillespie MT, Martin TJ (1999) Modulation of osteoclast differentiation and function by the new members of the tumor necrosis factor receptor and ligand families. *Endocr Rev* 20: 345–357
- Sun X, McLamore E, Kishore V, Fites K, Slipchenko M, Porterfield DM, Akkus O (2012) Mechanical stretch induced calcium efflux from bone matrix stimulates osteoblasts. *Bone* 50: 581–591
- Suzuki N, Hattori A (2002) Melatonin suppresses osteoclastic and osteoblastic activities in the scales of goldfish. *J Pineal Res* 33: 253–258
- Suzuki N, Suzuki T, Kurokawa T (2000) Suppression of osteoclastic activities by calcitonin in the scales of goldfish (freshwater teleost) and nibbler fish (seawater teleost). *Peptides* 21: 115–124
- Suzuki N, Kitamura K, Nemoto T, Shimizu N, Wada S, Kondo T, et al. (2007) Effect of vibration on osteoblastic and osteoclastic activities: Analysis of bone metabolism using goldfish scale as a model for bone. *Adv Space Res* 40: 1711–1722
- Suzuki N, Danks JA, Maruyama Y, Ikegame M, Sasayama Y, Hattori A, et al. (2011) Parathyroid hormone 1 (1–34) acts on the scales and involves calcium metabolism in goldfish. *Bone* 48: 1186–1193
- Takeda H (2008) Draft genome of the medaka fish: A comprehensive resource for medaka developmental genetics and vertebrate evolutionary biology. *Dev Growth Differ* 50: S157–S166
- Tamma R, Colaianni G, Camerino C, Di Benedetto A, Greco G, Strippoli M, et al. (2009) Microgravity during spaceflight directly affects *in vitro* osteoclastogenesis and bone resorption. *FASEB J* 23: 2549–2554
- Tanaka SM, Li J, Duncan RL, Yokota H, Burr DB, Turner CH (2003) Effects of broad frequency vibration on cultured osteoblasts. *J Biomech* 36: 73–80
- Teitelbaum SL (2000) Bone resorption by osteoclasts. *Science* 289: 1504–1508
- Tjandrawinata RR, Vincent VL, Hughes-Fulford M (1997) Vibrational force alters mRNA expression in osteoblasts. *FASEB J* 11: 493–497
- To TT, Witten PE, Renn J, Bhattacharya D, Huysseune A, Winkler C (2012) Rankl-induced osteoclastogenesis leads to loss of mineralization in a medaka osteoporosis model. *Development* 139: 141–150
- Watanabe-Asaka T, Mukai C, Mitani H (2010) Technologies and analyses using medaka to evaluate effects of space on health. *Biol Sci Space* 24: 3–9
- Yoshikubo H, Suzuki N, Takemura K, Hosono M, Yashima S, Iwamuro S, et al. (2005) Osteoblastic activity and estrogenic response in the regenerating scale of goldfish, a good model of osteogenesis. *Life Sci* 76: 2699–2709
- Zylberberg L, Bonaventure J, Cohen-Solal L, Hartmann DJ, Bereiter-Hahn J (1992) Organization and characterization of fibrillar collagens in fish scales *in situ* and *in vitro*. *J Cell Sci* 103: 273–285

(Received July 13, 2012 / Accepted October 20, 2012)