Recent insights into the origins of adrenal and sex steroid receptors

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Abstract

The recent cloning by Thornton (2001) of estrogen, progesterone and corticoid receptors from lamprey provides important insights into the early evolution of adrenal and sex steroid receptors and an opportunity to elucidate the ancient steroids that regulated gene transcription. Inclusion of lamprey sequences in a steroid receptor phylogeny indicates that the estrogen receptor is the most ancient of these receptors, followed by the progesterone receptor and the corticoid receptor. Thornton proposed that estradiol was the earliest of the steroids to activate a steroid receptor. An alternative hypothesis is that a steroid in the \( \Delta^5 \) pathway activated the ancestral estrogen receptor.

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Introduction

In the last few years, the origins of adrenal and sex steroid signaling have emerged as the sequences for the genes of androgen, estrogen, glucocorticoid, mineralocorticoid and progesterone receptors (AR, ER, GR, MR and PR, respectively) from mammals, amphibia and fish have been determined. Sequence analyses show that steroid receptors belong to the nuclear receptor family, a large diverse family of transcription factors (Laudet 1997, Owen & Zelent 2000). The nuclear receptor superfamily also contains receptors for thyroid hormone, prostaglandins, 1,25-dihydroxy-vitamin D3 and xenobiotics, as well as receptors with no known ligand, which are called orphan receptors (Enmark & Gustafsson 1996).

The importance of steroid receptors and other nuclear receptors in reproduction, differentiation, development and homeostasis in vertebrates provided an early stimulus for cloning and sequencing these proteins from a variety of multicellular animals. Thus, even 10 years ago, there was a sufficient number of diverse nuclear receptor sequences to allow a comprehensive phylogenetic analysis (Laudet et al. 1992), which showed that the adrenal and sex steroid receptors form a separate clade, distinct from other nuclear receptors. The AR, PR, GR and MR are in one subgroup and the ER is in a separate subgroup. In the following years, sequences from amphibia and teleosts (jawed fish) became available, which further clarified early events in steroid receptor evolution. These analyses showed that the AR and PR cluster were in one subgroup, and the MR and GR cluster in another subgroup (Baker 1997, Laudet 1997, Escriva et al. 1997). The phylogenetic tree indicated that an ancestral steroid receptor arose in a protochordate, such as a cephalochordate (e.g. amphioxus) or a urochordate (e.g. tunicate). If steroid receptors arose after the separation of deuterostomes and protostomes, then invertebrates such as Caenorhabditis elegans and Drosophila, which have nuclear receptors, would not have adrenal and sex steroid receptors (Baker 1997). Analysis of the genomes of C. elegans (Sluder & Maina 2001) and Drosophila supports this prediction (Robinson-Rechavi et al. 2001).
The patterns of the phylogenetic tree for steroid receptors indicate that there were two waves of gene duplications in the early evolution of steroid receptors (Baker 1997, Laudet 1997, Escriva et al. 1997, 2000). These duplications are proposed to be associated with genome size duplications that occurred early in the evolution of vertebrates (Holland 1999, Shimeld & Holland 2000).

The availability of a variety of nuclear receptor sequences was exploited by Escriva et al. (1997) to investigate when steroid receptors and other ligand-binding nuclear receptors arose. Escriva constructed PCR primers to the highly conserved sequences was exploited by Escriva (Holland 1999, Shimeld & Holland 2000). Occurred early in the evolution of vertebrates associated with genome size duplications that 1997, 2000). These duplications are proposed to be gene duplications in the early evolution of steroid receptors (Baker 1997, Laudet 1997, Escriva et al. 1997) to construct a comprehensive phylogenetic tree of the CR, which most resembles the GR. An intriguing proposal by Thornton (2001) is that estradiol is the ancestral ligand of the ER. As Thornton notes, estradiol is the last steroid in the pathway for synthesis of steroid hormones (Fig. 1). Selection for estradiol also selects for the intermediates, such as progesterone and testosterone despite the absence of their receptors. These upstream steroids began to regulate transcription after duplication and divergence of the ancestral ER to form the PR and the subsequent descent of the AR from a duplicated PR. Thornton calls this process ligand exploitation, in which the ligand is a driving force in the functional evolution of its receptor.

Also consistent with ligand exploitation, but simpler from the viewpoint of steroid synthesis, is the hypothesis that the ancestral ER was activated by a $\Delta^5$-steroid that is upstream of estradiol (Fig. 1) (Baker 2001a). For example, $\Delta^5$-androstenediol has long been known to have estrogenic activity (Huggins et al. 1954) and to bind to the ER (Garcia & Rochefort 1979). Kuiper et al. (1997) showed that $\Delta^5$-androstenediol and $\Delta^\beta$-androstenediol bind to recombinant rat ER$\alpha$ and ER$\beta$ with nanomolar affinity. They also found that androgens with $3\alpha$-alcohols have substantially lower affinity for the ER. Moreover, Miyamoto et al. (1998) showed that $\Delta^5$-androstenediol can regulate estrogen-responsive genes by binding to the ER. This may be ‘fossil’ evidence for one or more ancestral steroids with a saturated A-ring containing a $3\beta$ alcohol that activated the ancestral ER. It is not unreasonable to suppose that the ER, as well as PR and CR, in lamprey and in primitive fish has different ligand binding specificity than their orthologs in mammals and other land vertebrates. Indeed, fish PR recognizes $17\alpha$-hydroxy-progesterins (Todo et al. 2000), unlike the PR in mammals.

The above hypothesis does not require that the ER-containing organism express a $3\beta/\Delta^5$ hydroxysteroid dehydrogenase (3$\beta/\Delta^5$-HSD) that catalyzes the formation of $\Delta4$ steroids (Simard et al. 1996), which are precursors of estradiol (Fig. 1). Our recent BLAST database search (Altshul et al. 1997) did not find any proteins with at least 35% sequence identity to $3\beta/\Delta^4$-HSD in D. melanogaster, C. elegans or any other invertebrate (not shown). $3\beta/\Delta^4$-HSD is found in mammals and trout (Sakai et al. 1994). Sequences with over 40% identity to a known $3\beta/\Delta^4$-HSD are found in
cartilaginous fish. These data are consistent with the ancestral ER arising prior to the evolution of $3\beta/\Delta^5$-4-HSD that converted $\Delta^5$ steroids to $\Delta^4$ steroids in the pathway for estradiol synthesis. Diversification of steroid receptors would occur with the evolution of a $3\beta/\Delta^5$-4-HSD that catalyzed the conversion of pregnenolone to progesterone, providing ligands that would regulate transcriptional activity of the ancestral PR and its descendents, the CR and AR. Indeed, the early evolution of steroid hormone action depended on $3\beta/\Delta^5$-4-HSD and other hydroxysteroid dehydrogenases (Baker 2001b), as well as duplications of ancestral steroid receptors.

**What next?**

Investigation of the binding of various $\Delta^4$ and $\Delta^5$ steroids to lamprey ER, PR and CR will elucidate how these receptors compare with their orthologs in mammals and other land vertebrates, providing clues to the ancient ligands that regulated steroid hormone responses. In particular, analysis of the binding of estradiol and of $\Delta^5$ steroids with $3\alpha$- and $3\beta$-alcohols to lamprey ER and a reporter gene will clarify the nature of the ligand(s) that bound to the ancestral steroid receptor. Further information about the earliest steroid
receptors and the origins of $3\beta/\Delta^{5-4}$-HSD will come from the sequencing of the genomes of amphioxus, hagfish and lamprey. It also will facilitate identifying the genes that were regulated by the ancestral steroid receptors. Of special interest are hox genes, which are regulated by estrogens and progesterins in mammals and are critical for development and differentiation, including the brain of amphioxus (Manzanares et al. 2000). When did steroids begin to regulate expression of hox genes? By providing tools for answering this question, the identification of steroid receptors in lamprey is bringing us to the threshold of a deeper understanding of the origins of adrenal and sex steroid action.

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