Role of RANKL and RANK in bone loss and arthritis

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The tumour necrosis factor family molecule RANKL (RANKL, TRANCE, ODF) and its receptor RANK are key regulators of bone remodelling and regulate T cell/dendritic cell communications, and lymph node formation. Moreover, RANKL and RANK are expressed in mammary gland epithelial cells and control the development of a lactating mammary gland during pregnancy and the propagation of mammalian species. Importantly, RANKL and RANK are essential for the development and activation of osteoclasts and bone loss in response to virtually all triggers tested. Therapeutically, inhibition of RANKL function via the decoy receptor osteoprotegerin completely prevents bone loss at inflamed joints and has partially beneficial effects on cartilage destruction in all arthritis models studied. Modulation of these systems provides a unique opportunity to design novel treatments to inhibit bone loss and crippling in arthritis.

The tumour necrosis factor family molecule RANKL (RANKL, TRANCE, ODF) and its receptor RANK are key regulators of bone remodelling and regulate T cell/dendritic cell communications, and lymph node formation. Moreover, production of RANKL by activated T cells directly controls osteoclastogenesis and bone remodelling and explains why autoimmune diseases, cancers, leukemias, asthma, chronic viral infections, and periodontal disease result in systemic and local bone loss. In particular, RANKL seems to be the pathogenetic principle that causes bone and cartilage destruction in arthritis. Inhibition of RANKL function via the natural decay receptor osteoprotegerin (OPG, TNFRSF11B) prevents bone loss in postmenopausal osteoporosis and cancer metastases and completely blocks bone loss and crippling in various rodent models of arthritis. Intriguingly, RANKL and RANK play essential parts in the formation of a lactating mammary gland in pregnancy. This system provided a novel and unexpected molecular paradigm that links bone morphogenesis, T cell activation and the organisation of lymphoid tissues, and mammary gland formation required for the survival of mammalian species. Inhibition of RANKL function via its natural decay receptor OPG or small molecules might be the future treatment of choice to abolish osteoporosis, tooth loss, or crippling in arthritis.

RANKL
RANKL/OPGL/TRANCE/ODF/TNFSF11 was cloned simultaneously by four independent groups. The rankl gene encodes a TNF superfamily molecule of 316 amino acids (38 kDa) and three RANKL subunits assemble to form the functional trimeric molecule. Trimeric RANKL is made as a membrane anchored molecule and can then be released from the cell surface as a soluble homotrimeric molecules after proteolytic cleavage by the metalloprotease disintegrin TNFα convertase (TACE). It remains to be seen whether TACE is indeed the critical protease required for the release of RANKL from the cell surface. Although it has been proposed that soluble and membrane bound RANKL might have different biological functions, for example, membrane bound RANKL might work more efficiently than soluble RANKL, both soluble and membrane bound RANKL can function as potent agonistic ligands for osteoclastogenesis in vitro. The potential differences between soluble and membrane bound RANKL should be investigated further.

RANKL is highly expressed in osteoblast/stromal cells, primitive mesenchymal cells surrounding the cartilaginous anlagen and hypertrophying chondrocytes. RANKL mRNA has also been observed in prehypotrophic and hypertrophic chondrocytes at day 15 of embryogenesis and extraskeletal tissues such as the brain, heart, kidneys, skeletal muscle, and skin throughout mouse development. RANKL expression can be upregulated by bone resorbing factors such as glucocorticoids, vitamin D3, IL1, IL6, IL11, IL17, TNFα, PGE2.

Abbreviations:
TNF, tumour necrosis factor; RANKL, receptor activator of NFκB ligand; TRANCE, osteoclast differentiation factor; ODF, osteoclast differentiation factor; TACE, TNFα convertase; ODF, osteoclast differentiation factor; TRANCE, TNF related activation induced cytokine; TRAF, tumour necrosis factor receptor associated factor; RA, rheumatoid arthritis

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or PTH.1,12 Using in vitro culture systems, RANKL can both activate mature osteoclasts and mediate osteoclastogenesis in the presence of CSF1.13 As it was unclear whether RANKL was indeed essential for osteoclast development and function in vivo, our group created the first rankl mutant mice using gene targeting.14 Rankl-/- mice display severe osteopetrosis, stunted growth, and a defect in tooth eruption, and rankl-/- osteoblasts cannot support osteoclastogenesis. These mice still contain haematopoietic precursors that can differentiate into phenotypically and functionally mature osteoclasts in vitro.15 In vivo after injection of recombinant RANKL (JMP, unpublished data). Importantly, osteoclast cell lines derived from rankl-/- mice do not support osteoclast formation indicating that the defect in osteoclastogenesis observed in rankl-/- mice is attributable to an intrinsic defect in osteoblastic stroma.

Whereas csf1 mutant op/op mice display a developmental arrest in both monocyte/macrophage and osteoclast lineages, rankl-/- mice display normal monocyte/macrophage differentiation and normal differentiation of dendritic cells.16 The osteoclast defect in csf-1 mutant op/op mice is not absolute and older op/op mice do have, albeit only few osteoclasts. Moreover, the defect in op/op mice can be reversed by transgenic overexpression of Bcl-2 in the osteoblast/macrophage lineage indicating that—in contrast with RANKL—CSF1 expression is not essential for osteoclast development.17 Whether Bcl-2 overexpression would also rescue the phenotype in rankl-/- mice needs to be explored. Thus, our genetic data provided the first proof that RANKL is a specific and essential differentiation factor for osteoclast precursors. Moreover RANKL is an essential activation factor for mature osteoclasts (fig 1).

RECEPTOR ACTIVATOR OF NFκB LIGAND—RANK

The receptor for RANKL is RANK (receptor activator of NFκB also known as TRANCE-R, ODAR, or TNFRSF11A). RANK is a member of TNF-R superfamily, expressed as a transmembrane heterotrimer on the surface of haematopoietic osteoclasts progenitors, mature osteoclasts, chondrocytes, mammary gland epithelial cells,18 trophoblast cells, and multiple epithelial tumour cell lines (JMP, unpublished data). In vitro ligation of RANK with RANKL results in osteoclastogenesis from progenitor cells and the activation of mature osteoclasts.19,20 Mice with a genetic mutation of RANK are phenocopies of rankl-/- mice and have a complete block in osteoclast development that can be restored by reintroduction of RANK into bone marrow progenitor cells.20-22 The osteopetrosis observed in these mice can be reversed by transplantation of bone marrow from rank-/- mice, indicating that rank-/- mice have an intrinsic defect in osteoclast function. Thus, the interaction between RANKL expressed by stromal cells/osteoblasts and its receptor RANK expressed on osteoclast precursors are essential for osteoclastogenesis (fig 1). Importantly, in human familial expansile osteolysis, a rare autosomal dominant bone disorder characterised by focal areas of increased bone remodelling,23 a heterozygous insertion mutation in exon 1 of RANK has been noted that appears to increase RANK mediated NFκB activation and thus might be causal for the disease. All biochemical, functional, and genetic results in humans and mutant mice established the absolute dependency of osteoclast differentiation and activation of mature osteoclasts on the expression of RANKL and RANK.

When RANK on osteoclasts is activated it sends signals into the cells through adapter proteins (fig 2). RANK contains 383 amino acids in its intracellular domain (residues 234–616), which contain three putative binding domains (termed I, II, and III) for tumour necrosis factor receptor associated factors (TRAFs).24 Mapping of the structural requirements for TRAF/RANK interaction revealed multiple TRAF binding sites clustered in two distinct domains in the RANK cytoplasmic tail. These TRAF binding domains were shown to be functionally important for the RANK dependent induction of NFκB and c-Jun NH2-terminal kinase (JNK) activities. In particular, TRAF6 interacts with membrane proximal determinants distinct from those binding TRAFs 1, 2, 3, and 5. When this membrane proximal TRAF6 interaction domain was deleted, RANK mediated NFκB signalling was completely inhibited while JNK activation was only partially inhibited25,26 suggesting that interaction with TRAFs is necessary for NFκB activation.

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activation but not essential for activation of the JNK pathway. Indeed mice lacking TRAF6 have a similar bone phenotype as *rank*+/-- mice attributable to a partial block in osteoclastogenesis and defective activation of mature osteoclasts.24-27 It should be noted that TRAF6 mutant mice still contain a substantial number of TRAP+ osteoclasts28 whereas Nfkb1/Nfkb2 double mutant mice completely lack TRAP+ osteoclasts.29 29 Thus, TRAF6 is a critical factor involved in the activation of mature osteoclasts but other TRAFs (and possibly other molecules) seem to be able to partially substitute for the loss of TRAF6 during osteoclast development. In line with these data, osteoclastogenesis can be initiated in rank-- mice by transfer of mutant RANK that lacks the TRAF6 binding site.30

RANKL also activates the anti-apoptotic serine/threonine kinase Akt/PKB through a signalling complex involving c-Src and TRAF6.31 c-Src and TRAF6 interact with each other and with RANK after receptor engagement and a deficiency in c-Src or addition of Src family kinase inhibitors blocks TRANCE mediated activation in osteoclasts. TRAF6, in turn, increases the kinase activity of c-Src leading to tyrosine phosphorylation of downstream signalling molecules such as c-Cbl.32 Moreover, RANK can recruit TRAF6, Cbl family scaffolding proteins, and the phospholipid kinase PI3-K in a ligand and Src dependent manner. RANKL mediated Akt/PKB activation is defective in cbl-b/- dendritic cells.33 These findings implicate Cbl family proteins as not only negative regulators of signalling, but also as positive modulators of TNFR superfamily signalling. Moreover, these data provided the first evidence of a cross talk between TRAF proteins and Src family kinases. In addition, it should be noted that inhibition of p38 kinases using SB203580 and overexpression of dominant negative p38α or MKK6 can inhibit RANKL induced differentiation of the osteoclast-like cell line RAW264.7 in vitro culture systems.34 Whether JNK/SAPK kinases are also important for osteoclasts development or function, or both, has not been reported yet.

**OSTEOPROTEGERIN**

Osteoprotegerin (OPG; “protector of the bone”; also known as osteoclastogenesis inhibitory factor, OCIF) is a secreted protein with homology to members of the TNF receptor family.35 The OPG gene encodes a 44 kDa protein that is post-translationally modified to a 55 kDa molecule through N-linked glycosylation. Although OPG is a member of the TNFR family, which normally form molecular trimers, OPG is secreted as 110 kDa homodimer. OPG functions as a soluble decoy receptor to RANKL and competes with RANK for osteoclast regulated bone remodelling is critically dependent on these three molecules. However, although RANKL is also expressed in many other tissues than the bone, osteoclast development is restricted to the bone microenvironment suggesting that another tissue specific factor might exist that acts in concert with RANKL/RANK. It has recently been shown in vitro that TNFα and IL1 can apparently induce the development of TRAP+ osteoclasts in the absence of RANK/ RANKL.36 37 However, in our own genetic experiments using RANK deficient osteoclast progenitors, TNFα as well as IL1 dependent osteoclastogenesis are strictly dependent on RANK expression. Thus, whereas TNFα and IL1 seem to potentiate the development of osteoclasts,38 presumably via activation of common second messenger systems such as Nfkb activation, the effects of both IL1 and TNFα on osteoclasts rely on the expression of RANK/RANKL. It should be also noted that mutations of TNFα, TNFR1, or TNFR2 do not cause any changes in bone metabolisms or osteoclast development/activation in vivo.

In addition to the association between RANKL and OPG, OPG can also bind to the TNF family molecule TRAIL at low stoichiometry (about 10 000 times less binding to TRAIL than to RANKL). OPG-Fc binds TRAIL with an affinity of 3.0 nM, which is slightly weaker than the interaction of TRID-Fc or DR5- Fc with TRAIL. Functionally, high doses of OPG inhibit TRANCE mediated Akt/PKB activation in osteoclasts. These data suggest potential cross regulatory mechanisms by OPG and TRAIL. However, it is still not known whether OPG-TRAIL interactions have any functional relevance in vivo. Importantly, OPG expression is induced by oestrogen in cell lines and in vivo,39 40 which might explain postmenopausal osteoporosis in women, that is, reduced ovarian functions leads to reduced oestrogen levels and hence reduced OPG levels, which release RANKL from the inhibition by the decoy receptor. Injection of OPG into ovarectomised female rats blocks bone loss and osteoporosis normally associated with the loss of ovarian function.41 Thus, OPG and/or modulation of RANKL-RANK function via small molecules are promising avenues to prevent postmenopausal osteoporosis. In essence, OPG seems to function in bone loss similar to insulin in diabetes: injection of OPG prevents osteoclast activation and oestopenia in essentially every model system of osteoclast mediated bone loss.

**ROLE OF RANKL AND RANK IN THE IMMUNE SYSTEM**

At around the same time when we had the first evidence that RANKL might play a part in osteoclast development, RANKL (TRANCE) was independently cloned by two other groups as a molecule expressed on the surface of activated T cells. Both soluble and membrane-bound RANKL is produced by activated CD4+ and CD8+ T cells. RANKL is also expressed in lymph nodes, spleen, thymus and intestinal lymphoid patches, and immature CD4+CD8- thymocytes. Both
expression in T cells is induced by antigen receptor engagement and is regulated by calcineurin, ERK1/ERK-2, and PKC regulated signalling pathways.1,4 RANK is expressed on the surface of dendritic cells, B cells, or dendritic cells that cannot be compensated for. CD40L-CD40 interactions might primarily control the initial priming stage whereas RANKL-RANK might have a specific and essential role in lymph node morphogenesis.2,5-7 Defective lymph node development in rankl-/- mice correlates with a significant reduction in lymphotxin LTβR αβ+CD45+CD4+CD3+ cells and their failure to form clusters in the rudimentary mesenteric lymph node anlage.7 Transgenic RANK mediated restoration of lymph node development required LTβR expression on CD45+CD4+CD3+ cells as lymph node formation could not be induced in LTα mice. The authors proposed that both RANKL and LTβR regulate the colonisation and cluster formation by CD45+CD4+CD3+ cells during lymph node morphogenesis.8 Importantly, RANKL disruption provided the first evidence that development of lymph nodes and Peyers patches can be genetically uncoupled. The exact cellular and molecular mechanism of RANKL-RANK regulated lymph node morphogenesis needs to be established.

T CELLS AND BONE: OSTEOIMMUNOLOGY

Bone remodelling and bone loss is controlled by a balance between RANKL/RANK and the RANKL decoy receptor OPG. As RANKL is made by T cells after antigen-receptor stimulation, we asked the question whether T cell derived RANKL can indeed regulate the development and activation of osteoclasts—that is, whether activated T cells can modulate osteoclast turnover via RANKL. In an in vitro cell culture system, activated T cells can directly trigger osteoclastogenesis via RANKL. Importantly, systemic activation of T cells in vivo leads to a RANKL dependent increase in osteoclastogenesis followed by bone loss. All in vitro and in vivo effects of T cells on osteoclasts could be blocked by the administration of the decoy receptor OPG. In a recent study it has been confirmed that transgenic overexpression of RANKL in T cells restores osteoclastogenesis in a rankl-/- background and partially restores normal bone marrow cavities. These data showed that systemic activation of T cells leads to bone loss, indicating that, through their production of RANKL, T cells are crucial mediators of bone loss in vivo. The results also provided a novel paradigm for T cells as regulators of bone physiology.

As mutant mice that lack T cells still have normal bone cavities and tooth eruption, T cells are probably not required for normal bone homeostasis. However, chronic systemic T cell activation such as in autoimmune diseases or viral infections or local inflammation within the bone attributable to metastasis, infections, bone implants such as artificial hips, and fractures, or joint inflammation in arthritis probably attracts T cells that then actively participate in bone remodelling via production of RANKL. Moreover, glucocorticoids, which are used to treat autoimmune diseases and allergic disorders, strongly induce RANKL expression and decrease OPG. Intriguingly, it has been recently shown that ovarectomy induced bone loss in wild type mice but not in T cell deficient nude mice, which was restored by adoptive transfer of wild type T cells. Moreover, this effect seems to depend on TNFα-TNFRp55 interactions that act presumably upstream of RANKL. If this observation holds true in humans, it is possible that T cells are the principal cells that contribute to bone loss in old age.

These findings provide a molecular explanation for bone loss associated with diseases having immune system involvement, such as adult and childhood leukaemias, cancer metastasis, autoimmunity, and various viral infections. Inhibition of RANKL function via OPG or a related molecule might therefore prevent bone destruction in multiple diseases. Moreover, it has now become clear that many other molecules such as osteopontin that have functions in bone physiology also have important roles in the immune systems.
RANKL/RANK control osteoclast activation and bone loss in arthritis

Bone loss represents an important unsolved problem in rheumatoid arthritis (RA). The skeletal complications of RA consist of focal bone erosions and periarticular osteoporosis at sites of active inflammation, and generalised bone loss with reduced bone mass. Local bone loss at the affected joints frequently results in lifelong crippling. Arthritis in humans and animal models is characterised by synovial inflammation, erosion of bone and cartilage, severe joint pain, and ultimately lifelong crippling. For example, in Lewis rats, experimental induction of arthritis by subcutaneous injection of bacterial products in adjuvant leads to severe inflammation in the bone marrow and soft tissues surrounding joints accompanied by extensive local bone and cartilage destruction, loss of bone mineral density, and crippling. This condition in rats, called adjuvant induced arthritis, mimics many of the clinical and pathological features of human RA. Lesions in rat adjuvant induced arthritis are dependent on T cell activation, and T cells in the inflamed joints and draining lymph nodes of affected rats have been shown to produce many proinflammatory cytokines.

In the adjuvant induced arthritis model, RANKL protein is expressed on the surface of synovial effector T cells isolated at the clinical onset of arthritis. Inhibition of RANKL via OPG had no effect on the severity of inflammation. However, OPG treatment completely abolished the loss of mineral bone density in the inflamed joints of these animals in a dose-dependent manner. Histologically, OPG treated arthritis exhibited minimal loss of cortical and trabecular bone, whereas untreated arthritic animals developed severe bone lesions characterised by partial to complete destruction of cortical and trabecular bone, and erosion of the articular cartilages. Bone destruction in untreated arthritic rats correlated with a dramatic increase in osteoclast numbers whereas OPG treatment prevented the accumulation of osteoclasts. These results showed that RANKL is a key mediator of joint destruction and bone loss in adjuvant arthritis. Importantly, whereas untreated rats experienced severe crippling, rats treated with OPG at the onset of disease—similar to a patient consulting a doctor at the onset of joint swelling—did not show any signs of clinical crippling.

Alteration of cartilage structures leading to cartilage collapse constitutes a critical step in arthritic joint destruction. Controversy exists whether cartilage destruction occurs independently of bone loss, or whether damage to the subchondral bone indirectly causes cartilage deterioration. In untreated arthritic rats, partial or complete erosion of the cartilage in both the central and peripheral regions of joint surfaces is observed. In striking contrast, neither cartilage erosion nor matrix degeneration in the centres of joint surfaces occurred in OPG treated animals. OPG could protect the cartilage by maintaining the underlying subchondral bone therefore insulating the overlying cartilage from the inflammatory cell infiltrates in the bone marrow. Both RANKL and RANK are expressed on chondrocytes, and rankl as well as rank mutant mice exhibit significant changes in the columnar alignment of chondrocytes at the growth plate, it is possible that RANKL/RANK play a direct part in cartilage growth and cartilage homeostasis. RANK, RANKL, and OPG expression have been recently observed in normal cartilage. However, the functional relevance of RANKL/RANK expression in chondrocytes is still not known. Thus, inhibition of RANKL activity by OPG can prevent cartilage destruction, a critical, irreversible step in the pathogenesis of arthritis.

Arthritis can occur in the absence of T cells. Using in situ hybridisation of inflamed rat joints and isolation of different cell populations from these joints, we could show that RANKL is indeed expressed in lymphocytes, macrophages, and especially in synoviocytes. In line with these findings, genetic ablation of RANKL does not prevent inflammation in an antibody mediated model of arthritis using the KxBN serum transfer model. Multinucleated TRAP positive osteoclast-like cells were abundant in resorption lacunae in areas of bone erosion in arthritic control mice, and were completely absent in arthritic RANKL mutant mice, demonstrating the absolute requirement for RANKL in osteoclastogenesis in this serum transfer model of inflammatory arthritis. Cartilage damage was still observed in both arthritic TRANCE/RANKL knockout mice and arthritic control mice but a trend towards milder cartilage damage in the rankl−/− mice was noted. Thus, it seems that RANKL is not essential for cartilage destruction, but clearly plays a yet unidentified modulatory part.

It has recently been shown that interleukin 1 and to a lesser extent TNFα are critical mediators of antibody induced arthritis in the serum transfer model. Moreover, inhibition of RANKL via OPG prevents bone loss and has a beneficial effect on cartilage destruction without affecting inflammation in a TNFα induced arthritis model indicating that TNFα triggered joint destruction is critically dependent on RANKL expression. It has also been recently suggested that the RANKL-RANK system plays an important part for osteoclastogenesis in both local and systemic osteolytic lesions in autoimmune type II collagen induced arthritis in mice. Thus, in all animals for arthritis studied so far, the RANKL/RANK system is the trigger of bone loss and crippling making OPG the prime drug candidate for therapeutic intervention in different forms of arthritis.

To extend these rodent studies to human patients with arthritis, we collected inflammatory cells from the synovial fluids of patients with adult or juvenile RA and patients with osteoarthritis and evaluated OPG and RANKL expression. All RA patients and patients with advanced osteoarthritis tested (n>40) in our study exhibited RANKL expression in inflammatory cells while OPG expression was not detectable. Thus, the correlation between RANKL expression in inflamed joints and arthritis was absolute. To distinguish which cells were producing RANKL, inflammatory synovial fluids were separated into T cell and non-T cell populations. Consistent with our results in rats, both synovial T cell and non-T cell populations from RA patients expressed RANKL, but not OPG. In subsequent studies, it has been shown that synovial T cells, monocytes, and synovial fibroblasts express both membrane bound and soluble forms of RANKL. Moreover, activated human T cells expressing RANKL can induce osteoclastogenesis from autologous peripheral monocytes, which can be blocked by dose dependent inhibition using OPG. These data confirm our initial findings in rodent adjuvant arthritis models, and suggest that RANKL is the principal mediator of bone destruction in human arthritis. Moreover, these results provide a unifying mechanism between T cell activation, cytokine production, and osteoclast activation and joint destruction via the RANKL/OPG/RANK ligand-receptor system that explains the spectrum of skeletal disorders in RA.
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Activated T cell

Hormones cytokines
TNFα, IL1

RANKL

OPGL

OPG

Bone loss and crippling in arthritis

Addition of bone

Resorption of bone

Figure 3: Rational drug design to interfere with arthritic disease. Activated T cells produce cytokines such as TNFα, IL1, IL11, and IL17 that lead to RANKL expression on osteoblasts. Moreover, activated T cells directly express and produce RANKL that induces osteoclast formation and activation. The soluble decoy receptor for RANKL, OPG, blocks both pathways. In addition to inhibiting the function of cytokines to alleviate inflammation, inhibition of RANKL via OPG might be useful to block osteoclast activation and crippling in arthritis irrespective of the disease trigger.

However, short-term activation of T cells does not result in any detectable bone loss and even in some chronic T cell and TNFα mediated diseases such as ankylosis spondylitis,15 T cell activation does not result in bone loss. Moreover, T cells are working constantly to fight off the universe of foreign particles in which we live, so, at any point in time, some T cells are activated.15 So what is it that prevents these T cells from causing extensive bone loss every time we have an infection? A crucial counter-regulatory mechanism, by which activated T cells can inhibit the RANKL induced maturation and activation of osteoclasts has been recently discovered (fig 2).16 It turns out that interferon gamma blocks RANKL induced osteoclast differentiation in vitro. Moreover, interferon gamma receptor knockout mice develop more bone destruction in inflammatory arthritis than normal mice. Mechanistically, interferon gamma can activate the ubiquitin–proteasome pathway within the osteoclasts, resulting in the degradation of TRAF6. Thus, it seems that interferon gamma can prevent uncontrolled bone loss during inflammatory T cell responses. Moreover, T cell derived IL12 alone and IL12 in synergy with IL18 inhibits osteoclast formation in vitro17 and IL4 can abrogate osteoclastogenesis through STAT6 dependent inhibition of NFκB signalling.18 Thus, multiple T cell derived cytokine might be able to interfere with RANK signalling and therefore osteoclastogenesis and osteoclast functions. In the future it will be interesting to determine the mechanisms that control the balance between T cell mediated bone loss and inhibition of osteoclastogenesis.

CONCLUSIONS

It has become clear that inhibition of RANKL mediated activation of RANK via OPG or a related molecule ameliorates many osteopenic conditions. RANKL inhibition seems to be the most rational and advisable strategy to prevent bone destruction in multiple diseases and to possibly eradicate major human diseases such as osteoporosis and to curtail crippling in arthritis, diseases that affect millions of people.

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