The growth plate lacks vascular tissues and is solely composed of chondrocytes. The growth plate is composed of three layers, i.e., the resting, proliferating and hypertrophic chondrocyte layers. The chondrocytes in the resting and proliferating layers proliferate and then they uniformly mature toward the diaphysis to become hypertrophic chondrocytes, which lose the ability to proliferate. As the growth plate lacks vasculature, apoptotic chondrocytes are not phagocytosed, and the fragmented DNA detected by TUNEL remains until they reach the bone marrow. Therefore, the growth plate is an appropriate tissue to use for evaluation of cell proliferation, differentiation, and apoptosis.

We examined the effects of Cdk6 and Ccnd1 (cyclin D1) in chondrocyte proliferation, differentiation, and apoptosis. Transgenic mice overexpressing either Cdk6 or Ccnd1 in chondrocytes show no increase in the number of BrdU-positive cells, and the chondrocytes normally mature, although CCND1 is a well-established human oncogene. In contrast, transgenic mice overexpressing both Cdk6 and Ccnd1 show dwarfism. In Cdk6/Ccnd1 double transgenic mice, chondrocyte maturation to hypertrophic chondrocytes is inhibited, and the number of BrdU-positive cells is increased, but the proliferation of chondrocytes is not enhanced, and the frequency of apoptotic chondrocytes is greatly increased. The apoptosis is rescued by p53 deletion, but chondrocyte proliferation is still not enhanced in p53+/−Cdk6/Ccnd1 double transgenic mice.

Cdk6 and Ccnd1 regulate the activity of E2fs by phosphorylating Rb family proteins, Rb, p107, and p130, and trigger progression through the G0/G1, and G1/S transitions of the cell cycle. The effects of targeted deletions of Rb family genes in chondrocytes were reported by two groups. p107-knockout mice show most apparent inhibition of chondrocyte differentiation among the knockout mice of Rb family genes. Double knockout mice of p107/p130 or p107/Rb show more severe inhibition of chondrocyte differentiation and chondrocyte proliferation is enhanced without an increase in chondrocyte apoptosis. Therefore, all of the Rb family proteins are involved in chondrocyte proliferation and differentiation, and p107 plays a major role among them.

When we generated Cdk6/Ccnd1 double transgenic mice, we expected that overexpression of both Cdk6 and Ccnd1 would result in the inactivation of all Rb family proteins by their phosphorylation. However, the phenotype of Cdk6/Ccnd1 double transgenic mouse was different from those of p107/p130 or p107/Rb double knockout mice. BrdU-positive cells are increased, and chondrocyte differentiation is inhibited in p107/p130 and p107/Rb double knockout mice and Cdk6/Ccnd1 double transgenic mice. However, chondrocyte proliferation is enhanced without an increase in apoptosis in p107/p130 and p107/Rb double knockout mice, whereas chondrocyte proliferation is not enhanced, and apoptotic chondrocytes are greatly increased in Cdk6/Ccnd1 double transgenic mice. In Cdk6/Ccnd1 double transgenic mice, Rb but not p107 is highly phosphorylated, and mRNA and protein levels of p107 are increased. p107 transcription is regulated by E2f, and p107 is upregulated in Rb+/− and p130+/− mouse embryonic fibroblasts. Therefore, the phenotypic differences between p107/p130 and p107/Rb double knockout mice and Cdk6/Ccnd1 double transgenic mice could be explained by the absence or presence of p107.

When Cdk6 and Ccnd1 are overexpressed, Rb, p107, and p130 should be phosphorylated, leading to the release of repressing E2fs (E2f4, 5) and activation of activating E2fs (E2f1–3), both of which enhance the transcription of E2f target genes including p107 (Fig. 1A and B). Therefore, phosphorylation of Rb, p107, and p130 enhances the transcription of p107 by E2f and unphosphorylated p107 is continuously supplied. This is the reason why unphosphorylated p107 is dominant in Cdk6/Ccnd1 double transgenic mice. Although p107 binds to repressing E2fs at the physiological condition, upregulation of p107 allows complex formation of activating E2fs with p107. Therefore, the increased amount of unphosphorylated p107 associates not only with repressing E2fs, but also with activating E2fs (Fig. 1C). As p107 plays a major role in cell cycle regulation among Rb family proteins in chondrocytes, the association of p107 with repressing and activating E2fs would affect the expression of E2f target genes. It occurs in Cdk6/Ccnd1 double transgenic mice as shown by the downregulation of cyclin E, dhfr, cdc25a, and B-Myb. Further, chondrogenic ATDC5 cells overexpressing Cdk6 and Ccnd1 also had downregulated expression of these genes, and siRNA of p107 reversed the downregulated expression of these genes. Therefore, phosphorylation of Rb, p107, and p130 upregulates p107 expression, which dysregulates E2f target gene expression leading to p53-dependent apoptosis (Fig. 1B and C). p53 deletion in addition to Rb inactivation is still not sufficient for enhancement of chondrocyte

**Regulation of Rb family proteins by Cdk6/Ccnd1 in growth plates**

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proliferation, suggesting that p107 contributes to the low incidence of chondrosarcoma as an anti-oncogenic protein, because the frequency of chondrosarcoma is much less than those of sarcomas arising in soft tissues.

References

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