Role of G-proteins in the differentiation of epiphyseal chondrocytes

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Abstract

Herein, we review the regulation of differentiation of the growth plate chondrocytes by G-proteins. In connection with this, we summarize the current knowledge regarding each family of G-protein α subunit, specifically, Gαs, Gαq/11, Gα12/13, and Gαi/o. We discuss different mechanisms involved in chondrocyte differentiation downstream of G-proteins and different G-protein-coupled receptors (GPCRs) activating G-proteins in the epiphyseal chondrocytes. We conclude that among all G-proteins and GPCRs expressed by chondrocytes, Gαs has the most important role and prevents premature chondrocyte differentiation. Receptor for parathyroid hormone (PTHR1) appears to be the major activator of Gαs in chondrocytes and ablation of either one leads to accelerated chondrocyte differentiation, premature fusion of the postnatal growth plate, and ultimately short stature.

Key Words

- bone
- G proteins
- intracellular signaling
- parathyroid and bone
- skeletal

The growth plate

The majority of bones in the skeleton are formed via the process of endochondral bone formation. During this process, a cartilage template is first formed and then replaced by true bone tissue. Formation of skeletal elements starts with condensation of mesenchymal cells with their subsequent differentiation into chondrocytes (Hall & Miyake 1995). The chondrocytes proliferate thereby increasing the size of the primary skeletal element. The cells in the center of the element stop proliferating, change their genetic program, and enlarge (hypertrophic differentiation), further facilitating growth of the skeletal element. The cartilage elements are avascular and reach a substantial size, triggering hypoxia in the middle of the skeletal element. The hypertrophic chondrocytes secrete vascular endothelial growth factor that attracts blood vessels (Zelzer et al. 2004). Invasion by blood vessels is accompanied by closely associated pre-osteoblasts from the surrounding perichondrium (a thin layer of flat undifferentiated cells surrounding every cartilage element) into the center of the element (Maes et al. 2010). Thus, true bone tissue starts to be formed by osteoblasts in the center of cartilage anlagen, creating the primary ossification center. In the case of long bones, the secondary ossification centers are subsequently formed in a similar manner at the ends of the growing cartilage template. The secondary ossification center develops into the epiphysis and primary ossification center develops into the metaphysis and diaphysis. The cartilage remaining between the epiphysis and metaphysis forms the growth plate, a disc with spatially organized chondrocytes. The growth plate can be morphologically divided into three zones: a resting zone with round stem-like chondrocytes located toward the epiphysis, a flat cell zone with proliferating chondrocytes in the middle, and a hypertrophic zone containing differentiated enlarged chondrocytes located toward the metaphysis (Fig. 1). The
chondrocytes from the resting zone are recruited into the flat zone, where they go through several cycles of proliferation, thereby substantially increasing in number and thereafter further differentiate into hypertrophic chondrocytes. As soon as the cells cease proliferation and become pre-hypertrophic (changing from flat to round appearance), they start expressing the genes for Indian hedgehog (\(IHH\)) and the receptor for parathyroid hormone (\(PTHR1\)). \(IHH\) is a secreted molecule that diffuses throughout the cartilage and stimulates the production of PTH-related peptide (PTHRP) by resting cells at the top of the growth plate. The PTHRP, in turn, diffuses back to pre-hypertrophic cells, binds to the PTHR1, and inhibits chondrocyte differentiation. This inhibition increases the distance between the resting zone and the pre-hypertrophic chondrocytes and decreases the levels of \(IHH\), which reach cells of the resting zone. This expansion of the growth plate and decrease in \(IHH\) levels, in turn, leads to a decrease in PTHRP expression and a decrease in the distance between round and pre-hypertrophic cells. Thus, together \(IHH\) and PTHRP form a feedback loop, which controls the height of the growth plate (reviewed by Kronenberg (2003)). Subsequently, chondrocyte differentiation is associated with dramatic cell enlargement (hypertrophy); this cellular enlargement accounts for 59% of bone lengthening (up to 73% with associated matrix (Wilsman et al. 1996)). Eventually, hypertrophic chondrocytes die, allowing new bone to be formed on the cartilage template. The zone of cartilage to bone transition is called the chondro-osseous junction and the entire process is called endochondral bone formation.

Thus, the rate of bone growth depends on the following steps: recruitment of stem-like quiescent cells into flat zone, chondrocyte proliferation, differentiation from flat to hypertrophic chondrocytes, chondrocyte enlargement and, finally, replacement of hypertrophic chondrocytes by bone tissue. The rates of all these processes are tightly balanced; deregulation in the rate of any of them will lead to growth abnormalities, usually leading to short stature.

**G-proteins**

G-protein-coupled receptors (GPCRs), a large family of seven-transmembrane domain receptors, mediate their signaling via heterotrimeric G-protein complexes, which consists of \(\alpha\), \(\beta\), and \(\gamma\) subunits. Sixteen genes encode \(G\alpha\) subunits, five encode \(G\beta\), and 12 genes encode \(G\gamma\) subunits. When inactive, guanosine diphosphate (GDP) is bound to the \(\alpha\) subunit, stabilizing the complex between \(\alpha\), \(\beta\), and \(\gamma\). Upon activation of the GPCR, the receptor functions as a nucleotide exchanger: GDP is replaced by the more abundant GTP. This leads to the dissociation of \(G\alpha\)-GTP from \(G\beta\gamma\) and allows \(G\alpha\)-GTP to activate downstream effectors. The \(G\beta\gamma\) dimer also may mediate signaling (reviewed in Gautam et al. (1998) and Oldham & Hamm (2008)), but the role of this signaling pathway in chondrocytes is largely unknown. The \(G\alpha\)-GTP complex remains active until GTP is hydrolyzed. \(G\alpha\) has an intrinsic hydrolytic activity (GTPase), which is enhanced by the regulators of G protein signaling (or RGS). There are about 30 different RGSs and their role in bone is comprehensively discussed in a recent review (Keinan et al. 2014).

On the basis of similarity of their \(\alpha\)-subunits, 16 members of the \(G\alpha\) subunit family are divided into four
major classes: $G_{\alpha_1}$, $G_{\alpha_{11}}$, $G_{\alpha_{21/23}}$, and $G_{\alpha_{16}}$ (Freissmuth et al. 1989, Simon et al. 1991, Neves et al. 2002).

The stimulatory $\alpha$ subunit ($G_{\alpha_s}$) family consists of three members: $G_{\alpha_s}$ small and large splice isoforms of the same $GNAS1$ gene and $G_{\text{olf}}$. The active $G_{\alpha_s}$ activates adenylate cyclase, an enzyme that catalyzes the synthesis of cAMP from ATP within cells. The GPCRs are activated by many types of ligands, including glycoproteins, many peptide hormones, catecholamines, and neurotransmitters; all such types of ligands can activate $G_{\alpha_s}$ to raise the concentration of intracellular cAMP in their target cells. cAMP works as a second messenger activating several downstream targets including protein kinase A (PKA, also known as the cAMP-dependent protein kinase or A kinase), cAMP-regulated guanine nucleotide exchange factors 1 and 2 (Epac1 and Epac2), and cyclic nucleotide-gated ion channels (Freissmuth et al. 1989, Simon et al. 1991, Kaupp & Seifert 2002, Neves et al. 2002).

The $G_{\alpha_{1/11}}$ family includes four members, $G_{\alpha_9}$, $G_{\alpha_{11}}$, $G_{\alpha_{14}}$, and $G_{\alpha_{15}}$. Activation of $G_{\alpha_{1/11}}$ leads to activation of PLC$\beta$, which cleaves phosphatidylinositol-4,5-bisphosphate (PIP2; also known as PTDINS(4,5)P$_2$) into diacylglycerol and inositol 1,4,5-trisphosphate, leading to calcium mobilization and PKC activation. In turn, PKC can activate guanine nucleotide exchange factors of the Rho family (Rho GEFs) and MAPK cascades. In addition, $G_{\alpha_q}$ can activate AKT kinase, which modulates mTOR and NF-$\kappa$B signaling pathways (Freissmuth et al. 1989, Simon et al. 1991, Neves et al. 2002).

The $G_{\alpha_{12/13}}$ family consists of two members, $G_{\alpha_{12}}$ and $G_{\alpha_{13}}$. Activation of these proteins induces Rho GEFs, which initiate Rho-dependent signaling through Rho-associated coiled-coil containing protein kinase (ROCK) and p38 MAPK (Freissmuth et al. 1989, Simon et al. 1991, Neves et al. 2002).

The $G_{\alpha_{16}}$, family includes nine members: $G_{\alpha_{11}}$, $G_{\alpha_{12}}$, $G_{\alpha_{13}}$, $G_{\alpha_{32}}$, and $G_{\alpha_{0b}}$ (splice isoforms), $G_{\alpha_s}$, $G_{\alpha_{11}}$, $G_{\alpha_{21}}$, and $G_{\alpha_{32}}$. The signaling events downstream of this family include inhibition of cAMP and calcium channels and activation of K$^+$ channels, SRC, phosphoinositide 3-kinase, RAC–MEK–ERK and CDC42–PAK, and Rho-mediated signals.

The role of each of these signaling pathways in chondrocyte differentiation in the growth plate is discussed below. The data characterizing the expression of different G-proteins in the growth plate are quite limited and in this review we assume that the expression is ubiquitous, but easiest to see in pre-hypertrophic and hypertrophic chondrocytes as it is seen for $G_{\alpha_{16}}$, XL$\alpha_s$, and $G_{\alpha_{13}}$ (Chagin et al. 2014).

**$G_{\alpha_s}$ and chondrocyte differentiation**

It appears that $G_{\alpha_s}$ is a major participant in chondrocyte differentiation, and it inhibits the differentiation process. In humans, mutation of the $G_{\alpha_s}$-encoding gene, $GNAS1$, leads to Albright’s hereditary osteodystrophy, which is associated with growth abnormalities, short stature, brachyactyly, and premature fusion of the growth plates (Steinbach et al. 1965). The mechanism underlying these abnormalities has been explored using genetic mouse models. Targeted ablation of $G_{\alpha_s}$ in fetal (Sakamoto et al. 2005) or postnatal (Chagin et al. 2014) chondrocytes leads to dramatic acceleration of chondrocyte differentiation and cessation of longitudinal bone growth. Chimeric mice with cells deficient in the $Gnas1$ gene demonstrate ectopically differentiated chondrocytes throughout the growth plate (Bastepe et al. 2004), further supporting the role of $G_{\alpha_s}$ in prevention of chondrocyte differentiation. There is a splice isofrom of $G_{\alpha_s}$ (namely extra-large stimulatory alpha subunit (XL$\alpha_s$)), which has an alternative exon 1, with the rest of the protein identical to $G_{\alpha_s}$ and capable of activating the downstream cAMP signaling pathway (Klemke et al. 2000, Pasolli et al. 2000). Thus, this splice isofrom may partially compensate for the lack of $G_{\alpha_s}$. Despite being expressed by hypertrophic chondrocytes, the functional role of XL$\alpha_s$ seems to be negligible, because simultaneous ablation of XL$\alpha_s$ and $G_{\alpha_s}$ appears phenotypically indistinguishable from $G_{\alpha_s}$ ablation alone (Chagin et al. 2014).

Multiple *in vitro* experiments with administration of forskolin (adenylate cyclase activator) or 8-cAMP (long-lasting analog of cAMP) confirm the inhibitory effect of this pathway on chondrocyte differentiation (Jikko et al. 1996). Interestingly, activation of cAMP pathway by N$^6$-2’-O-dibutyril cAMP in differentiated cultured rabbit chondrocytes inhibits ALPase activity and collagen type X expression, markers of hypertrophic chondrocytes (Jikko et al. 1996), and treatment of metatarsal bones with forskolin inhibits the expression of type X collagen by hypertrophic chondrocytes (Chagin, unpublished observation). These findings suggest high plasticity of the hypertrophic differentiation stage. Altogether these observations demonstrate that chondrocyte hypertrophy is tightly controlled by the $G_{\alpha_s}$ signaling pathway.

Canonical signaling downstream of $G_{\alpha_s}$ includes the activation of adenylate cyclase, followed by cAMP accumulation and subsequent activation of PKA, which in turn lead to phosphorylation and activation of cAMP-response element-binding protein (CREB) transcription factor (Neves et al. 2002). However, in addition to PKA,
high levels of cAMP activate EPAC1 and EPAC2, whereas PKA also has multiple additional targets, including SOX9 transcription factor (Huang et al. 2000).

The highest levels of both Gαs mRNA and active PKA are observed in pre-hypertrophic and early hypertrophic chondrocytes (Chagin et al. 2014). Phosphorylation of CREB at serine 133, a PKA-phosphorylation site, is also observed in pre-hypertrophic chondrocytes (Long et al. 2001). However, the expression of dominant-negative CREB in chondrocytes delays cell differentiation (Long et al. 2001) in contrast to the accelerated differentiation upon genetic ablation of Gαs. Furthermore, the levels of p-CREB were not changed upon ablation of the PTHR1 (Long et al. 2001), a major activator of Gαs signaling in chondrocytes. Thus, the Gαs-dependent inhibition of chondrocyte differentiation is unlikely to be mediated by CREB.

To date, there are no reports of chondrocyte-specific PKA ablation, but global inactivation of the ubiquitously expressed C-α catalytic subunit of PKA results in early post-natal lethality in 73% of animals (Skalhegg et al. 2002). The remaining 27% survive till weaning and showed marked growth retardation, which, according to the authors, is associated with low serum insulin-like growth factor 1 levels (Skalhegg et al. 2002). Unfortunately, the growth plate morphology was not presented for these animals and it is difficult to determine the exact mechanisms of growth retardation in this global PKA knockout model. In these mice, only one of the two PKA catalytic subunits was removed. Thus, the milder growth plate phenotype of these mice as compared with the chondrocyte-specific ablation of Gαs (lethal) is likely due to the activity of the remaining catalytic subunit Cβ.

An exciting downstream mechanism of Gαs- and PKA-dependent regulation of chondrocyte differentiation has been recently proposed by Prof. A B Lassar (Harvard Medical School). In vitro experiments from his group suggest that activation of PKA stimulates serine/threonine protein phosphatase 2A, which in turn removes phosphate from serine 246 of class IIa histone deacetylase HDAC4. This decreases binding of HDAC4 to 14-3-3 protein and allows translocation of HDAC4 to the nucleus, where it represses transcription activated by MEF2C (Kozhemyakina et al. 2009). The importance of both HDAC4 and MEF2C for chondrocytes differentiation was convincingly demonstrated in vivo (Vega et al. 2004, Arnold et al. 2007). This mechanism outlines a plausible downstream pathway toward Gαs- and PKA-mediated inhibition of chondrocyte differentiation and has now been confirmed in vivo (Nishimori et al. 2012).

Other targets downstream of Gαs, which are likely involved in Gαs-regulated chondrocyte differentiation, include the suppression of the cyclin-CDK inhibitor p57; the PKA-dependent phosphorylation and activation of the transcription factor SOX9; and the suppression of the transcription of RUNX2, probably as a consequence of suppression of MEF2C action (reviewed by Kronenberg (2006)).

The large family of GPCRs is responsible for activating Gαs. There are several GPCRs expressed by chondrocytes that can activate Gαs. These include PTHR1 (Lee et al. 1993), receptors for prostaglandins (de Brum-Fernandes et al. 1996, Clark et al. 2005), membrane estrogen receptor GPER (Chagin & Savendahl 2007), RDC1 receptor (Jones et al. 2006), adenosine (nucleotide P2Y) receptors (Kaplan et al. 1996, Hoebertz et al. 2000), β-adrenergic receptors (Lai & Mitchell 2008), histamine H2 receptors (Fukuda et al. 1993), and probably others. Despite the fact that several of these receptors are known to signal through Gαs, PTHR1 seems to be the predominant activator of Gαs in the growth plate. Indeed, ablation of PTHR1 either recapitulates the Gαs cKO phenotype or results in a more profound effect. Specifically, ablation of either Gαs or PTHR1 in chondrocytes during development (utilizing collagen 2 driven CRE) results in almost identical phenotypes (compare (Kobayashi et al. 2002) and (Sakamoto et al. 2005)). Postnatal ablation of PTHR1 in chondrocytes has a more profound phenotype than ablation of Gαs (Hirai et al. 2011, Chagin et al. 2014): ablation of PTHR1 leads to growth plate fusion, preceded by a decrease in chondrocyte proliferation, and ectopic apoptosis of stem-like chondrocytes in the resting zone, effects not observed upon ablation of Gαs (Chagin et al. 2014). Interestingly, chimeric mice containing PTHR1-deficient cells have ectopic hypertrophic chondrocytes throughout the growth plate similar to chimeric mice containing Gαs-deficient cells, but in contrast have an expanded zone of flat cells (Basteppe et al. 2004), thus again showing that ablation of PTHR1 confers a more profound phenotype than does ablation of Gαs.

Ectopically differentiated chondrocytes, observed in the experiments with chimeric mice, suggest that the PTHR1–Gαs–PKA signaling pathway needs to be active in resting and flat chondrocytes in order to prevent their hypertrophic differentiation. Difficulties to detect PTHR1 mRNA in these cells might be explained by plausible downregulation of PTHR1 upon constitutive exposure of round and flat chondrocytes to PTHrP, the phenomenon described for other GPCR (Collins et al. 1989) and for PTHR1 at high PTH levels (Collins et al. 1994, Picton et al. 2000).
Gαq and Gα11

The role of Gαq/11 G-proteins in chondrocyte differentiation is less known. To date there are no experiments describing the genetic ablation or overexpression of either Gαq or G11 in chondrocytes. The best understanding of the Gαq/11 role in chondrocyte differentiation comes from mice with Pthrl1 mutated in the way that it signals via Gαq but not via Gαq/11 (DSEL point mutation, Guo et al. 2002). Developmental delay in chondrocyte mineralization was observed in these mice (Guo et al. 2002), suggesting a function of Gαq/11 (activated by PTH1R) opposed to that of Gαq. This role of Gαq/11 signaling is supported by in vitro experiments showing that pharmacological activation of PKC, the main downstream signaling pathway of Gαq/11, promotes chondrocyte differentiation (Nurminsky et al. 2007, Matta & Mobasheri 2014). On the other hand, synergism between PKA and PKC was also reported: i) inhibition of chondrocyte differentiation by prostaglandin PGE2 requires activation of both PKA and PKC (Li et al. 2004a) and ii) PTHRP-dependent inhibition of the transcription factor RUNX2 requires activation of both PKA and PKC (Li et al. 2004b).

It is important to note that the effect of delayed mineralization is observed during the development of Dsel mice, whereas post-natal growth is rather normal (Guo et al. 2002, Chagin et al. 2014). Furthermore, despite opposing Gαq at mineralization, activation of Gαq/11 by PTH1R is needed for the survival of stem-like cells of the resting zone in the absence of Gαq. Activation of PTH1R is required for round cells to stay quiescent, which is mediated predominantly via Gαq signaling and its absence triggers proliferation of these cells whereas absence of both Gαq and Gαq/11 pathways triggers their apoptosis (Fig. 2, Chagin et al. 2014). Very little is known about the regulation of this cell population and, accordingly, it is plausible that transition from quiescent round-to-flat chondrocytes is regulated differently as compared with flat-to-hypertrophic transition.

Despite revealing the role of Gαq/11, activated by PTH1R, and providing valuable information of what can be expected from Gαq/11 activation/inactivation, the above experiments do not entirely reveal the role of this G-protein family. Indeed, other potential GPCR can mediate their responses via Gαq/11 signaling in chondrocytes. To date, genetic ablation of Gαq/11 has not been performed and, accordingly, it cannot be excluded that activation of Gαq/11 by other GPCRs impacts chondrocyte differentiation.

Gα12/Gα13

Gα12 and Gα13 mainly signal via their downstream target, RHOA (Worzfeld et al. 2008). Chondrocyte-specific ablation of RAC1, a member of the Rho family of small G proteins, leads to severe growth retardation associated with growth plate disorganization, hypocellularity, and decreased proliferation (Wang et al. 2007). In the ATDC5 chondrocytic cell line, RHOA stimulates cell proliferation and inhibits hypertrophic differentiation (Wang et al. 2004), which likely occurs via RHOA-dependent actin polymerization, which has been shown to activate SOX9 in chondrocytes (Kumar & Lassar 2009). Furthermore, PTH1R activates Gα12/13 family of G-proteins in the osteoblastic cell line UMR-106 (Singh et al. 2005).

Taken together, these observations suggest that Gα12/13 might be involved in chondrocyte differentiation. We have ablated both Gα12 and Gα13 in chondrocytes (using a global Gα12 KO combined with a Collagen 2 CRE-mediated ablation of floxed Gα13 in chondrocytes), but found no changes either in post-natal bone growth or growth plate morphology (Chagin et al. 2014). This observation suggests that if existing, the role of Gα12/13 family in growth plate chondrocytes is rather minor.
G\(\alpha_i\) in chondrocytes

Proper genetic analysis of G\(\alpha_i\) function in chondrocytes has never been carried out. In general, G\(\alpha_i\) inhibits the cAMP pathway and opposes G\(\alpha_q\) action (Neves et al. 2002). Thus, it can be predicted that G\(\alpha_i\) would accelerate chondrocyte differentiation by inhibiting the cAMP pathway. In the growth plate, NPR-C receptor for C-type natriuretic peptide is expressed by hypertrophic chondrocytes (Yamashita et al. 2000) and can activate G\(\alpha_i\) in some settings (Rose & Giles 2008). In articular chondrocytes, G\(\alpha_i\) can be activated by chemokine receptors, which are expressed by chondrocytes (Borzi et al. 2000).

Conclusion

Among all G-proteins and GPCRs expressed by chondrocytes, G\(\alpha_{q/11}\) has the most important role and prevents premature chondrocyte differentiation, whereas PTHR1 is the major activator of G\(\alpha_q\) in chondrocytes and ablation of either one leads to abrupt chondrocyte differentiation, premature fusion of the growth plate postnatally and ultimately short stature. The role of G\(\alpha_{q/11}\) G-proteins is less defined and G\(\alpha_{q/11}\) might have an important role in the prevention of apoptosis in the absence of G\(\alpha_q\) and oppose its action to delay differentiation in the presence of G\(\alpha_q\). G\(\alpha_{q/11}\) G-proteins seem have no major role in chondrocyte differentiation and bone elongation.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the review.

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