









# THE CONCISE GUIDE TO PHARMACOLOGY 2019/20: Nuclear hormone receptors

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## Abstract

The Concise Guide to PHARMACOLOGY 2019/20 is the fourth in this series of biennial publications. The Concise Guide provides concise overviews of the key properties of nearly 1800 human drug targets with an emphasis on selective pharmacology (where available), plus links to the open access knowledgebase source of drug targets and their ligands ([www.guidetopharmacology.org](http://www.guidetopharmacology.org)), which provides more detailed views of target and ligand properties. Although the Concise Guide represents approximately 400 pages, the material presented is substantially reduced compared to information and links presented on the website. It provides a permanent, citable, point-in-time record that will survive database updates. The full contents of this section can be found at <http://onlinelibrary.wiley.com/doi/10.1111/bph.14750>. Nuclear hormone receptors are one of the six major pharmacological targets into which the Guide is divided, with the others being: G protein-coupled receptors, catalytic receptors, enzymes and transporters. These are presented with nomenclature guidance and summary information on the best available pharmacological tools, alongside key references and suggestions for further reading. The landscape format of the Concise Guide is designed to facilitate comparison of related targets from material contemporary to mid-2019, and supersedes data presented in the 2017/18, 2015/16 and 2013/14 Concise Guides and previous Guides to Receptors and Channels. It is produced in close conjunction with the International Union of Basic and Clinical Pharmacology Committee on Receptor Nomenclature and Drug Classification (NC-IUPHAR), therefore, providing official IUPHAR classification and nomenclature for human drug targets, where appropriate.

## Conflict of interest

The authors state that there are no conflicts of interest to disclose.

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**Overview:** Nuclear receptors are specialised transcription factors with commonalities of sequence and structure, which bind as homo- or heterodimers to specific consensus sequences of DNA (response elements) in the promoter region of particular target genes. They regulate (either promoting or repressing)

transcription of these target genes in response to a variety of endogenous ligands. Endogenous agonists are hydrophobic entities which, when bound to the receptor promote conformational changes in the receptor to allow recruitment (or dissociation) of protein partners, generating a large multiprotein complex.

Two major subclasses of nuclear receptors with identified endogenous agonists can be identified: steroid and non-steroid hormone receptors. Steroid hormone receptors function typically as dimeric entities and are thought to be resident outside the nucleus in the unliganded state in a complex with chaperone proteins, which

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are liberated upon agonist binding. Migration to the nucleus and interaction with other regulators of gene transcription, including RNA polymerase, acetyltransferases and deacetylases, allows gene transcription to be regulated. Non-steroid hormone receptors typically exhibit a greater distribution in the nucleus in

the unliganded state and interact with other nuclear receptors to form heterodimers, as well as with other regulators of gene transcription, leading to changes in gene transcription upon agonist binding.

Selectivity of gene regulation is brought about through

interaction of nuclear receptors with particular consensus sequences of DNA, which are arranged typically as repeats or inverted palindromes to allow accumulation of multiple transcription factors in the promoter regions of genes.

### Family structure

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## 1A. Thyroid hormone receptors

Nuclear hormone receptors → 1A. Thyroid hormone receptors

**Overview:** Thyroid hormone receptors (**TRs**, nomenclature as agreed by the **NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [39]**) are nuclear hormone receptors of the NR1A family, with diverse roles regulating macronutrient metabolism, cognition and cardiovascular homeostasis. TRs are activated by thyroxine (**T<sub>4</sub>**) and thyroid hormone (**triiodothyronine**). Once activated by a ligand, the receptor acts as a transcription factor either as a monomer, homodimer or heterodimer with members of the retinoid X receptor family. **NH-3** has been described as an antagonist at TRs with modest selectivity for TR $\beta$  [105].

Nomenclature	Thyroid hormone receptor- $\alpha$	Thyroid hormone receptor- $\beta$
Systematic nomenclature	NR1A1	NR1A2
HGNC, UniProt	<i>THRA</i> , P10827	<i>THRB</i> , P10828
Rank order of potency	triiodothyronine > T <sub>4</sub>	triiodothyronine > T <sub>4</sub>
Agonists	dextrothyroxine [17]	dextrothyroxine [17]
Selective agonists	–	sobetirome [23, 125]

**Comments:** An interaction with integrin  $\alpha$ V $\beta$ 3 has been suggested to underlie plasma membrane localization of TRs and non-genomic signalling [6]. One splice variant, TR $\alpha$ <sub>2</sub>, lacks a functional DNA-binding domain and appears to act as a transcription suppressor.

Although radioligand binding assays have been described for these receptors, the radioligands are not commercially available.

### Further reading on 1A. Thyroid hormone receptors

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- Flamant F *et al.* (2006) International Union of Pharmacology. LIX. The pharmacology and classification of the nuclear receptor superfamily: thyroid hormone receptors. *Pharmacol. Rev.* **58**: 705-11 [PMID:17132849]
- Mendoza A *et al.* (2017) New insights into thyroid hormone action. *Pharmacol. Ther.* **173**: 135-145 [PMID:28174093]

## 1B. Retinoic acid receptors

Nuclear hormone receptors → 1B. Retinoic acid receptors

**Overview:** Retinoic acid receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [44]**) are nuclear hormone receptors of the NR1B family activated by the vitamin A-derived agonists **tretinoin** (ATRA) and **alitretinoin**, and the RAR-selective synthetic agonists **TTNPB** and **adapalene**. **BMS493** is a family-selective antagonist [45].

Nomenclature	Retinoic acid receptor- $\alpha$	Retinoic acid receptor- $\beta$	Retinoic acid receptor- $\gamma$
Systematic nomenclature	NR1B1	NR1B2	NR1B3
HGNC, UniProt	<a href="#">RARA</a> , <a href="#">P10276</a>	<a href="#">RARB</a> , <a href="#">P10826</a>	<a href="#">RARG</a> , <a href="#">P13631</a>
Agonists	tretinoin [22]	tretinoin [22]	tretinoin [22]
Sub/family-selective agonists	tazarotene [22]	tazarotene [22], adapalene [21]	tazarotene [22], adapalene [21]
Selective agonists	BMS753 [51], tamibarotene [143], Ro 40-6055 [30]	AC261066 [84], AC55649 [83, 84]	AHPN [21]
Selective antagonists	Ro 41-5253 (pIC <sub>50</sub> 6.3–7.2) [1, 65]	–	MM 11253 [72]

**Comments:** Ro 41-5253 has been suggested to be a PPAR $\gamma$  agonist [124]. LE135 is an antagonist with selectivity for RAR $\alpha$  and RAR $\beta$  compared with RAR $\gamma$  [80].

### Further reading on 1B. Retinoic acid receptors

- Duong V *et al.* (2011) The molecular physiology of nuclear retinoic acid receptors. From health to disease. *Biochim. Biophys. Acta* **1812**: 1023-31 [PMID:20970498]
- Larange A *et al.* (2016) Retinoic Acid and Retinoic Acid Receptors as Pleiotropic Modulators of the Immune System. *Annu. Rev. Immunol.* **34**: 369-94 [PMID:27168242]
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- Saeed A *et al.* (2017) The interrelationship between bile acid and vitamin A homeostasis. *Biochim. Biophys. Acta* **1862**: 496-512 [PMID:28111285]

# 1C. Peroxisome proliferator-activated receptors

Nuclear hormone receptors → 1C. Peroxisome proliferator-activated receptors

**Overview:** Peroxisome proliferator-activated receptors (**PPARs**, **nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [96]**) are nuclear hormone receptors of the NR1C family, with diverse roles regulating lipid homeostasis, cellular differentiation, proliferation and the immune response. PPARs have many potential endogenous agonists [11, 96], including 15-deoxy- $\Delta^{12,14}$ -PGJ<sub>2</sub>, prostacyclin

(PGI<sub>2</sub>), many fatty acids and their oxidation products, lysophosphatidic acid (LPA) [93], 13-HODE, 15S-HETE, Paz-PC, azelaoyl-PAF and leukotriene B<sub>4</sub> (LTB<sub>4</sub>). Bezafibrate acts as a non-selective agonist for the PPAR family [152]. These receptors also bind hypolipidaemic drugs (PPAR $\alpha$ ) and anti-diabetic thiazolidinediones (PPAR $\gamma$ ), as well as many non-steroidal anti-inflammatory drugs, such as sulindac and indomethacin. Once

activated by a ligand, the receptor forms a heterodimer with members of the retinoid X receptor family and can act as a transcription factor. Although radioligand binding assays have been described for all three receptors, the radioligands are not commercially available. Commonly, receptor occupancy studies are conducted using fluorescent ligands and truncated forms of the receptor limited to the ligand binding domain.

Nomenclature	Peroxisome proliferator-activated receptor- $\alpha$	Peroxisome proliferator-activated receptor- $\beta/\delta$	Peroxisome proliferator-activated receptor- $\gamma$
Systematic nomenclature	NR1C1	NR1C2	NR1C3
HGNC, UniProt	<a href="#">PPARA</a> , Q07869	<a href="#">PPARD</a> , Q03181	<a href="#">PPARG</a> , P37231
Selective agonists	<a href="#">GW7647</a> [15, 16], <a href="#">CP-775146</a> [63], <a href="#">pirinixic acid</a> [152], <a href="#">gemfibrozil</a> [28]	<a href="#">GW0742X</a> [48, 137], <a href="#">GW501516</a> [107]	<a href="#">GW1929</a> [15], <a href="#">bardoxolone</a> (Partial agonist) [146], <a href="#">rosiglitazone</a> [55, 76, 158], <a href="#">troglitazone</a> [55, 158], <a href="#">pioglitazone</a> [55, 122, 158], <a href="#">ciglitazone</a> [55]
Selective antagonists	<a href="#">GW6471</a> (pIC <sub>50</sub> 6.6) [155]	<a href="#">GSK0660</a> (pIC <sub>50</sub> 6.5) [126]	<a href="#">T0070907</a> (pK <sub>i</sub> 9) [73], <a href="#">GW9662</a> (Irreversible inhibition) (pIC <sub>50</sub> 8.1) [74], <a href="#">CDDO-Me</a> (pK <sub>i</sub> 6.9) [146]

**Comments:** As with the estrogen receptor antagonists, many agents show tissue-selective efficacy (e.g. [10, 104, 119]). Agonists with mixed activity at PPAR $\alpha$  and PPAR $\gamma$  have also been described (e.g [31, 50, 156]).

## Further reading on 1C. Peroxisome proliferator-activated receptors

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 Gross B *et al.* (2017) PPARs in obesity-induced T2DM, dyslipidaemia and NAFLD. *Nat Rev Endocrinol* **13**: 36–49 [PMID:27636730]  
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 Sauer S. (2015) Ligands for the Nuclear Peroxisome Proliferator-Activated Receptor Gamma. *Trends Pharmacol. Sci.* **36**: 688–704 [PMID:26435213]

## 1D. Rev-Erb receptors

Nuclear hormone receptors → 1D. Rev-Erb receptors

**Overview:** Rev-erb receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand, but are thought to be activated by heme.

Nomenclature	Rev-Erb- $\alpha$	Rev-Erb- $\beta$
Systematic nomenclature	NR1D1	NR1D2
HGNC, UniProt	<a href="#">NR1D1</a> , <a href="#">P20393</a>	<a href="#">NR1D2</a> , <a href="#">Q14995</a>
Endogenous agonists	<a href="#">heme</a> [116, 157]	<a href="#">heme</a> [92, 116, 157]
Selective agonists	<a href="#">GSK4112</a> [49], <a href="#">GSK4112</a> [68]	–
Selective antagonists	<a href="#">SR8278</a> (pIC <sub>50</sub> 6.5) [68]	–

### Further reading on 1D. Rev-Erb receptors

- Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [[PMID:17132856](#)]
- Gonzalez-Sanchez E *et al.* (2015) Nuclear receptors in acute and chronic cholestasis. *Dig Dis* **33**: 357-66 [[PMID:26045270](#)]
- Gustafson CL *et al.* (2015) Emerging models for the molecular basis of mammalian circadian timing. *Biochemistry* **54**: 134-49 [[PMID:25303119](#)]
- Sousa EH *et al.* (2017) Drug discovery targeting heme-based sensors and their coupled activities. *J. Inorg. Biochem.* **167**: 12-20 [[PMID:27893989](#)]

## 1F. Retinoic acid-related orphans

Nuclear hormone receptors → 1F. Retinoic acid-related orphans

**Overview:** Retinoic acid receptor-related orphan receptors (ROR, **nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be assigned a definitive endogenous ligand, although ROR $\alpha$  may be synthesized with a ‘captured’ agonist such as [cholesterol](#) [61, 62].

Nomenclature	<a href="#">RAR-related orphan receptor-<math>\alpha</math></a>	<a href="#">RAR-related orphan receptor-<math>\beta</math></a>	<a href="#">RAR-related orphan receptor-<math>\gamma</math></a>
Systematic nomenclature	NR1F1	NR1F2	NR1F3
HGNC, UniProt	<a href="#">RORA, P35398</a>	<a href="#">RORB, Q92753</a>	<a href="#">RORC, P51449</a>
Endogenous agonists	<a href="#">cholesterol</a> [62, 109]	–	–
Selective agonists	<a href="#">7-hydroxycholesterol</a> [12], <a href="#">cholesterol sulphate</a> [12, 62]	–	–
Comments	–	–	The immune system function of RORC proteins most likely resides with expression of the ROR $\gamma$ t isoform by immature CD4 <sup>+</sup> /CD8 <sup>+</sup> cells in the thymus [33, 136] and in lymphoid tissue inducer (LTi) cells [34].

**Comments:** [Tretinoin](#) shows selectivity for ROR $\beta$  within the ROR family [131]. ROR $\alpha$  has been suggested to be a nuclear receptor responding to [melatonin](#) [151].

### Further reading on 1F. Retinoic acid-related orphans

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798–836 [PMID:17132856]  
 Cyr P *et al.* (2016) Recent progress on nuclear receptor ROR $\gamma$  modulators. *Bioorg. Med. Chem. Lett.* **26**: 4387–4393 [PMID:27542308]  
 Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685–704 [PMID:17132848]

Guillemot-Legris O *et al.* (2016) Oxysterols in Metabolic Syndrome: From Bystander Molecules to Bioactive Lipids. *Trends Mol Med* **22**: 594–614 [PMID:27286741]  
 Mutemberezi V *et al.* (2016) Oxysterols: From cholesterol metabolites to key mediators. *Prog. Lipid Res.* **64**: 152–169 [PMID:27687912]

## 1H. Liver X receptor-like receptors

Nuclear hormone receptors → 1H. Liver X receptor-like receptors

**Overview:** Liver X and farnesoid X receptors (LXR and FXR, **nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [100]**) are members of a steroid analogue-activated nuclear receptor subfamily, which form heterodimers with members of the retinoid X receptor family. Endogenous ligands for LXRs include hydroxycholesterols (OHC), while FXRs appear to be activated by bile acids. In humans and primates, *NR1H5P* is a pseudogene. However, in other mammals, it encodes a functional nuclear hormone receptor that appears to be involved in cholesterol biosynthesis [108].

Nomenclature	<a href="#">Farnesoid X receptor</a>	<a href="#">Farnesoid X receptor-β</a>	<a href="#">Liver X receptor-α</a>	<a href="#">Liver X receptor-β</a>
Systematic nomenclature	NR1H4	NR1H5	NR1H3	NR1H2
HGNC, UniProt	<a href="#">NR1H4</a> , <a href="#">Q96R11</a>	<a href="#">NR1H5P</a> , –	<a href="#">NR1H3</a> , <a href="#">Q13133</a>	<a href="#">NR1H2</a> , <a href="#">P55055</a>
Potency order	<a href="#">chenodeoxycholic acid</a> > <a href="#">lithocholic acid</a> , <a href="#">deoxycholic acid</a> [87, 110]	–	<a href="#">20S-hydroxycholesterol</a> , <a href="#">22R-hydroxycholesterol</a> , <a href="#">24(S)-hydroxycholesterol</a> > <a href="#">25-hydroxycholesterol</a> , <a href="#">27-hydroxycholesterol</a> [75]	<a href="#">20S-hydroxycholesterol</a> , <a href="#">22R-hydroxycholesterol</a> , <a href="#">24(S)-hydroxycholesterol</a> > <a href="#">25-hydroxycholesterol</a> , <a href="#">27-hydroxycholesterol</a> [75]
Endogenous agonists	–	<a href="#">lanosterol</a> [108] – Mouse	–	–
Selective agonists	<a href="#">GW4064</a> [89], <a href="#">obeticholic acid</a> [111], <a href="#">fexaramine</a> [32]	–	–	–
Selective antagonists	<a href="#">guggulsterone</a> (pIC <sub>50</sub> 5.7–6) [154]	–	–	–

**Comments:** [T0901317](#) [117] and [GW3965](#) [24] are synthetic agonists acting at both LXRα and LXRβ with less than 10-fold selectivity.

#### Further reading on 1H. Liver X receptor-like receptors

- Courtney R *et al.* (2016) LXR Regulation of Brain Cholesterol: From Development to Disease. *Trends Endocrinol. Metab.* **27**: 404–414 [PMID:27113081]
- El-Gendy BEM *et al.* (2018) Recent Advances in the Medicinal Chemistry of Liver X Receptors. *J. Med. Chem.* **61**: 10935–10956 [PMID:30004226]
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- Mouzat K *et al.* (2016) Liver X receptors: from cholesterol regulation to neuroprotection—a new barrier against neurodegeneration in amyotrophic lateral sclerosis? *Cell. Mol. Life Sci.* **73**: 3801–8 [PMID:27510420]
- Schulman IG. (2017) Liver X receptors link lipid metabolism and inflammation. *FEBS Lett.* **591**: 2978–2991 [PMID:28555747]

## 1I. Vitamin D receptor-like receptors

Nuclear hormone receptors → 1I. Vitamin D receptor-like receptors

**Overview:** Vitamin D (VDR), Pregnane X (PXR) and Constitutive Androstane (CAR) receptors (nomenclature as agreed by the **NC-IUPHAR Subcommittee on Nuclear Hormone Receptors** [100]) are members of the NR1I family of nuclear receptors, which form heterodimers with members of the retinoid X receptor family. PXR and CAR are activated by a range of exogenous compounds, with no established endogenous physiological agonists, although high concentrations of bile acids and bile pigments activate PXR and CAR [100].

Nomenclature	<a href="#">Vitamin D receptor</a>	<a href="#">Pregnane X receptor</a>	<a href="#">Constitutive androstane receptor</a>
Systematic nomenclature	NR111	NR112	NR113
HGNC, UniProt	<a href="#">VDR</a> , <a href="#">P11473</a>	<a href="#">NR112</a> , <a href="#">O75469</a>	<a href="#">NR113</a> , <a href="#">Q14994</a>
Endogenous agonists	<a href="#">1,25-dihydroxyvitamin D3</a> [9, 37]	<a href="#">17<math>\beta</math>-estradiol</a> [60]	–
Selective agonists	<a href="#">seocalcitol</a> [25, 150], <a href="#">doxercalciferol</a>	<a href="#">hyperforin</a> [101, 149], <a href="#">5<math>\beta</math>-pregnane-3,20-dione</a> [60], <a href="#">lovastatin</a> [77], <a href="#">rifampicin</a> [13, 77]	<a href="#">TCPOBOP</a> [141] – Mouse, <a href="#">CITCO</a> [86]
Selective antagonists	<a href="#">TEI-9647</a> (pIC <sub>50</sub> 8.2) [121] – Chicken, <a href="#">ZK159222</a> (pIC <sub>50</sub> 7.5) [40, 56]	–	–
Comments	–	–	<a href="#">Clotrimazole</a> [102] and <a href="#">T0901317</a> [64] although acting at other sites, function as antagonists of the constitutive androstane receptor.

### Further reading on 1I. Vitamin D receptor-like receptors

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798–836 [PMID:17132856]

Long MD *et al.* (2015) Vitamin D receptor and RXR in the post-genomic era. *J. Cell. Physiol.* **230**: 758–66 [PMID:25335912]

Moore DD *et al.* (2006) International Union of Pharmacology. LXII. The NR1H and NR1I receptors: constitutive androstane receptor, pregnane X receptor, farnesoid X receptor alpha, farnesoid X receptor beta, liver X receptor alpha, liver X receptor beta, and vitamin D receptor. *Pharmacol. Rev.* **58**: 742–59 [PMID:17132852]

## 2A. Hepatocyte nuclear factor-4 receptors

Nuclear hormone receptors → 2A. Hepatocyte nuclear factor-4 receptors

**Overview:** The nomenclature of hepatocyte nuclear factor-4 receptors is agreed by the **NC-IUPHAR Subcommittee on Nuclear Hormone Receptors** [5]. While linoleic acid has been identified as the endogenous ligand for HNF4 $\alpha$  its function remains ambiguous [160]. HNF4 $\gamma$  has yet to be paired with an endogenous ligand.

Nomenclature	<a href="#">Hepatocyte nuclear factor-4-<math>\alpha</math></a>	<a href="#">Hepatocyte nuclear factor-4-<math>\gamma</math></a>
Systematic nomenclature	NR2A1	NR2A2
HGNC, UniProt	<a href="#">HNF4A</a> , <a href="#">P41235</a>	<a href="#">HNF4G</a> , <a href="#">Q14541</a>
Endogenous agonists	<a href="#">linoleic acid</a> [160]	–
Selective antagonists	<a href="#">B16015</a> [67]	–
Comments	HNF4 $\alpha$ has constitutive transactivation activity [160] and binds DNA as a homodimer [59].	–



### Further reading on 2A. Hepatocyte nuclear factor-4 receptors

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [PMID:17132856]  
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 Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [PMID:17132848]

Lu H. (2016) Crosstalk of HNF4 $\alpha$  with extracellular and intracellular signaling pathways in the regulation of hepatic metabolism of drugs and lipids. *Acta Pharm Sin B* **6**: 393-408 [PMID:27709008]  
 Walesky C *et al.* (2015) Role of hepatocyte nuclear factor 4 $\alpha$  (HNF4 $\alpha$ ) in cell proliferation and cancer. *Gene Expr.* **16**: 101-8 [PMID:25700366]

## 2B. Retinoid X receptors

Nuclear hormone receptors → 2B. Retinoid X receptors

**Overview:** Retinoid X receptors (nomenclature as agreed by the **NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [43]**) are NR2B family members activated by **alitretinoin** and the RXR-selective agonists **bexarotene** and **LG100268**, sometimes referred to as **rexinoids**. **UVI3003 [103]** and **HX 531 [35]** have been described as a pan-RXR antagonists. These receptors form RXR-RAR heterodimers and RXR-RXR homodimers [20, 91].

Nomenclature	Retinoid X receptor- $\alpha$	Retinoid X receptor- $\beta$	Retinoid X receptor- $\gamma$
Systematic nomenclature	NR2B1	NR2B2	NR2B3
HGNC, UniProt	<a href="#">RXRA</a> , <a href="#">P19793</a>	<a href="#">RXRB</a> , <a href="#">P28702</a>	<a href="#">RXRG</a> , <a href="#">P48443</a>
Sub/family-selective agonists	<a href="#">bexarotene [14, 19, 138]</a>	<a href="#">bexarotene [14, 19, 138]</a>	<a href="#">bexarotene [14, 19, 138]</a>
Selective agonists	<a href="#">CD3254 [46]</a>	–	–

### Further reading on 2B. Retinoid X receptors

Germain P *et al.* (2006) International Union of Pharmacology. LXIII. Retinoid X receptors. *Pharmacol. Rev.* **58**: 760-72 [PMID:17132853]  
 Long MD *et al.* (2015) Vitamin D receptor and RXR in the post-genomic era. *J. Cell. Physiol.* **230**: 758-66 [PMID:25335912]

Menéndez-Gutiérrez MP *et al.* (2017) The multi-faceted role of retinoid X receptor in bone remodeling. *Cell. Mol. Life Sci.* **74**: 2135-2149 [PMID:28105491]

## 2C. Testicular receptors

Nuclear hormone receptors → 2C. Testicular receptors

**Overview:** Testicular receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand, although testicular receptor 4 has been reported to respond to retinoids.

Nomenclature	<a href="#">Testicular receptor 2</a>	<a href="#">Testicular receptor 4</a>
Systematic nomenclature	NR2C1	NR2C2
HGNC, UniProt	<a href="#">NR2C1</a> , <a href="#">P13056</a>	<a href="#">NR2C2</a> , <a href="#">P49116</a>
Endogenous agonists	–	<a href="#">retinol</a> [166], <a href="#">tretinoin</a> [166]
Comments	Forms a heterodimer with TR4; gene disruption appears without effect on testicular development or function [127].	Forms a heterodimer with TR2.

### Further reading on 2C. Testicular receptors

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [PMID:17132856]

Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [PMID:17132848]

Safe S *et al.* (2014) Minireview: role of orphan nuclear receptors in cancer and potential as drug targets. *Mol. Endocrinol.* **28**: 157-72 [PMID:24295738]

Wu D *et al.* (2016) The emerging roles of orphan nuclear receptors in prostate cancer. *Biochim. Biophys. Acta* **1866**: 23-36 [PMID:27264242]

## 2E. Tailless-like receptors

Nuclear hormone receptors → 2E. Tailless-like receptors

**Overview:** Tailless-like receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	<a href="#">TLX</a>	<a href="#">PNR</a>
Systematic nomenclature	NR2E1	NR2E3
HGNC, UniProt	<a href="#">NR2E1</a> , <a href="#">Q9Y466</a>	<a href="#">NR2E3</a> , <a href="#">Q9Y5X4</a>
Comments	Gene disruption is associated with abnormal brain development [71, 99].	–

### Further reading on 2E. Tailless-like receptors

- Benod C *et al.* (2016) TLX: An elusive receptor. *J. Steroid Biochem. Mol. Biol.* **157**: 41-7 [PMID:26554934]  
 Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [PMID:17132848]  
 Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [PMID:17132856]  
 O'Leary JD *et al.* (2018) Regulation of behaviour by the nuclear receptor TLX. *Genes Brain Behav.* **17**: e12357 [PMID:27790850]

## 2F. COUP-TF-like receptors

Nuclear hormone receptors → 2F. COUP-TF-like receptors

**Overview:** COUP-TF-like receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	<a href="#">COUP-TF1</a>	<a href="#">COUP-TF2</a>	<a href="#">V-erbA-related gene</a>
Systematic nomenclature	NR2F1	NR2F2	NR2F6
HGNC, UniProt	<a href="#">NR2F1</a> , <a href="#">P10589</a>	<a href="#">NR2F2</a> , <a href="#">P24468</a>	<a href="#">NR2F6</a> , <a href="#">P10588</a>
Comments	Gene disruption is perinatally lethal [115].	Gene disruption is embryonically lethal [112].	Gene disruption impairs CNS development [148].

### Further reading on 2F. COUP-TF-like receptors

- Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [PMID:17132856]  
 Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [PMID:17132848]  
 Wu D *et al.* (2016) The emerging roles of orphan nuclear receptors in prostate cancer. *Biochim. Biophys. Acta* **1866**: 23-36 [PMID:27264242]  
 Wu SP *et al.* (2016) Choose your destiny: Make a cell fate decision with COUP-TFII. *J. Steroid Biochem. Mol. Biol.* **157**: 7-12 [PMID:26658017]

## 3B. Estrogen-related receptors

Nuclear hormone receptors → 3B. Estrogen-related receptors

**Overview:** Estrogen-related receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	<a href="#">Estrogen-related receptor-<math>\alpha</math></a>	<a href="#">Estrogen-related receptor-<math>\beta</math></a>	<a href="#">Estrogen-related receptor-<math>\gamma</math></a>
Systematic nomenclature	NR3B1	NR3B2	NR3B3
HGNC, UniProt	<a href="#">ESRRA, P11474</a>	<a href="#">ESRRB, O95718</a>	<a href="#">ESRRG, P62508</a>
Comments	Activated by some dietary flavonoids [133]; activated by the synthetic agonist <a href="#">GSK4716</a> [169] and blocked by <a href="#">XCT790</a> [153].	May be activated by <a href="#">DY131</a> [159].	May be activated by <a href="#">DY131</a> [159].

### Further reading on 3B. Estrogen-related receptors

- Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [PMID:17132856]
- Divekar SD *et al.* (2016) Estrogen-related receptor  $\beta$  (ERR $\beta$ ) - renaissance receptor or receptor renaissance? *Nucl Recept Signal* **14**: e002 [PMID:27507929]
- Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [PMID:17132848]
- Tam IS *et al.* (2016) There and back again: The journey of the estrogen-related receptors in the cancer realm. *J. Steroid Biochem. Mol. Biol.* **157**: 13-9 [PMID:26151739]
- Wu D *et al.* (2016) The emerging roles of orphan nuclear receptors in prostate cancer. *Biochim. Biophys. Acta* **1866**: 23-36 [PMID:27264242]

## 4A. Nerve growth factor IB-like receptors

[Nuclear hormone receptors](#) → [4A. Nerve growth factor IB-like receptors](#)

**Overview:** Nerve growth factor IB-like receptors (**nomenclature as agreed by the [NC-IUPHAR Subcommittee on Nuclear Hormone Receptors](#) [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	<a href="#">Nerve Growth factor IB</a>	<a href="#">Nuclear receptor related 1</a>	<a href="#">Neuron-derived orphan receptor 1</a>
Systematic nomenclature	NR4A1	NR4A2	NR4A3
HGNC, UniProt	<a href="#">NR4A1, P22736</a>	<a href="#">NR4A2, P43354</a>	<a href="#">NR4A3, Q92570</a>
Comments	An endogenous agonist, <a href="#">cytosporone B</a> , has been described [161], although structural analysis and molecular modelling has not identified a ligand binding site [3, 38, 147].	–	–

### Further reading on 4A. Nerve growth factor IB-like receptors

- Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [PMID:17132856]
- Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [PMID:17132848]
- Ranhotra HS. (2015) The NR4A orphan nuclear receptors: mediators in metabolism and diseases. *J. Recept. Signal Transduct. Res.* **35**: 184-8 [PMID:25089663]
- Rodríguez-Calvo R *et al.* (2017) The NR4A subfamily of nuclear receptors: potential new therapeutic targets for the treatment of inflammatory diseases. *Expert Opin. Ther. Targets* **21**: 291-304 [PMID:28055275]
- Safe S *et al.* (2016) Nuclear receptor 4A (NR4A) family - orphans no more. *J. Steroid Biochem. Mol. Biol.* **157**: 48-60 [PMID:25917081]

## 5A. Fushi tarazu F1-like receptors

Nuclear hormone receptors → 5A. Fushi tarazu F1-like receptors

**Overview:** Fushi tarazu F1-like receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	Steroidogenic factor 1	Liver receptor homolog-1
Systematic nomenclature	NR5A1	NR5A2
HGNC, UniProt	<a href="#">NR5A1</a> , <a href="#">Q13285</a>	<a href="#">NR5A2</a> , <a href="#">O00482</a>
Comments	Reported to be inhibited by <a href="#">AC45594</a> [29] and <a href="#">SID7969543</a> [85].	–

### Further reading on 5A. Fushi tarazu F1-like receptors

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798-836 [[PMID:17132856](#)]

Garattini E *et al.* (2016) Lipid-sensors, enigmatic-orphan and orphan nuclear receptors as therapeutic targets in breast-cancer. *Oncotarget* **7**: 42661-42682 [[PMID:26894976](#)]

Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685-704 [[PMID:17132848](#)]

Zhi X *et al.* (2016) Structures and regulation of non-X orphan nuclear receptors: A retinoid hypothesis. *J. Steroid Biochem. Mol. Biol.* **157**: 27-40 [[PMID:26159912](#)]

Zimmer V *et al.* (2015) Nuclear receptor variants in liver disease. *Dig Dis* **33**: 415-9 [[PMID:26045277](#)]

## 6A. Germ cell nuclear factor receptors

Nuclear hormone receptors → 6A. Germ cell nuclear factor receptors

**Overview:** Germ cell nuclear factor receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	Germ cell nuclear factor
Systematic nomenclature	NR6A1
HGNC, UniProt	<a href="#">NR6A1</a> , <a href="#">Q15406</a>

### Further reading on 6A. Germ cell nuclear factor receptors

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798–836 [PMID:17132856]  
 Garattini E *et al.* (2016) Lipid-sensors, enigmatic-orphan and orphan nuclear receptors as therapeutic targets in breast-cancer. *Oncotarget* **7**: 42661–42682 [PMID:26894976]  
 Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685–704 [PMID:17132848]

Safe S *et al.* (2014) Minireview: role of orphan nuclear receptors in cancer and potential as drug targets. *Mol. Endocrinol.* **28**: 157–72 [PMID:24295738]  
 Zhi X *et al.* (2016) Structures and regulation of non-X orphan nuclear receptors: A retinoid hypothesis. *J. Steroid Biochem. Mol. Biol.* **157**: 27–40 [PMID:26159912]

## 0B. DAX-like receptors

Nuclear hormone receptors → 0B. DAX-like receptors

**Overview:** Dax-like receptors (nomenclature as agreed by the **NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [5]**) have yet to be officially paired with an endogenous ligand.

Nomenclature	DAX1	SHP
Systematic nomenclature	NROB1	NROB2
HGNC, UniProt	<i>NROB1</i> , P51843	<i>NROB2</i> , Q15466

### Further reading on 0B. DAX-like receptors

Benoit G *et al.* (2006) International Union of Pharmacology. LXVI. Orphan nuclear receptors. *Pharmacol. Rev.* **58**: 798–836 [PMID:17132856]  
 Garattini E *et al.* (2016) Lipid-sensors, enigmatic-orphan and orphan nuclear receptors as therapeutic targets in breast-cancer. *Oncotarget* **7**: 42661–42682 [PMID:26894976]  
 Germain P *et al.* (2006) Overview of nomenclature of nuclear receptors. *Pharmacol. Rev.* **58**: 685–704 [PMID:17132848]

Safe S *et al.* (2014) Minireview: role of orphan nuclear receptors in cancer and potential as drug targets. *Mol. Endocrinol.* **28**: 157–72 [PMID:24295738]  
 Wu D *et al.* (2016) The emerging roles of orphan nuclear receptors in prostate cancer. *Biochim. Biophys. Acta* **1866**: 23–36 [PMID:27264242]

## Steroid hormone receptors

Nuclear hormone receptors → Steroid hormone receptors

**Overview:** Steroid hormone receptors (nomenclature as agreed by the **NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [27, 82]**) are nuclear hormone receptors of the NR3 class, with endogenous agonists that may be divided into 3-hydroxysteroids (*estrone* and *17β-estradiol*) and 3-ketosteroids (*dihydrotestosterone* [DHT], *aldosterone*, *cortisol*, *corticosterone*, *progesterone* and *testosterone*). These receptors exist as dimers coupled with chaperone molecules (such as *hsp90β* (*HSP90ABI*, P08238) and immunophilin FKBP52:*FKBP4*, Q02790), which are shed on binding the steroid hormone. Although rapid signalling

phenomena are observed [79, 114], the principal signalling cascade appears to involve binding of the activated receptors to nuclear hormone response elements of the genome, with a 15-nucleotide consensus sequence AGAACAnnnTGTTCT (*i.e.* an inverted palindrome) as homo- or heterodimers. They also affect

transcription by protein-protein interactions with other transcription factors, such as activator protein 1 (AP-1) and nuclear factor  $\kappa$ B (NF- $\kappa$ B). Splice variants of each of these receptors can form functional or non-functional monomers that can dimerize to form functional or non-functional receptors. For example, alternative

splicing of PR mRNA produces A and B monomers that combine to produce functional AA, AB and BB receptors with distinct characteristics [142].

A 7TM receptor responsive to estrogen (*GPER1*, *Q99527*, also known as GPR30, see [113]) has been described. Human

orthologues of 7TM 'membrane progesterin receptors' (*PAQR7*, *PAQR8* and *PAQR5*), initially discovered in fish [167, 168], appear to localize to intracellular membranes and respond to 'non-genomic' progesterone analogues independently of G proteins [129].

## 3A. Estrogen receptors

Nuclear hormone receptors → Steroid hormone receptors → 3A. Estrogen receptors

**Overview:** Estrogen receptor (ER) activity regulates diverse physiological processes *via* transcriptional modulation of target genes. The selection of target genes and the magnitude of the response, be it induction or repression, are determined by many factors, including the effect of the hormone ligand and DNA binding on ER structural conformation, and the local cellular regulatory environment. The cellular environment defines the specific complement of DNA enhancer and promoter elements present and the availability of coregulators to form functional transcription complexes. Together, these determinants control the resulting biological response.

Nomenclature	Estrogen receptor- $\alpha$	Estrogen receptor- $\beta$
Systematic nomenclature	NR3A1	NR3A2
HGNC, UniProt	<i>ESR1</i> , P03372	<i>ESR2</i> , Q92731
Endogenous agonists	estriol [70], estrone [70]	–
Selective agonists	propylpyrazoletriol [69, 130], ethinylestradiol [58]	WAY200070 [88], diarylpropionitrile [95, 130], prinaberel [26, 88]
Sub/family-selective antagonists	bazedoxifene (pIC <sub>50</sub> 7.6) [98]	bazedoxifene (pIC <sub>50</sub> 7.1) [98]
Selective antagonists	clomiphene (pK <sub>i</sub> 8.9) [2], methyl-piperidino-pyrazole (pK <sub>i</sub> 8.6) [134]	R,R-THC (pK <sub>i</sub> 8.4) [94, 135], PHTPP (pK <sub>i</sub> 6.9) [165]

**Comments:** R,R-THC exhibits partial agonist activity at ER $\alpha$  [94, 135]. Estrogen receptors may be blocked non-selectively by **tamoxifen** and **raloxifene** and labelled by [<sup>3</sup>H]17 $\beta$ -estradiol and [<sup>3</sup>H]tamoxifen. Many agents thought initially to be antagonists

at estrogen receptors appear to have tissue-specific efficacy (*e.g.* **Tamoxifen** is an antagonist at estrogen receptors in the breast, but is an agonist at estrogen receptors in the uterus), hence the descriptor SERM (selective estrogen receptor modulator) or SnuRM

(selective nuclear receptor modulator). **Y134** has been suggested to be an ER $\alpha$ -selective estrogen receptor modulator [106].

**Further reading on 3A. Estrogen receptors**

- Coons LA *et al.* (2017) DNA Sequence Constraints Define Functionally Active Steroid Nuclear Receptor Binding Sites in Chromatin. *Endocrinology* **158**: 3212–3234 [PMID:28977594]
- Dahlman-Wright K *et al.* (2006) International Union of Pharmacology. LXIV. Estrogen receptors. *Pharmacol. Rev.* **58**: 773–81 [PMID:17132854]
- Gonzalez-Sanchez E *et al.* (2015) Nuclear receptors in acute and chronic cholestasis. *Dig Dis* **33**: 357–66 [PMID:26045270]
- Hewitt SC *et al.* (2016) What's new in estrogen receptor action in the female reproductive tract. *J. Mol. Endocrinol.* **56**: R55–71 [PMID:26826253]
- Jameera Begam A *et al.* (2017) Estrogen receptor agonists/antagonists in breast cancer therapy: A critical review. *Bioorg. Chem.* **71**: 257–274 [PMID:28274582]
- Warner M *et al.* (2017) Estrogen Receptor  $\beta$  as a Pharmaceutical Target. *Trends Pharmacol. Sci.* **38**: 92–99 [PMID:27979317]

## 3C. 3-Ketosteroid receptors

Nuclear hormone receptors → Steroid hormone receptors → 3C. 3-Ketosteroid receptors

**Overview:** Steroid hormone receptors (**nomenclature as agreed by the NC-IUPHAR Subcommittee on Nuclear Hormone Receptors [27, 82]**) are nuclear hormone receptors of the NR3 class, with endogenous agonists that may be divided into 3-hydroxysteroids (**estrone** and **17 $\beta$ -estradiol**) and 3-ketosteroids (**dihydrotestosterone [DHT]**, **aldosterone**, **cortisol**, **corticosterone**, **progesterone** and **testosterone**).

Nomenclature	Androgen receptor	Glucocorticoid receptor	Mineralocorticoid receptor	Progesterone receptor
Systematic nomenclature	NR3C4	NR3C1	NR3C2	NR3C3
HGNC, UniProt	AR, P10275	NR3C1, P04150	NR3C2, P08235	PGR, P06401
Rank order of potency	dihydrotestosterone > testosterone	cortisol, corticosterone $\gg$ aldosterone, deoxycortisone [120]	corticosterone, cortisol, aldosterone, progesterone [120]	progesterone
Endogenous agonists	dihydrotestosterone [139]	–	aldosterone [54, 120]	progesterone [36]
Selective agonists	testosterone propionate [90], mibolerone [47], fluoxymesterone [57], methyltrienolone [145], dromostanolone propionate	fluticasone propionate [8], flunisolide [2], beclometasone [2], methylprednisolone [2], betamethasone [2], budesonide [97]	–	medroxyprogesterone (Affinity at human PR-A) [163], ORG2058, levonorgestrel [7, 123]
Selective antagonists	bicalutamide (pK <sub>i</sub> 7.7) [66], PF0998425 (pIC <sub>50</sub> 7.1–7.5) [81], enzalutamide (pIC <sub>50</sub> 7.4) [140], nilutamide (pIC <sub>50</sub> 7.1–7.1) [128], hydroxyflutamide (pEC <sub>50</sub> 6.6) [145], galeterone (pIC <sub>50</sub> 6.4) [53], flutamide (Displacement of <sup>3</sup> [H] testosterone from wild-type androgen receptors) (pK <sub>i</sub> 5.4) [144]	onapristone (pIC <sub>50</sub> 7.6) [162], ZK112993	finerenone (pIC <sub>50</sub> 7.7) [18], eplerenone (pK <sub>i</sub> 6.9) [4], onapristone (pIC <sub>50</sub> 6.3) [162], RU28318, ZK112993	ulipristal acetate (pIC <sub>50</sub> 9.7) [118], mifepristone (Mixed) (pK <sub>i</sub> 9) [164], onapristone (pK <sub>i</sub> 7.7) [52], ZK112993
Labelled ligands	[ <sup>3</sup> H]dihydrotestosterone (Selective Agonist), [ <sup>3</sup> H]methyltrienolone (Selective Agonist), [ <sup>3</sup> H]mibolerone (Agonist)	[ <sup>3</sup> H]dexamethasone (Agonist)	[ <sup>3</sup> H]aldosterone (Selective Agonist) [42, 132] – Rat	[ <sup>3</sup> H]ORG2058 (Selective Agonist)



**Comments:** [<sup>3</sup>H]dexamethasone also binds to MR *in vitro*. PR antagonists have been suggested to subdivide into Type I (e.g. [onapristone](#)) and Type II (e.g. [ZK112993](#)) groups. These groups appear to promote binding of PR to DNA with different efficacies and evoke distinct conformational changes in the receptor, leading to a transcription-neutral complex [41, 78]. Mutations in AR underlie testicular feminization and androgen insensitivity syndromes, spinal and bulbar muscular atrophy (Kennedy's disease).

### Further reading on 3C. 3-Ketosteroid receptors

- Baker ME *et al.* (2017) 30 YEARS OF THE MINERALOCORTICOID RECEPTOR: Evolution of the mineralocorticoid receptor: sequence, structure and function. *J. Endocrinol.* **234**: T1-T16 [[PMID:28468932](#)]
- Carroll JS *et al.* (2017) Deciphering the divergent roles of progestogens in breast cancer. *Nat. Rev. Cancer* **17**: 54-64 [[PMID:27885264](#)]
- Cohen DM *et al.* (2017) Nuclear Receptor Function through Genomics: Lessons from the Glucocorticoid Receptor. *Trends Endocrinol. Metab.* **28**: 531-540 [[PMID:28495406](#)]
- de Kloet ER *et al.* (2017) Brain mineralocorticoid receptor function in control of salt balance and stress-adaptation. *Physiol. Behav.* **178**: 13-20 [[PMID:28089704](#)]
- Garg D *et al.* (2017) Progesterone-Mediated Non-Classical Signaling. *Trends Endocrinol. Metab.* **28**: 656-668 [[PMID:28651856](#)]
- Lu NZ *et al.* (2006) International Union of Pharmacology. LXV. The pharmacology and classification of the nuclear receptor superfamily: glucocorticoid, mineralocorticoid, progesterone, and androgen receptors. *Pharmacol. Rev.* **58**: 782-97 [[PMID:17132855](#)]
- Lucas-Herald AK *et al.* (2017) Genomic and non-genomic effects of androgens in the cardiovascular system: clinical implications. *Clin. Sci.* **131**: 1405-1418 [[PMID:28645930](#)]
- Wadosky KM *et al.* (2017) Androgen receptor splice variants and prostate cancer: From bench to bedside. *Oncotarget* **8**: 18550-18576 [[PMID:28077788](#)]
- Weikum ER *et al.* (2017) Glucocorticoid receptor control of transcription: precision and plasticity via allosterity. *Nat. Rev. Mol. Cell Biol.* **18**: 159-174 [[PMID:28053348](#)]

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