Osteoclasts are the cells responsible for bone resorption, a process that is essential for the maintenance of healthy bones. Bone diseases, such as osteoporosis, which are characterized by high rates of bone resorption and loss of bone mass, may benefit from treatments that inhibit osteoclast formation and/or function. The RANKL/RANK pathway is critical for both osteoclast formation and function, and these effects are thought to be mediated by the transcription factor nuclear factor of activated T cells, cytoplasmic 1 (NFATc1). In this issue of the *JCI*, Bae et al. challenge the convention that NFATc1 is the sole critical regulator of RANKL/RANK-dependent osteoclast activation. Specifically, the authors show that MYC drives metabolic reprogramming in osteoclasts and that MYC induces estrogen receptor–related receptor α (ERRα) to regulate osteoclastogenesis. Importantly, both loss of MYC and pharmacological inhibition of ERRα attenuated bone loss in a mouse model of osteoporosis. Together, the results of this study suggest that the MYC/ERRα pathway should be further explored as a drug target for bone diseases.
The many ways of osteoclast activation

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Osteoclasts in bone health and disease

Osteoclasts are the cells responsible for bone resorption, a process that is essential for the maintenance of healthy bones. Bone diseases, such as osteoporosis, which are characterized by high rates of bone resorption and loss of bone mass, may benefit from treatments that inhibit osteoclast formation and/or function. The RANKL/RANK pathway is critical for both osteoclast formation and function, and these effects are thought to be mediated by the transcription factor nuclear factor of activated T cells, cytoplasmic 1 (NFATc1). In this issue of the JCI, Bae et al. challenge the convention that NFATc1 is the sole critical regulator of RANKL/RANK-dependent osteoclast activation. Specifically, the authors show that MYC drives metabolic reprogramming in osteoclasts and that MYC induces estrogen receptor–related receptor α (ERRα) to regulate osteoclastogenesis. Importantly, both loss of MYC and pharmacological inhibition of ERRα attenuated bone loss in a mouse model of osteoporosis. Together, the results of this study suggest that the MYC/ERRα pathway should be further explored as a drug target for bone diseases.

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expression and RANKL-stimulated recruitment of MYC to the Nfatc1 promoter (19). Hence, they hypothesized that MYC is an upstream signal utilized by RANKL-RANK interaction at the cell surface to enhance NFATc1 production and stimulate osteoclast formation and function. Now, these authors have studied a mouse model in which MYC was conditionally deleted in myeloid lineage cells (MYCΔM mice). Not surprisingly, given their previous data demonstrating that MYC is an upstream signal that mediates RANKL-induced NFATc1 expression, MYCΔM mice had increased bone mass and decreased osteoclasts, with a normal number of bone-forming osteoblasts. In vitro, cultured bone marrow osteoclast precursor cells (OCPs) from MYCΔM mice completely failed to form mature osteoclasts in response to RANKL and M-CSF and had decreased NFATc1 expression. However, transduction of MYC-deficient OCPs with a conditionally active NFATc1 construct did not rescue osteoclastogenesis in these cells. This unexpected result argues that additional, NFATc1-independent pathways downstream of MYC mediate the ability of RANKL/RANK signaling to influence osteoclasts.

Bae et al. performed transcriptomic analysis of RANKL-treated WT and MYCΔM cells to identify additional pathways downstream of RANKL and MYC. This analysis revealed that the expression of genes associated with metabolic pathways, such as the TCA cycle and oxidative phosphorylation, were MYC dependent, as they were induced by RANKL in WT, but not MYCΔM, cells. Furthermore, oxygen consumption, ATP production, and respiratory capacity and reserve were decreased in MYCΔM cells, with no difference in mitochondrial mass between WT and MYCΔM cells. These findings are complementary to the work of Nishikawa et al. (20), who previously described an important role of mitochondrial respiration in osteoclast differentiation.

Bae et al. subsequently used gene set enrichment analysis to identify transcription factor–binding motifs that were enriched in the promoters of the MYC-dependent genes identified in their transcriptomic analysis. This enrichment revealed estrogen-related receptor α (ERRα) to be a MYC-dependent transcription factor with binding motifs within the first 2 kb of MYC-regulated gene promoters. Additionally, RANKL stimulated ERRα expression in WT, but not MYCΔM cells, and ChIP analysis showed that RANKL treatment recruits MYC to the Esrrα promoter. Moreover, MYC expression did not rescue osteoclastogenesis in MYCΔM cells in which ERRα was inhibited with the small-molecule inhibitor XCT790. Additional studies showed that the effects of RANKL on resorption were lost when ERRα was inhibited or deficient. Finally, coexpression of conditionally activated NFATc1 and ERRα in MYC-deficient OCP cultures partially rescued osteoclastogenesis. In total, these results demonstrate that ERRα mediates some of the effects of MYC on osteoclasts and synergizes with NFATc1 to mediate RANKL-stimulated bone resorption.

Bae et al. also evaluated the effect of the MYC/ERRα pathway on in vivo osteoclastogenesis and resorption (14). Specifically, the authors used the well-described ovariectomy model in mice to produce estrogen deficiency, which mimics postmenopausal osteoporosis and enhances osteoclastogenesis and bone resorption rates (21). Compared with ovariectomized WT mice, ovariectomized MYCΔM mice had considerably less bone loss. Importantly, treatment of ovariectomized WT mice with the ERRα inhibitor XCT790 reduced bone loss, although, not to the same degree as that seen in MYCΔM mice.

Concluding remarks

Taken together, the studies by Bae and colleagues (14) demonstrate that MYC functions as an important molecule mediating RANKL/RANK signaling in osteoclasts through mechanisms that are both dependent on and independent of NFATc1 (Figure 1). Hence, these results argue that NFATc1 is not the only critical regulator of RANKL/RANK-mediated signaling in osteoclasts. Additionally, this study shows that RANKL/RANK-mediated MYC signaling has significant effects on osteoclast energy metabolism, which is essential for these cells to perform the work of bone resorption. Most important, these studies identify the MYC/ERRα pathway as a potential drug target for the development of novel therapies to treat metabolic bone diseases caused by excessive osteoclast activity.

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