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**Vitamin K-Dependent Carboxylation of Osteocalcin Affects the Efficacy of Teriparatide
(PTH₁₋₃₄) for Skeletal Repair**

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Running head: Effect of Teriparatide on Fracture in Vitamin K insufficiency

3 Supplemental figures and 2 Supplemental tables are included with the submission

Disclosure

All authors state that they have no conflict of interest.

Abstract (296/300 words):

Teriparatide (PTH₁₋₃₄) promotes skeletal repair and increases bone mass. Vitamin K is implicated in bone mineralization as a coenzyme of γ -carboxylase for the Gla proteins, and therefore vitamin K insufficiency caused by malnutrition or therapeutic intake of the vitamin K antagonist warfarin could affect the efficacy of PTH₁₋₃₄ therapy for bone repair. In the present study, we investigated whether vitamin K influences the efficacy of PTH₁₋₃₄ therapy for bone repair in a rat osteotomy model. Female 12-week-old Sprague-Dawley rats were subjected to a closed midshaft osteotomy of the femur and randomized into four groups (n=10 per group): Vehicle, PTH₁₋₃₄ (daily 30 μ g/kg/day subcutaneous injection) + solvent (orally, three times a week), PTH₁₋₃₄ + warfarin (0.4 mg/kg/day orally, three times a week), and PTH₁₋₃₄ + vitamin K₂ (menatetrenone, 30 mg/kg/day orally, three times a week). Serum γ -carboxylated and uncarboxylated osteocalcin (Gla-OC and Glu-OC) levels and radiographic healing were monitored every 2 weeks. Skeletal repair was assessed by micro-computed tomography, mechanical testing, and histology at 8 weeks after the surgery. PTH₁₋₃₄ amplified the osteotomy-induced increase in Gla-OC and improved the mechanical properties as well as the volumetric bone mineral tissue density of the fracture callus. Concurrent use of warfarin decreased the response to PTH₁₋₃₄ therapy in terms of mechanical recovery, probably by impairing mineralization due to the lack of Gla-OC. Although the effects of combination therapy with PTH₁₋₃₄ and vitamin K₂ on bone repair did not significantly exceed those of PTH₁₋₃₄ monotherapy in rats fed sufficient dietary vitamin K, postoperative Gla-OC levels were correlated with the mechanical properties of the osteotomized femur in PTH₁₋₃₄ treated rats regardless of the use of warfarin or vitamin K₂. These findings suggest the importance of vitamin K dependent γ -carboxylation of OC for PTH₁₋₃₄ to fully exert its effect on skeletal repair.

1 **Keywords:** Vitamin K; Teriparatide; Fracture; Gla-osteocalcin; Mineralization; Parathyroid
2 hormone (1-34)
3
4

1 **Introduction**

2 Intermittent administration of teriparatide (PTH₁₋₃₄), an active recombinant human peptide
3 sequence of the parathyroid hormone, increases bone mass in patients with osteoporosis [1]. Based
4 on this anabolic property, a number of animal studies have demonstrated that PTH₁₋₃₄ also
5 enhances skeletal repair, regardless of the skeletal site and mode of bone healing [2-6] [7].
6 Although the effects of this drug on fracture healing are remarkable in normal, skeletally mature
7 animals, whether PTH₁₋₃₄ exerts beneficial skeletal repair effects in pathologic conditions is
8 unknown.

9 Vitamin K insufficiency might affect the efficacy of PTH₁₋₃₄ therapy for bone repair. Vitamin
10 K is well known to be important for the normal functioning of blood coagulation factors, but it is
11 also thought to be involved in bone metabolism by regulating the activation of bone matrix
12 proteins [8]. Vitamin K acts as a coenzyme of γ -carboxylase, which converts the glutamic acid
13 (Glu) residue in Gla protein to γ -carboxyglutamic acid (Gla) [9-13]. In bone, vitamin K acts on
14 osteocalcin (OC), a highly abundant noncollagenous protein in bone, and Gla-OC is thought to be
15 associated with bone mineralization due to its specific interaction with hydroxyapatite [14].

16 Mineralization of soft fracture calluses is a critical step for fractured bone to regain mechanical
17 strength and stiffness. Because the hallmarks of PTH₁₋₃₄ therapy during fracture healing are
18 enhanced mineralization and increased callus formation, impaired mineralization may attenuate
19 the efficacy of PTH₁₋₃₄ on bone healing [15]. Given that vitamin K insufficiency is frequently
20 caused by low dietary vitamin K intake and the use of the vitamin K antagonist warfarin as
21 anticoagulant therapy, it is of great interest whether vitamin K insufficiency affects the clinical
22 efficacy of PTH₁₋₃₄ on skeletal repair. In contrast, concomitant use of vitamin K might enhance the
23 efficacy of PTH₁₋₃₄ therapy on skeletal repair based on a recent study showing that vitamin K

1 promotes bone healing in a rat fracture model [16].

2 In the present study, we used a rat femoral osteotomy model to investigate whether vitamin K
3 insufficiency or administration of vitamin K affects the efficacy of PTH₁₋₃₄ therapy on bone repair.
4 This study provides important information that facilitates clinical translation of PTH₁₋₃₄ therapy
5 for bone repair.

6

Materials and methods

Animals and osteotomy model

All animal studies were performed in accordance with protocols approved by the Hokkaido University's Committee on Animal Resources. Female Sprague–Dawley rats (n = 40; 10 weeks of age; CLEA Japan, Inc., Tokyo, Japan) were maintained at 20°C on a 12-h light/12-h dark cycle with free access to water and rat food containing 0.98% Ca, 0.80% Pi, and 15.4 mg/kg vitamin K₃ (Labo MR Stock; Nosan Corporation Life-Tech Department, Yokohama, Japan). Following a 2-week adaptation period to the new environment, all rats were stratified according to bodyweight and underwent a unilateral osteotomy of the femur. Briefly, transverse osteotomy at the mid-shaft femur was performed using a threaded wire saw (MDS36-30 T-saw, MANI, Tochigi, Japan), which was inserted percutaneously, and then the osteotomized femur was stabilized with an intramedullary titanium wire (Ø= 1.0 mm; Synthes, Tokyo, Japan). This closed osteotomy procedure does not preserve periosteum but minimizes other soft tissue damage compared to conventional open osteotomy. This model was modified for the femur from a previous report [17].

Experimental design

After osteotomy, all rats were randomized into four groups within each stratum according to the following treatment schedule: vehicle control group (n = 10), PTH₁₋₃₄ group (n = 10), PTH₁₋₃₄ + warfarin group (n = 10), and PTH₁₋₃₄ + vitamin K₂ group (n = 10). Recombinant human PTH₁₋₃₄ (Forteo®; Eli Lilly, Ltd., Kobe, Japan) at a dosage of 30 µg/kg/day or phosphate-buffered saline was administered to the animals by daily subcutaneous injections [15, 18]. Vitamin K₂ (menatetrenone; Eisai Co., Ltd., Tokyo, Japan) was suspended in fatty acid (Miglyol 812; Mitsuba

Trading, Co., Ltd, Tokyo, Japan) at a dose of 30 mg/ml/kg bodyweight and administered by gavage three times a week [16, 19, 20]. To cancel the effect of dietary vitamin K, warfarin was suspended in distilled water at a dose of 0.4 mg/ml/kg body weight and administered by gavage three times a week [21]. Every two weeks after the surgery, bodyweight was monitored, tail vein blood was collected, and micro-computed tomography (micro-CT) of the femur was performed under inhaled sedation with isoflurane (Forene®). At 8 weeks after the osteotomy, the animals were killed and the treated femora were collected. Micro-CT was performed for all femora. Half of the 10 femora were subjected to biomechanical testing and the other half were subjected to histologic examination.

Serum Gla-OC and Glu-OC levels

Sandwich enzyme-linked immunosorbent assays were performed using commercially available kits to determine the serum Gla-OC and Glu-OC levels (Takara Bio Inc., Shiga, Japan). All samples were assayed in duplicate. A standard curve was generated for each protein, and the absolute concentrations were determined from the standard curve.

Biomechanical testing

A three-point bending breakdown test was performed at the fracture site of the femora using a load mechanical universal testing machine (Model 3365, Instron Corp., Norwood, MA, USA). The femur was placed with its anterior surface facing upward on the two lower support bars 15 mm apart, and the loading bar was positioned at the fracture site (anteroposterior position). The load was applied at a rate of 0.2 mm/min until breakage. The ultimate load (N) and stiffness (N/mm) were calculated from the load–deformation curve. As previously described, the load-displacement data were normalized to obtain intrinsic material properties such as ultimate stress and elastic

modulus, which are independent of cross-sectional size and shape [5].

Micro-CT analysis.

Femora were scanned individually by micro-CT (CT, R_mCT2; Rigaku, Tokyo, Japan) at a 20- μ m isotropic resolution. Three-dimensional reconstruction of mineralized tissue and quantitative analysis of fracture calluses were performed using TRI-BONE software (Ratoc System Engineering, Tokyo, Japan) in accordance with the guidelines described in Buxsein et al [22]. The region of interest was set at the osteotomy site including the region 2.5 mm extending proximally and distally to the center of the gap with a total of 250 CT axial scans. The total bone volume (BV_{total}) was quantified first and then original bone volume ($BV_{original}$) was calculated by manually segmenting the original bone from the surrounding mineralized callus. The difference between BV_{total} and $BV_{original}$ was computed to determine the mineralized callus volume (BV_{callus}). The threshold for segmentation of the mineralized callus was 200 mg of hydroxyapatite/cm³, based on a phantom comprising known hydroxyapatite concentrations [23]. Bone mineral content of callus (BMC_{callus}) was measured and tissue mineral density of mineralized callus ($mBMD_{callus} = BMC_{callus}/BV_{callus}$) was calculated [24].

Histology and histomorphometry

For dynamic bone formation analysis, calcein (10 mg/kg, Dojindo Laboratories, Kumamoto, Japan) was injected subcutaneously at 7 days and 2 days, respectively, before the rat was killed. The femora were fixed in 70% ethanol, and stained with Villanueva Bone Stain. These specimens were then subjected to undecalcified tissue processing. The specimens were embedded in methyl-methacrylate (Wako Chemicals, Kanagawa, Japan) and sectioned at 5 μ m in the sagittal plane. The osteotomy site of the femur was examined by fluorescence microscopy (BX53,

Olympus, Tokyo, Japan) to evaluate the dynamic parameters of bone formation. Histomorphometric analysis was performed using an Image PRO-Plus (Media Cybernetics, Rockville, MD, USA). The measured parameters for callus bone included total tissue volume (TV), bone volume (BV), osteoid volume (OV), bone surface (BS), osteoblast number, osteoblast surface, single and double labeling surfaces (sLS and dLS, respectively), and inter-label width. These data were used to calculate percent bone volume (BV/TV), percent osteoid volume (OV/BV), osteoblast number (N.Ob/BS), osteoblast surface (Ob/BS), mineralizing surface (MS/BS), mineral apposition rate (MAR), and bone formation rate (BFR)/BS in accordance with the standard nomenclature proposed by Dempster et al [25].

Statistical Analysis

All data are expressed as means and standard error of the mean (SEM). Comparisons of data among the groups were performed using a one-way analysis of variance and Newman-Kuels tests. A significance level of P less than 0.05 was used for all comparisons. Correlations between serum Gla-OC level and mechanical properties were performed using Pearson product-moment correlation coefficient, with level of significance set at $p < 0.05$. All statistical analyses were performed using GraphPad Prism (GraphPad Software, Inc., San Diego, CA, USA) on a Windows computer.

Results

Gla- and Glu-OC levels during bone repair

Serum levels of Gla-OC and Glu-OC were measured at the time of surgery, and 2, 4, 6, and 8 weeks after osteotomy, and the time course of change in Gla- and Glu-OC levels was assessed in each individual (Fig. 1). The Gla- and Glu-OC data in the vehicle group showed a natural course of changes in Gla- and Glu-OC after bone injury. In the vehicle group, Gla-OC increased by 18% from the baseline at 2 weeks after osteotomy and then decreased from 2 to 8 weeks after osteotomy. PTH₁₋₃₄ treatment amplified the postoperative increase in Gla-OC production. The rats in the PTH₁₋₃₄ group showed 100% to 140% increase in Gla-OC from the baseline at 2, 4, and 6 weeks after surgery. While supplementation of vitamin K₂ did not further change the postoperative course of the Gla-OC levels of PTH₁₋₃₄-treated rats, warfarin blocked the increasing effect of PTH₁₋₃₄ on Gla-OC and decreased Gla-OC levels to baseline (-50 ± 12 and $-88 \pm 14\%$ from baseline at 2 and 6 weeks after osteotomy, respectively).

Glu-OC increased during first 4 weeks after the surgery and then decreased from 4 to 8 weeks after the surgery in the vehicle treated rats. While PTH₁₋₃₄ and PTH₁₋₃₄ + vitamin K₂ groups showed no significant effect on the time course of change in Glu-OC, administration of warfarin remarkably upregulated Glu-OC at any time point after the surgery (mean change of Glu-OC at 2 weeks after osteotomy from the baseline; $2238 \pm 789\%$ in PTH₁₋₃₄ + warfarin group vs. $185 \pm 47\%$ in PTH₁₋₃₄ group).

Effect of vitamin K insufficiency or supplementation on the efficacy of PTH₁₋₃₄ therapy in biomechanical parameters of bone repair

We assessed biomechanical properties of osteotomized femurs at 8 weeks after osteotomy to

allow for adequate healing for the three-point bending test. Consistent with previous reports, PTH₁₋₃₄ administration increased the ultimate stress and stiffness of the osteotomized femur to 2.4 and 1.7 times those in the vehicle group [18, 26]. Concomitant use of warfarin attenuated the effect of PTH₁₋₃₄ administration on the biomechanical properties (ultimate stress and stiffness to 0.5 and 0.6 times those in the PTH₁₋₃₄ group). Meanwhile, concurrent use of vitamin K₂ and PTH₁₋₃₄ showed some additive, albeit statistically insignificant, effects on the biomechanical properties (ultimate stress and stiffness to 1.5 and 1.3 times those in the PTH₁₋₃₄ group). The effects of warfarin and vitamin K₂ on intrinsic material properties of the osteotomized femur in PTH₁₋₃₄-treated rats, including elastic modulus and bending strength, were similar to those on ultimate stress and stiffness (Table 1). Although we failed to detect a statistically significant difference among the PTH₁₋₃₄ administration groups, we found a statistically significant correlation between Gla-OC levels at 2, 4, and 6 weeks after surgery and the mechanical properties (Table 2).

Effect of vitamin K insufficiency or supplementation on the efficacy of PTH₁₋₃₄ therapy in radiographic parameters of bone repair

To assess the bone repair process after osteotomy, longitudinal micro-CT analysis was performed at 2, 4, 6, and 8 weeks after osteotomy. The effect of PTH₁₋₃₄ on bone repair was apparent on micro-CT reconstruction images by the large and solid callus formation (Fig. 2A) [5, 15, 27]. The gap at the osteotomy site was filled with calcified bone within 6 weeks after osteotomy in PTH₁₋₃₄ and PTH₁₋₃₄ + vitamin K₂ groups, whereas mineralization of the osteotomy gap tended to be delayed in PTH₁₋₃₄ + warfarin group.

To more carefully assess the effect of PTH₁₋₃₄ and vitamin K level on radiographic healing, quantitative analysis of the calcified callus was performed after removal of the intramedullary

metal pin 8 weeks after osteotomy. BV_{callus} and $mBMD_{\text{callus}}$ were higher in the PTH_{1-34} administration groups than in the vehicle groups (Fig. 2B, C). Although PTH_{1-34} + warfarin group tended to show lower BV_{callus} and $mBMD_{\text{callus}}$ than the other two PTH_{1-34} groups, we failed to detect a significant difference in BV_{callus} and $mBMD_{\text{callus}}$ among the PTH_{1-34} administration groups.

Effect of vitamin K insufficiency or supplementation for the efficacy of PTH_{1-34} therapy on histologic parameters of bone repair

To better understand the mechanism responsible for the drug effects on biomechanical properties, we analyzed the histology at 8 weeks after surgery. Similar to the findings of the micro-CT study, the calluses were densely formed (Fig. 3A-D) and BV/TV was greater in the PTH_{1-34} administered groups than in the vehicle group (Fig. 3M). The osteoid, which is unmineralized bone matrix stained red-purple with Villanueva staining, was abundant in the specimens of the PTH_{1-34} + warfarin group (Fig. 3G and K), and the OV/BV was higher in the PTH_{1-34} + warfarin group compared to the vehicle and PTH_{1-34} + vitamin K groups (Fig. 3N). $N.Ob/BS$, $Ob.S/BS$, and MS/BS were greater in the PTH_{1-34} administered groups than in the vehicle group but these are similar among PTH_{1-34} , PTH_{1-34} + warfarin, and PTH_{1-34} + vitamin K_2 groups (Fig. 3O and P). Analysis of the BFR revealed that PTH_{1-34} enhanced the mineralization of the fracture callus based on an increase in MAR and BFR/BS (Fig. 3I-L and Q-S) [6] While concomitant use of vitamin K_2 did not further increase MAR and BFR/BS, concomitant use of warfarin blunted the enhancing effects of PTH_{1-34} on MAR and BFR/BS.

Discussion

The present study addressed whether vitamin K levels affect the efficacy of PTH_{1-34} therapy for

bone repair. Although we could not provide direct evidence for the correlation between vitamin K levels and the efficacy of PTH₁₋₃₄ therapy for bone repair, our data suggest that impaired γ -carboxylation of OC, which is induced by vitamin K insufficiency, attenuates the enhancing effect of PTH₁₋₃₄ therapy for biomechanical recovery of osteotomized bone. There are, however, conflicting results with respect to the effect of impaired carboxylation of OC on bone repair. Einhorn et al. demonstrated that despite a significant decrease in γ -carboxylated OC, vitamin K deficiency due to a diet lacking vitamin K did not impair fracture-healing in a rat femoral fracture model [28]. On the other hand, some studies have demonstrated that warfarin, a vitamin K antagonist, retards fracture healing [29]. Given that PTH₁₋₃₄ therapy upregulated Gla-OC level 5-fold greater than vehicle control after the osteotomy, PTH₁₋₃₄-treated subjects may be more susceptible to vitamin K insufficiency in terms of bone repair.

We also examined whether vitamin K₂ supplementation enhances the efficacy of PTH₁₋₃₄ therapy for bone repair. Although vitamin K₂ therapy promotes long bone repair in rats [16], we demonstrated only a trend for additive effects of PTH₁₋₃₄ and vitamin K₂ on bone repair. A possible reason for this discrepancy is that all of the animals used in this study were fed a normal diet containing vitamin K₃ and were thus thought to have adequate vitamin K levels, suggesting that this combination therapy is not effective in patients taking sufficient dietary vitamin K. Vitamin K₂ may be worth administering in combination with PTH₁₋₃₄ in elderly patients, however, because elderly people are likely to have lower vitamin K levels [30]. Given that vitamin K₂ promotes the differentiation of osteoblasts through SXR receptors, vitamin K₂ might enhance bone healing through a mechanism other than γ -carboxylation of OC [31, 32].

An interesting finding of the present study is that warfarin remarkably decreased Gla-OC levels, but did not significantly reduce the mineral content of fracture calluses in PTH₁₋₃₄-treated

1 rats. This indicates that Gla-OC is not critical for mineralization of the fracture callus. Because of
2 its specific interaction with hydroxyapatite, Gla-OC is thought to affect mineralization of the bone
3 matrix [33, 34]. Recent studies assessing the role of OC, however, indicate that OC is not related
4 to mineral deposition but does participate in the growth and maturation of hydroxyapatite.
5 Amizuka et al. demonstrated that warfarin administration did not change histochemical and
6 histomorphometrical appearance of bone but resulted in crystalline particles being dispersed
7 throughout the osteoid without forming mineralized nodules, which could be observed by electron
8 microscopy, in a rat model [35]. Genetic studies showed that OC depletion increases bone mass but
9 do not change the mineral content of bone matrix histologically [36]. In a more sensitive assay of
10 mineralization, Fourier transform infrared spectroscopy analysis revealed that hydroxyapatite
11 crystals in OC-deficient mice were smaller and less perfect compared to wild-type animals,
12 suggesting that OC plays an important role in bone mineral maturation. Our finding that Gla-OC
13 correlated with the mechanical properties of the operative femur indicates that Gla-OC contributes
14 to the biomechanical recovery of fractured bone by regulating the crystallization behavior of
15 hydroxyapatite, such as orientation and crystallinity, which are considered important bone
16 qualitative factors for the mechanical properties of bone.

17 It should be noted that the dosage of PTH₁₋₃₄ used in this study corresponds to tens or hundreds of
18 multiples of the FDA approved doses of 20 µg/day for treatment of osteoporosis. We selected the
19 dosage of 30 µg/kg body weight PTH₁₋₃₄ per day because a greater dose of PTH₁₋₃₄ is needed to
20 observe significant effects in rodent fracture models possibly due to the species difference.
21 Animal models typically employ doses of 5–200 (average 40, minimum effective dose is 5) µg/kg
22 body weight per day. Because we hypothesized that the impact of vitamin K insufficiency or
23 supplementation became more significant as production of osteocalcin increased by PTH₁₋₃₄

1 therapy, we selected a promising dose, 30 $\mu\text{g/kg}$, for anabolic effects on rat bone repair. However,
2 the effect of combination therapy of lower dose PTH_{1-34} and vitamin K on bone healing should be
3 examined in the future study. If vitamin K could minimize the required dosage of PTH_{1-34} to
4 enhance bone healing, the combination therapy would be helpful for clinical translation of PTH_{1-34}
5 therapy for bone repair by overcoming the problems associated with high dose PTH_{1-34} therapy
6 such as high cost, incidence of hypercalcemia and osteosarcoma.

7 There are several limitations to this study. First, we measured OC levels but did not measure
8 serum vitamin K levels because of technical difficulties in precisely measuring vitamin K levels
9 from the small amounts of serum collected. Because animals had free access to food containing
10 vitamin K₃, the vitamin K levels might have differed among rats. This might be why we detected a
11 correlation between postoperative Gla-OC levels and mechanical properties, but failed to detect a
12 significant difference in the mechanical properties among the PTH_{1-34} , PTH_{1-34} + warfarin, and
13 PTH_{1-34} + vitamin K groups. Second, the number of rats studied ($n = 5$ per group for biomechanical
14 testing) may be insufficient to detect “small” effects of vitamin K₂ on the mechanical properties of
15 the osteotomized femur. However, the power analysis suggests that $n=34$ rats per groups would be
16 necessary to detect significant difference in bending strength and such larger studies would not
17 alter the major conclusions in this study. Third, we did not evaluate the effect of other Gla-proteins,
18 such as Matrix Gla protein (MGP) on bone repair. MGP is another major Gla-protein in bone and
19 cartilage. While the function of MGP is not yet fully understood, it is thought to regulate the
20 development of cartilage and to inhibit mineralization. Therefore, the involvement of MGP in
21 bone repair requires further investigation.

22 In summary, we demonstrated that PTH_{1-34} therapy cannot fully exert its effect on bone repair
23 under conditions of vitamin K insufficiency in rats. This finding suggests that PTH_{1-34} therapy is

1 less effective for enhancing bone repair in patients with a low dietary vitamin K intake or patients
2 using the vitamin K antagonist warfarin as an anticoagulant therapy. Conversely, concomitant use
3 of vitamin K₂ with PTH₁₋₃₄ should improve mechanical recovery of fractured bone by regulating
4 the growth and maturation of hydroxyapatite crystal especially in patients with a low dietary
5 vitamin K intake.

6 7 **Disclosure**

8 All authors state that they have no conflict of interest.

9 10 **Acknowledgements**

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References

- [1]Neer RM, Arnaud CD, Zanchetta JR, Prince R, Gaich GA, Reginster JY, Hodsman AB, Eriksen EF, Ish-Shalom S, Genant HK, Wang O, Mitlak BH. Effect of parathyroid hormone (1-34) on fractures and bone mineral density in postmenopausal women with osteoporosis. *N Engl J Med* 2001;344: 1434-41.
- [2]Andreassen TT, Ejersted C, Oxlund H. Intermittent parathyroid hormone (1-34) treatment increases callus formation and mechanical strength of healing rat fractures. *J Bone Miner Res* 1999;14: 960-8.
- [3]Nakajima Y, Ishida M, Mikami K. Microtubules mediate germ-nuclear behavior after meiosis in conjugation of *Paramecium caudatum*. *J Eukaryot Microbiol* 2002;49: 74-81.
- [4]Andreassen TT, Willick GE, Morley P, Whitfield JF. Treatment with parathyroid hormone hPTH(1-34), hPTH(1-31), and monocyclic hPTH(1-31) enhances fracture strength and callus amount after withdrawal fracture strength and callus mechanical quality continue to increase. *Calcif Tissue Int* 2004;74: 351-6.
- [5]Komatsubara S, Mori S, Mashiba T, Nonaka K, Seki A, Akiyama T, Miyamoto K, Cao Y, Manabe T, Norimatsu H. Human parathyroid hormone (1-34) accelerates the fracture healing process of woven to lamellar bone replacement and new cortical shell formation in rat femora. *Bone* 2005;36: 678-87.
- [6]Nakazawa T, Nakajima A, Shiomi K, Moriya H, Einhorn TA, Yamazaki M. Effects of low-dose, intermittent treatment with recombinant human parathyroid hormone (1-34) on chondrogenesis in a model of experimental fracture healing. *Bone* 2005;37: 711-9.
- [7]Takahata M, Awad HA, O'Keefe RJ, Bukata SV, Schwarz EM. Endogenous tissue engineering: PTH therapy for skeletal repair. *Cell Tissue Res* 2012;347: 545-52.

- 1 **[8] Shearer MJ. Vitamin K. Lancet 1995;345: 229-34.**
- 2 **[9] Nelsestuen GL, Zytkevich TH, Howard JB. The mode of action of vitamin K.**
3 **Identification of gamma-carboxyglutamic acid as a component of prothrombin. J Biol Chem**
4 **1974;249: 6347-50.**
- 5 **[10]Stenflo J, Fernlund P, Egan W, Roepstorff P. Vitamin K dependent modifications of**
6 **glutamic acid residues in prothrombin. Proc Natl Acad Sci U S A 1974;71: 2730-3.**
- 7 **[11]Hauschka PV, Lian JB, Gallop PM. Direct identification of the calcium-binding amino**
8 **acid, gamma-carboxyglutamate, in mineralized tissue. Proc Natl Acad Sci U S A 1975;72:**
9 **3925-9.**
- 10 **[12]Abrahams MJ, Price J, Whitlock FA, Williams G. The Brisbane floods, January 1974:**
11 **their impact on health. Med J Aust 1976;2: 936-9.**
- 12 **[13]Price PA, Williamson MK, Lothringer JW. Origin of the vitamin K-dependent bone**
13 **protein found in plasma and its clearance by kidney and bone. J Biol Chem 1981;256:**
14 **12760-6.**
- 15 **[14]Hoang QQ, Sicheri F, Howard AJ, Yang DS. Bone recognition mechanism of porcine**
16 **osteocalcin from crystal structure. Nature 2003;425: 977-80.**
- 17 **[15]Aiko S, Kumano I, Yamanaka N, Tsujimoto H, Takahata R, Maehara T. Effects of an**
18 **immuno-enhanced diet containing antioxidants in esophageal cancer surgery following**
19 **neoadjuvant therapy. Dis Esophagus 2012;25: 137-45.**
- 20 **[16]Iwamoto J, Seki A, Sato Y, Matsumoto H, Tateda T, Yeh JK. Vitamin K2 promotes bone**
21 **healing in a rat femoral osteotomy model with or without glucocorticoid treatment. Calcif**
22 **Tissue Int 2010;86: 234-41.**
- 23 **[17]Tobita K, Ohnishi I, Matsumoto T, Ohashi S, Bessho M, Kaneko M, Matsuyama J,**

1 Nakamura K. Effect of low-intensity pulsed ultrasound stimulation on callus remodelling in
2 a gap-healing model: evaluation by bone morphometry using three-dimensional
3 quantitative micro-CT. *J Bone Joint Surg Br* 2011;93: 525-30.

4 [18]Alkhiary YM, Gerstenfeld LC, Krall E, Westmore M, Sato M, Mitlak BH, Einhorn TA.
5 Enhancement of experimental fracture-healing by systemic administration of recombinant
6 human parathyroid hormone (PTH 1-34). *J Bone Joint Surg Am* 2005;87: 731-41.

7 [19]Iwamoto J, Yeh JK, Takeda T. Effect of vitamin K2 on cortical and cancellous bones in
8 orchidectomized and/or sciatic neurectomized rats. *J Bone Miner Res* 2003;18: 776-83.

9 [20]Iwamoto J, Yeh JK, Schmidt A, Rowley E, Stanfield L, Takeda T, Sato M. Raloxifene
10 and vitamin K2 combine to improve the femoral neck strength of ovariectomized rats. *Calcif*
11 *Tissue Int* 2005;77: 119-26.

12 [21]Patel NN, Shah PR, Wilson E, Haray PN. An unexpected supraclavicular swelling.
13 *World J Surg Oncol* 2007;5: 90.

14 [22]Bouxsein ML, Boyd SK, Christiansen BA, Guldberg RE, Jepsen KJ, Muller R.
15 Guidelines for assessment of bone microstructure in rodents using micro-computed
16 tomography. *J Bone Miner Res* 2010;25: 1468-86.

17 [23]Malizos KN, Papachristos AA, Protopappas VC, Fotiadis DI. Transosseous application
18 of low-intensity ultrasound for the enhancement and monitoring of fracture healing process
19 in a sheep osteotomy model. *Bone* 2006;38: 530-9.

20 [24]Nyman JS, Munoz S, Jadhav S, Mansour A, Yoshii T, Mundy GR, Gutierrez GE.
21 Quantitative measures of femoral fracture repair in rats derived by micro-computed
22 tomography. *J Biomech* 2009;42: 891-7.

23 [25]Dempster DW, Compston JE, Drezner MK, Glorieux FH, Kanis JA, Malluche H,

Meunier PJ, Ott SM, Recker RR, Parfitt AM. Standardized nomenclature, symbols, and units for bone histomorphometry: a 2012 update of the report of the ASBMR Histomorphometry Nomenclature Committee. *J Bone Miner Res* 2013;28: 2-17.

[26]Li YF, Zhou CC, Li JH, Luo E, Zhu SS, Feng G, Hu J. The effects of combined human parathyroid hormone (1-34) and zoledronic acid treatment on fracture healing in osteoporotic rats. *Osteoporos Int* 2012;23: 1463-74.

[27]Manabe T, Mori S, Mashiba T, Kaji Y, Iwata K, Komatsubara S, Seki A, Sun YX, Yamamoto T. Human parathyroid hormone (1-34) accelerates natural fracture healing process in the femoral osteotomy model of cynomolgus monkeys. *Bone* 2007;40: 1475-82.

[28]Einhorn TA, Gundberg CM, Devlin VJ, Warman J. Fracture healing and osteocalcin metabolism in vitamin K deficiency. *Clin Orthop Relat Res* 1988: 219-25.

[29]Lindner T, Cockbain AJ, El Masry MA, Katonis P, Tsiridis E, Schizas C. The effect of anticoagulant pharmacotherapy on fracture healing. *Expert Opin Pharmacother* 2008;9: 1169-87.

[30]Tsugawa N, Shiraki M, Suhara Y, Kamao M, Tanaka K, Okano T. Vitamin K status of healthy Japanese women: age-related vitamin K requirement for gamma-carboxylation of osteocalcin. *Am J Clin Nutr* 2006;83: 380-6.

[31]Sokoll LJ, Booth SL, O'Brien ME, Davidson KW, Tsaion KI, Sadowski JA. Changes in serum osteocalcin, plasma phylloquinone, and urinary gamma-carboxyglutamic acid in response to altered intakes of dietary phylloquinone in human subjects. *Am J Clin Nutr* 1997;65: 779-84.

[32]Tabb MM, Sun A, Zhou C, Grun F, Errandi J, Romero K, Pham H, Inoue S, Mallick S, Lin M, Forman BM, Blumberg B. Vitamin K2 regulation of bone homeostasis is mediated by

1 the steroid and xenobiotic receptor SXR. *J Biol Chem* 2003;278: 43919-27.

2 [33]Boskey AL, Gadaleta S, Gundberg C, Doty SB, Ducy P, Karsenty G. Fourier transform
3 infrared microspectroscopic analysis of bones of osteocalcin-deficient mice provides insight
4 into the function of osteocalcin. *Bone* 1998;23: 187-96.

5 [34]Roy ME, Nishimoto SK, Rho JY, Bhattacharya SK, Lin JS, Pharr GM. Correlations
6 between osteocalcin content, degree of mineralization, and mechanical properties of C.
7 carpio rib bone. *J Biomed Mater Res* 2001;54: 547-53.

8 [35]Amizuka N, Li M, Hara K, Kobayashi M, de Freitas PH, Ubaidus S, Oda K, Akiyama Y.
9 Warfarin administration disrupts the assembly of mineralized nodules in the osteoid. *J*
10 *Electron Microsc (Tokyo)* 2009;58: 55-65.

11 [36]Ducy P, Desbois C, Boyce B, Pinero G, Story B, Dunstan C, Smith E, Bonadio J,
12 Goldstein S, Gundberg C, Bradley A, Karsenty G. Increased bone formation in
13 osteocalcin-deficient mice. *Nature* 1996;382: 448-52.

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Figure legends

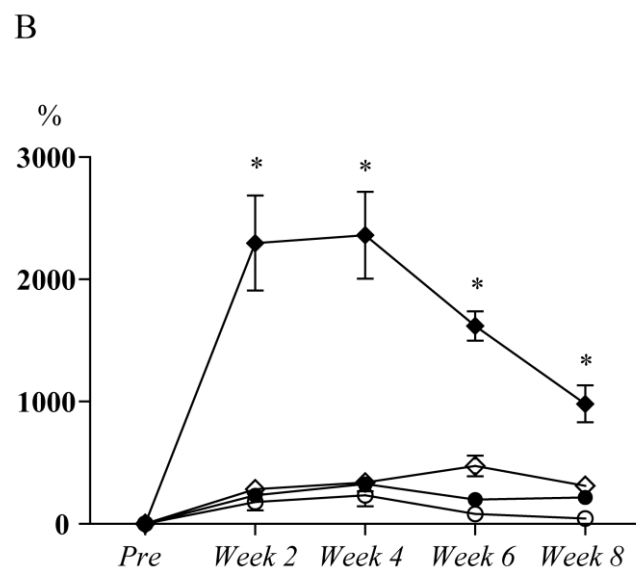
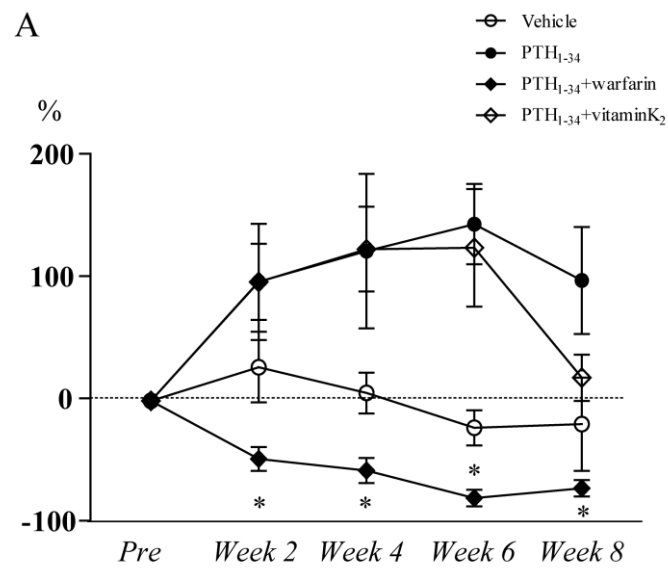
Fig.1. Percent change in Gla-OC (A) and Glu-OC (B) after osteotomy. (A) In the vehicle group, Gla-OC increased 18% from the baseline at week 2 and decreased thereafter. PTH₁₋₃₄ increased 5-fold more in the Gla-OC group compared with the vehicle group at week 2 and the high Gla-OC level was maintained at week 6. Warfarin cancelled the effect of PTH₁₋₃₄ and further decreased Gla-OC to lower than baseline level throughout the observation period. Administration of vitamin K₂ did not have additive effects with Gla-OC for PTH₁₋₃₄ therapy. (B) Glu-OC increased by 100%-200% after osteotomy in all groups except in the PTH₁₋₃₄ + warfarin group. Glu-OC markedly increased in PTH₁₋₃₄ + warfarin group. Values shown are mean $\pm$ SEM (n=6). * P < 0.05 vs. PTH₁₋₃₄ group.

Fig. 2. Effect of vitamin K insufficiency or supplementation on the efficacy of PTH₁₋₃₄ therapy for radiographic healing of osteotomized femurs. (A) Longitudinal 2D-reconstructed micro-CT images of representative specimens in each group are shown. (B) Mineralized bone volume (BV_{callus}) and (C) volumetric bone mineral density (mBMD_{callus}) of the callus at 8 weeks postsurgery were calculated from the micro-CT data. PTH₁₋₃₄ groups had higher BV_{callus} and mBMD_{callus} than the vehicle group. Warfarin tended to blunt the efficacy of PTH₁₋₃₄ therapy in terms of BV_{callus} and mBMD_{callus}. Values shown are mean $\pm$ SEM (n=10). * P < 0.05 vs. vehicle group.

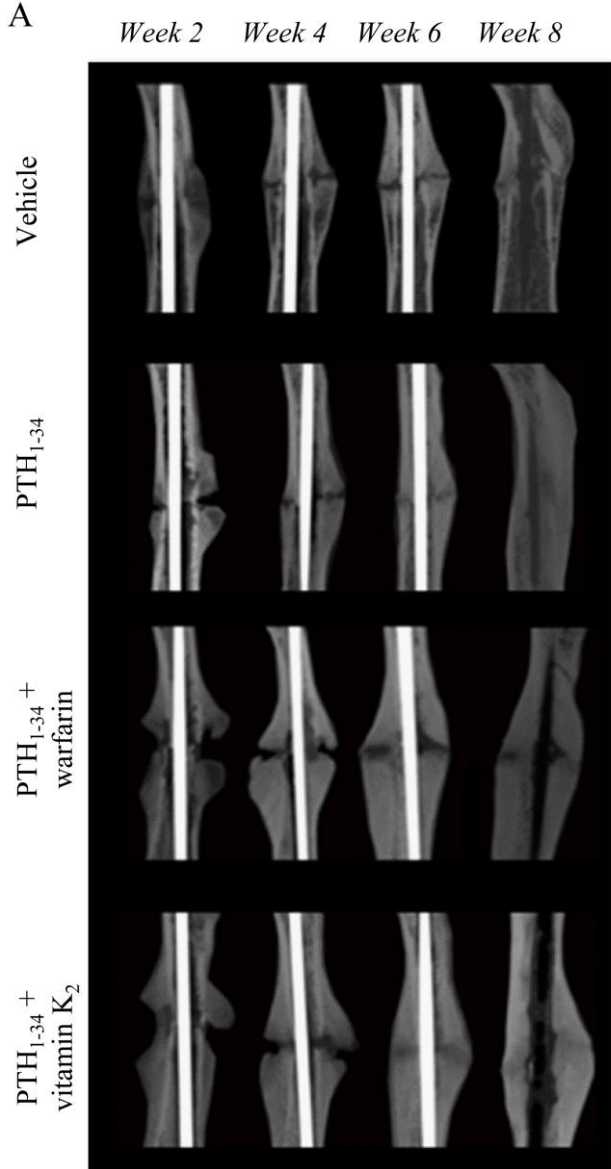
Fig. 3. Histology and histomorphometry of the callus. Longitudinal sections of the osteotomized femurs at 8 weeks postsurgery with Villanueva bone staining were observed by light microscopy (A-H) and under epifluorescent light (I-L). A-D and E-H are low and high

1 magnification micrographs of the callus, respectively. Osteoids, shown as red-purple in brightfield
2 images or red in epifluorescent light images, were abundant in the PTH₁₋₃₄ and vitamin K groups.
3 Bone histomorphometry data, including (M) bone volume of tissue volume (BV/TV), (N) osteoid
4 volume of bone volume (OV/BV), (O) osteoblast number (N.Ob/BS), (P) osteoblast surface
5 (Ob/BS), (Q) mineralizing surface (MS/BS), (R) mineral apposition rate (MAR), and (S) bone
6 formation rate of bone surface (BFR/BS), are shown. Bars = 100 μ m. Values shown are mean $\pm$
7 SEM (n=5). *: P < 0.05 vs. vehicle group. **: P < 0.05 vs. PTH₁₋₃₄ group.

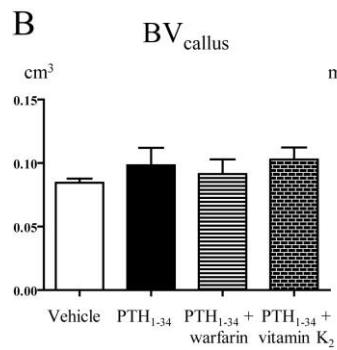
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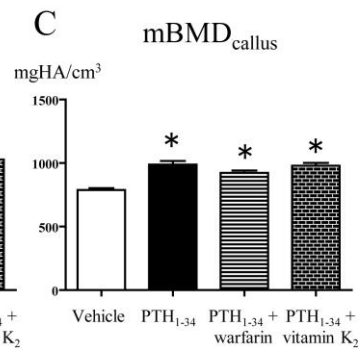
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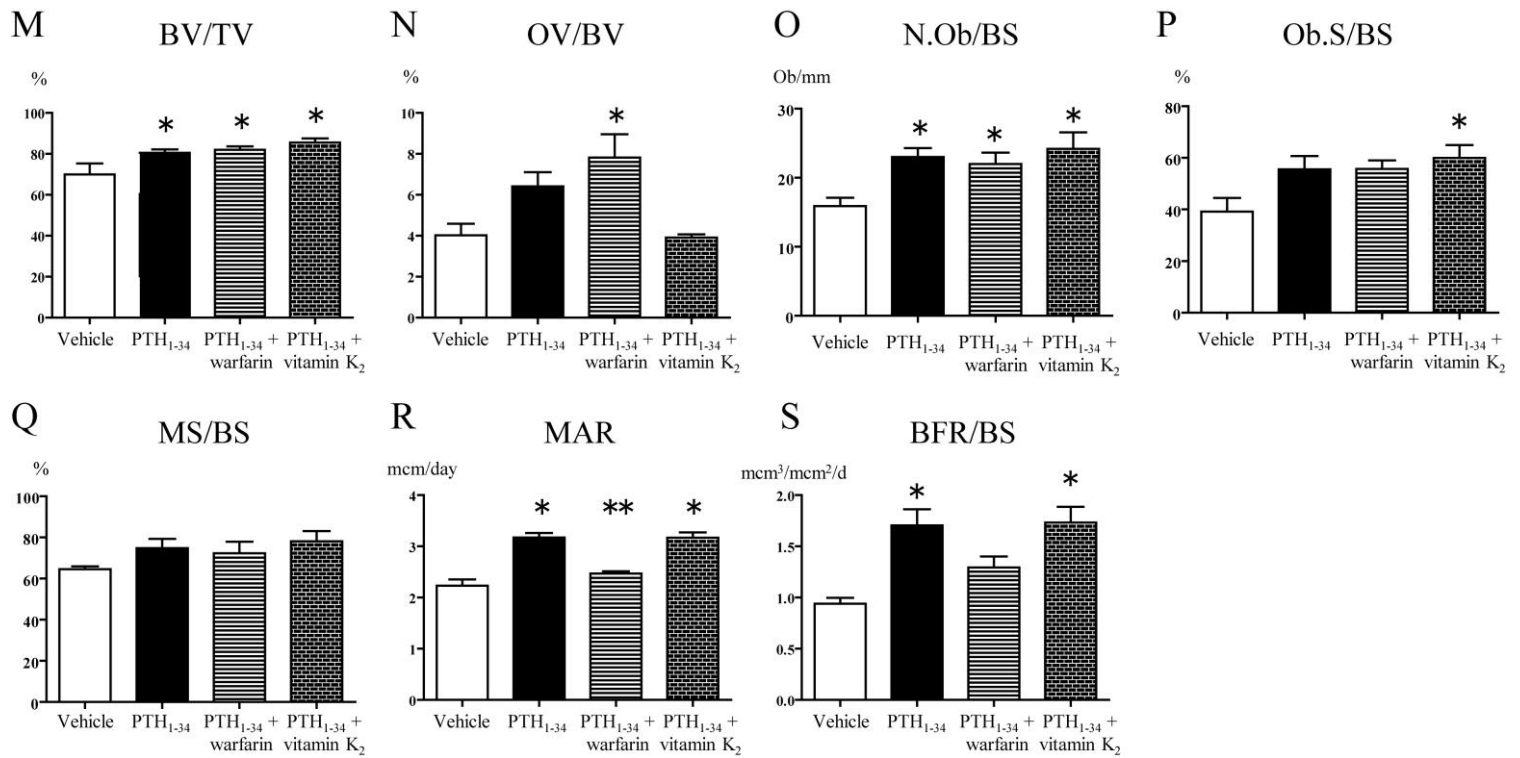
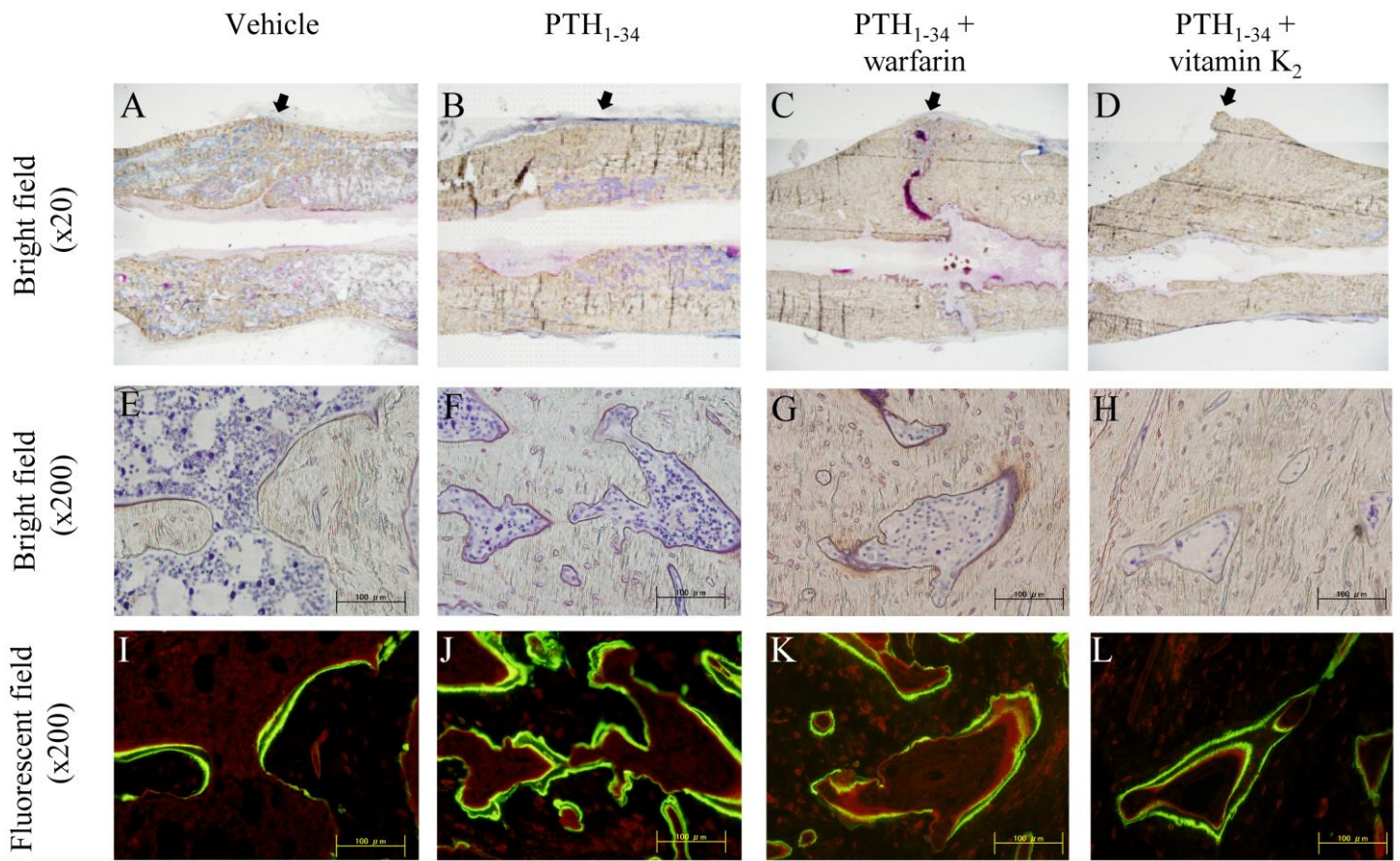


Table 1. Biomechanical properties of the osteotomized femurs at 8-week postsurgery.

	Vehicle	PTH ₁₋₃₄	PTH ₁₋₃₄ warfarin	PTH ₁₋₃₄ vitamin K ₂
Ultimate stress (N)	74.6 ± 8.8	180.7 ± 37.9	97.4 ± 33.4	265.9 ± 42.9*
Stiffness (N/mm)	20.0 ± 5.2	34.9 ± 6.0	21.4 ± 8.4	46.3 ± 4.4*
Elastic modulus (MPa)	139.9 ± 36.5	390.9 ± 126.1	188.5 ± 62.9	517.2 ± 89.0*
Bending strength (MPa)	10.0 ± 1.8	34.0 ± 10.0	15.3 ± 4.8	46.1 ± 5.6*

Values are mean ± SEM. n=5 for each group

*:p<0.05 vs. vehicle

Table 2: Correlations between 8-week mechanical properties of osteotomized femurs and postoperative serum Gla-OC levels

	Ultimate load	Stiffness	Elastic modulus	Bending strength
Gla-OC <i>Week 2</i>	0.6348 p=0.015*	0.4125 p=0.142	0.5050 p=0.061	0.7695 p=0.0013*
Gla-OC <i>Week 4</i>	0.7367 p=0.003*	0.6467 p=0.012*	0.6454 p=0.013*	0.6918 p=0.0061*
Gla-OC <i>Week 6</i>	0.7339 p=0.003*	0.6333 p=0.015*	0.6365 p=0.014*	0.7764 p=0.0011*
Gla-OC <i>Week 8</i>	0.2689 p=0.352	0.2668 p=0.357	0.5052 p=0.062	0.4603 p=0.098

Upper; Pearson r, Lower; p value.

* indicates statistically significant correlation $p < 0.05$