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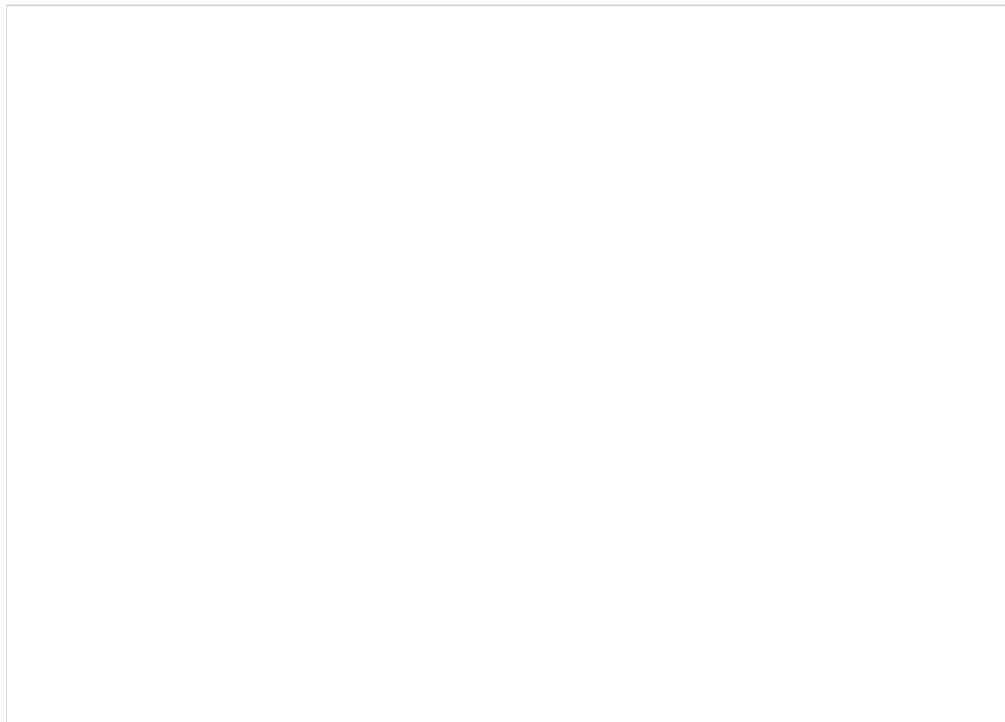
SNAPSHOT

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AOP 21: aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2

Short Title: AhR mediated mortality

Graphical Representation



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Abstract

This adverse outcome pathway details the linkage between activation of the aryl hydrocarbon receptor (AhR) and early life stage mortality in oviparous vertebrates. This AOP can be initiated by a range of planar aromatic hydrocarbons, but is best known as the target of dioxin-like compounds (DLCs). These planar compounds are able to bind to the AhR causing heterodimerization with the aryl hydrocarbon nuclear translocator (ARNT) and interaction with dioxin-responsive elements on the DNA causing an up-regulation in dioxin responsive genes. Hundreds to thousands of genes are regulated, either directly or indirectly, by the AhR. One dioxin-responsive gene is cyclooxygenase 2 (COX-2) which has roles in development of the cardiovascular system. Up-regulation in expression of COX-2 causes alteration in cardiovascular development and function which results in reduced heart pumping efficiency, reduced blood flow, and eventual cardiac collapse and death. Comparable apical manifestations of activation of the AhR have been recorded across freshwater and marine teleost and non-teleost fishes, as well as birds.

Therefore, this AOP might be broadly applicable across oviparous vertebrate taxa. Despite conservation in the AOP across taxa, great differences in sensitivity to perturbation exist both among and within taxonomic groups. Therefore, this AOP has utility in support of application toward the mechanistic understanding of adverse effects of chemicals that act as agonists of the AhR, particularly with regard to cross-chemical, cross-species, and cross-taxa extrapolation.

In general, biological plausibility of this AOP is strong based heavily on evidence collected from zebrafish (*Danio rerio*) through mechanistic investigations by use of targeted knockdown of AhR, ARNT, or COX-2 and through use of selective agonists and antagonists of COX-2. However, uncertainties exist regarding the interaction of multiple potential targets of AhR activation, including CYP1A, Sox9b, and HIF1a/VEGF. Quantitative understanding is largely limited to the indirect KER between AhR activation and early life stage mortality.

Since activation of the AhR causes pleiotropic responses, it is a challenge to elucidate the precise series of key events which link activation of the AhR to early life stage mortality. Because of this uncertainty, other possible AOPs (ex. AOP 150) have also been proposed and likely occur simultaneously with COX-2 to cause altered cardiovascular development and function leading to early life stage mortality.

Background

- The aryl hydrocarbon receptor (AhR) is a ligand-activated transcription factor in the basic helix-loop-helix-PER-ARNT-SIM (bHLH-PAS) family of proteins (Okey 2007). The AhR is a highly conserved and ancient protein with homologs having been identified in most major animal groups, apart from the most ancient lineages, such as sponges (Porifera) (Hahn et al 2002).
- Investigations of invertebrates possessing early homologs of the AhR suggest that the AhR evolutionarily functioned in regulation of the cell cycle, cellular proliferation and differentiation, and cell-to-cell communications (Hahn et al 2002). However, critical functions in angiogenesis, regulation of the immune system, neuronal processes, metabolism, development of the heart and other organ systems, and detoxification have emerged sometime in early vertebrate evolution (Duncan et al 1998; Lahvis and Bradfield 1998; Emmons et al 1999).
- Activation of the AhR by anthropogenic pollutants that act as agonists can result in a range of adverse biological effects. These effects can include hepatotoxicity, histological lesions, hemopoiesis, suppression of immune responses and healing, impaired reproductive and endocrine processes, teratogenesis, carcinogenesis, wasting syndrome, and mortality (Kleeman et al 1988; Spitsbergen et al 1986; Walter et al 2000; Giesy et al 2002; Spitsbergen et al 1988a; 1988b).
- Despite the AhR being a highly conserved protein, differences in relative sensitivity to adverse effects both among and within vertebrate taxa are greater than 1000-fold (Cohen-Barnhouse et al 2011; Doering et al 2013; Hengstler et al 1999; Korkalainen et al 2001).
- Differences in binding affinity and transactivation of the AhR have been implicated as a key mechanism contributing to differences in sensitivity to agonists of the AhR among species and taxa. However, the precise mechanisms are not fully understood for all taxa.
- High-throughput, next-generation 'OMICS' technologies have identified hundreds to thousands of different genes that are regulated, either directly or indirectly, by the AhR (Brinkmann et al 2016; Doering et al 2016; Huang et al 2014; Li et al 2013; Whitehead et al 2010). These genes include Phase I and Phase II biotransformation enzymes, such as cytochrome P450 1A (CYP1A). Expressions and activities of CYP1A are routinely used as biomarkers of exposure to anthropogenic pollutants that act as agonists of the AhR (Whyte et al 2008).
- One gene which is regulated by AhR is cyclooxygenase-2 (COX-2) which is known to have roles in development of the heart in vertebrates (Dong et al 2010; Teraoka et al 2008; 2014). AhR-mediated dysregulation of COX-2 is associated with altered cardiovascular development, decreased blood flow, and cardiac failure causing mortality in early life stages of fish and birds (Dong et al 2010; Teraoka et al 2008; 2014).
- Exposure to mixtures of agonists of the AhR during the 1950's, 1960's, and 1970's has been implicated in early life stage mortality of Lake Ontario lake trout (*Salvelinus namaycush*) leading to population collapse (Cook et al 2003). However, populations of mummichog (*Fundulus heteroclitus*) and Atlantic tomcod (*Microgadus tomcod*) exposed to lethal concentrations of agonists of the AhR have evolved tolerance through several mechanisms which has protected against population collapse (Nacci et al 2010; Wirgin et al 2011).

Summary of the AOP

Events

Molecular Initiating Events (MIE), Key Events (KE), Adverse Outcomes (AO)

Sequence	Type	Event ID	Title	Short name
1	MIE	18	Activation, AhR (https://aopwiki.org/events/18)	Activation, AhR
2	KE	944	dimerization, AHR/ARNT (https://aopwiki.org/events/944)	dimerization, AHR/ARNT
3	KE	1269	Increase, COX-2 expression (https://aopwiki.org/events/1269)	Increase, COX-2 expression
4	KE	317	Altered, Cardiovascular development/function (https://aopwiki.org/events/317)	Altered, Cardiovascular development/function

Sequence	Type	Event ID	Title	Short name
5	KE	947	Increase, Early Life Stage Mortality (https://aopwiki.org/events/947)	Increase, Early Life Stage Mortality

Key Event Relationships

Upstream Event	Relationship Type	Downstream Event	Evidence	Quantitative Understanding
Activation, AhR (https://aopwiki.org/relationships/972)	adjacent	dimerization, AHR/ARNT	High	Moderate
dimerization, AHR/ARNT (https://aopwiki.org/relationships/1350)	adjacent	Increase, COX-2 expression	High	Moderate
Increase, COX-2 expression (https://aopwiki.org/relationships/1351)	adjacent	Altered, Cardiovascular development/function	Moderate	Moderate
Altered, Cardiovascular development/function (https://aopwiki.org/relationships/1567)	adjacent	Increase, Early Life Stage Mortality	High	Low
Activation, AhR (https://aopwiki.org/relationships/984)	non-adjacent	Increase, Early Life Stage Mortality	High	Moderate

Stressors

Name	Evidence
2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)	High

2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)

- The AhR is activated by numerous planar aromatic hydrocarbons. Specifically, chemicals with molecular dimensions of 12 Å x 14 Å x 5 Å are potential ligands of the AhR (Waller & McKinney 1992; 1995).
- However, the AhR is best known as the molecular target of dioxin-like compounds (DLCs). DLCs include polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and planar polychlorinated biphenyls (PCBs). A total of seven PCDDs, ten PCDFs, and 12 PCBs are considered 'dioxin-like' because they bind to the AhR with relatively great affinity (Denison & Heath-Pagliuso 1998; Van den Berg et al 1998).
- The prototypical and among the most potent of the DLCs is 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD).

Overall Assessment of the AOP

Assessment of WoE calls:

Activation, AhR leads to dimerization, AHR/ARNT: High

Rationale: The call of 'High' is based on overwhelming empirical evidence in numerous species of mammals, birds, amphibians, and fishes. Further, because of overwhelming evidence of essentiality based on targeted knockdown/knockout studies. No uncertainties or inconsistencies are known which affect the WoE call.

Dimerization, AHR/ARNT leads to increase, COX-2 expression: High

Rationale: The call of "High" is based on convincing empirical evidence in three species (two fish and one bird). Further, because of convincing biological plausibility based on identification of dioxin-response elements in the promoter region of COX-2. Uncertainties and inconsistencies are only related to lack of any information on species outside of the three model species that have been investigated.

Increase, COX-2 expression leads to altered, cardiovascular development/function: Moderate

Rationale: The call of "Moderate" is based on overwhelming empirical evidence and evidence of essentiality in three species (two fish and one bird) based on studies using targeted knockdown of genes and selective agonists/antagonists. However, a lack of information on the role of COX-2 in cardiovascular development/function makes biological plausibility questionable at this time. Further, there is some uncertainty associated with pleiotropic effects of AhR activation and the high probability of multiple mechanisms acting concurrently to cause altered cardiovascular development/function.

Altered, cardiovascular development/function leads to increase, early life stage mortality: High

Rationale: The call of "High" is based on overwhelming empirical evidence and biological plausibility in numerous species of mammals, birds, and

fish. There are no known uncertainties or inconsistencies at this time.

Activation, AhR leads to increase, early life stage mortality: High

Rationale: The call of "High" is based on overwhelming empirical evidence and evidence of essentiality in numerous species of mammals, birds, amphibians, and fishes using regression analysis and targeted knockdown/knockout of AhR. There are no known uncertainties or inconsistencies at this time.

Domain of Applicability

Life Stage Applicability

Life Stage	Evidence
Embryo	High
Development	High

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
medaka	Oryzias latipes	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8090)
Gallus gallus	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)

Sex Applicability

Sex	Evidence
Unspecific	High

Sex: This AOP is only applicable to early life stages prior to sexual differentiation.

Life stages: This AOP is only applicable starting from embryonic development. In zebrafish, this critical window extends from fertilization to approximately 24 hours post fertilization (hpf) (Belair et al 2001; Goldstone & Stegeman 2008).

Taxonomic: The specific characteristics of altered cardiovascular development and function vary to some degree among taxonomic groups of vertebrates.

This AOP is applicable to:

- All teleost and non-teleost fishes that have been investigated as embryos so far (Buckler et al 2015; Doering et al 2013; Elonen et al 1998; Johnson et al 1998; Park et al 2014; Tillitt et al 2016; Toomey et al 2001; Walker et al 1991; Yamauchi et al 2006; Zabel et al 1995).
- All birds (Canga et al 1993; Cohen-Barnhouse et al 2011; Fujisawa et al 2014; Heid et al 2001; Ivnitski et al 2001; Walker & Catron 2000). However, some details of the AOP might be different in birds as cyclooxygenase-2 (COX-2) is believed to be up-regulated through non-genomic mechanisms in these taxa based on investigations in chicken (*Gallus gallus*) (Fujisawa et al 2014).
- Amphibians and reptiles have insufficient mechanistic and early life stage mortality information to demonstrate applicability at this time. However, amphibians and reptiles express AhRs that are activated by agonists in a manner consistent with other vertebrates and express AhRs during embryonic development (Lavine et al 2005; Shoots et al 2015; Ohi et al 2003; Oka et al 2016). However, altered cardiovascular development and function and early life stage mortality have not been observed at any investigated concentration of DLC in amphibians studied to date (Jung et al 1997). This tolerance is believed to result from AhRs of amphibians having very low affinity for agonists (Lavine et al 2005; Shoots et al 2015). Therefore, it is acknowledged that this AOP is likely to be applicable to reptiles. However, it might not be applicable to amphibians due to their extreme tolerance to activation of the AhR.
- Cartilaginous fishes (Chondrichthyes) have insufficient mechanistic and early life stage mortality information to demonstrate applicability at this time. However, sharks and rays are known to express AhRs that are structurally comparable to AhRs of teleost fishes (Hahn 2002). Sharks and rays have also been shown to respond to exposure to agonists of the AhR through responses that are comparable to teleost fishes, specifically through induction of CYP1A (Hahn et al 1998). Therefore, it is acknowledged that this AOP is likely to be applicable to Chondrichthyes.

This AOP is not applicable to:

- Mammals because the cause of mortality of the young is primarily a result of wasting syndrome and not necessarily altered cardiovascular development and function (Kopf & Walker 2009). Further, studies of CYP1A1 and CYP1A2 null mice (*Mus musculus*) demonstrate that wasting syndrome and mortality are mediated by CYP1A1 in mammals (Uno et al 2004).

- Invertebrates because AhRs of invertebrates have less diverse functionalities relative to vertebrates, AhRs of most invertebrates likely do not bind agonists that represent anthropogenic pollutants, and no AhR-mediated, critical adverse effects are known in invertebrates as a result of exposure to AhR agonists (Hahn 2002; Hahn et al 1994).
- Jawless fishes, such as lamprey (*Petromyzontiformes*) and hagfish (*Myxiniiformes*), because of a lack of measurable AhR-mediated responses (Hahn et al 1998). Although additional information is necessary for this taxa, it is currently acknowledged that this AOP is likely not applicable to jawless fishes.

Essentiality of the Key Events

Support for essentiality for key events in the AOP was provided by a series of knockdown and targeted agonist and antagonist experiments. These investigations were conducted mainly with zebrafish as the model species and TCDD as the model agonist of the AhR.

Rationale for essentiality calls:

- AhR, activation: [Strong] Knockdown of AhR prevents TCDD induced alteration in cardiovascular development and function (Clark et al 2010; Hanno et al 2010; Karchner et al 1999; Prasch et al 2003; Van Tiem & Di Giulio 2011).
- AhR/ARNT, dimerization: [Strong] Knockdown of ARNT prevents TCDD induced alteration in cardiovascular development and function (Antkiewicz et al 2006; Prasch et al 2004). Depletion of ARNT lessens or prevents TCDD induced alteration in cardiovascular development and function (Prasch et al 2004).
- COX-2, increase: [Strong] Knockdown of COX-2 and selective antagonists of COX-2 prevent TCDD induced alteration in cardiovascular development and function (Dong et al 2010; Teraoka et al 2008; 2014). COX-2 inducers that are not agonists of the AhR cause altered cardiovascular development and function that is consistent with activation of the AhR (Huang et al 2007). Knockdown of and selective antagonists of thromboxane A synthase 1 (CYP5A), which is down-stream of COX-2 in the prostaglandin synthesis pathway, prevents TCDD induced alteration in cardiovascular development and function (Teraoka et al 2008). Exposure to the substrate for COX-2, arachidonic acid, causes an up-regulation in COX-2 and altered cardiovascular development and function that is consistent with exposure to TCDD (Dong et al 2010).
- Cardiovascular development and function, altered: [Strong] Isosmotic rearing solution prevents yolk sac edema, but has no effect on TCDD induced alteration in cardiovascular development and function or mortality (Hill et al 2004). This indicates that mortality is not caused by yolk sac edema. Knockdown of cytochrome P450 1A (CYP1A) or injection with antioxidants decreases oxidative stress but has no effect on TCDD induced alteration in cardiovascular development and function or mortality (Carney et al 2004; Scott et al 2011). This is suggestive that mortality is not caused by oxidative stress. Exposure to agonists of the AhR post-heart development lessens or prevents alteration in cardiovascular development, decreased blood flow, and cardiac failure (Carney et al 2004; Lanham et al 2012). Exposure to agonists of the AhR post-heart development dramatically reduces mortality (Carney et al 2004; Lanham et al 2012). This suggests that mortality is caused by circulatory failure as a result of cardiovascular teratogenesis. Concentrations of DLCs tested in amphibians studied to date were not sufficient to cause altered cardiovascular development or function and no increase in mortality was observed (Jung et al 1997).

Weight of Evidence Summary

Biological Plausibility:

- In general, the biological plausibility and coherence linking activation of the AhR through early life stage mortality from COX-2 induced alteration in cardiovascular development and function is strong.
- The AhR is known to have critical roles in development of the heart and therefore dysregulation of these roles would be expected to result in altered cardiac development.
- The prostaglandin synthesis pathway, of which COX-2 is a rate limiting step, is known to have roles in development of the heart (Delgado et al 2004; Gullestad & Aukrust 2005; Hoehrl et al 2002; Huang et al 2007; Wong et al 1998; Dong et al 2010; Huang et al 2007; Teraoka et al 2008; 2014).
- A properly functioning circulatory system is widely acknowledged to be crucial for survival of vertebrates (Kardong 2006). General dysfunction of the heart or associated vasculature is widely documented to have the potential to result in mortality through cardiac failure, regardless of the mechanism of dysfunction.

Concordance of dose-response relationships:

- There is significant evidence showing concordance of dose-response for incidence and severity of alteration in cardiovascular development and function and subsequently mortality across at least 16 different species of fish (Buckler et al 2015; Elonen et al 1998; Huang et al 2012; Johnson et al 1998; Park et al 2014; Tillitt et al 2016; Toomey et al 2001; Walker et al 1991; Yamauchi et al 2006; Zabel et al 1995) and 8 different species of birds (Cohen-Barnhouse et al 2011; Brunstrom 1990; Brunstrom & Andersson 1988; Hoffman et al 1996; 1998; Powell et al 1998) for several PCDDs, PCDFs, planar PCBs, and PAHs. Concordance of dose-response has not been observed in amphibians studied to date because no elevated mortality or altered cardiovascular development and function was observed at any tested concentration of agonist (Jung et al 1997).
- Less is known regarding concordance of dose-response relationships for COX-2. In Japanese medaka (*Oryzias latipes*), abundance of transcript of COX-2 is significantly greater than controls at concentrations of TCDD of 0.2 ppb and greater (Dong et al 2010). Likewise, incidence of cardiovascular development and heart area were both significantly different than controls at concentrations of TCDD of 0.2 ppb and greater (Dong et al 2010).

Temporal concordance among the key events and adverse effect:

- Alterations in cardiovascular development or function is first observable in zebrafish around 48 hours post fertilization (hpf), while mortality does not begin to occur until around 86 hpf (Goldstone & Stegeman 2006).
- AhR transcript and protein is first detectable in zebrafish around 24 hpf (Tanguay et al 1999).
- COX-2 transcript is first detectable in zebrafish around 6 hpf (Teraoka et al 2008). Expression of COX-2 was investigated in zebrafish exposed to TCDD at 55 and 72 hpf (Teraoka et al 2014). At 55 hpf there was a trend towards up-regulation of COX-2 (~ 1.5-fold), while at 72 hpf there was a significant up-regulation of COX-2 (~ 4.5-fold) (Teraoka et al 2014).
- Therefore, there is a general temporal concordance in this AOP.
- However, there is some uncertainty in the early manifestations of altered cardiovascular development and up-regulation of COX-2. It is possible that the first manifestations of altered cardiovascular development result from mechanisms other than COX-2. For example, sex determining region Y-box-9b (Sox9b) is first expressed in zebrafish at around 24 hpf and has been known to cause some altered cardiovascular phenotypes (Hofsteen et al 2013; Li et al 2002). However, no studies have yet investigated temporal concordance of regulation of Sox9b by the AhR prior to 72 hpf (Hofsteen et al 2013). It is also possible that temporal concordance of early increases in COX-2 is obscured by the relatively little fold-changes observed for COX-2. Additional investigations into up-regulation of COX-2 by activation of the AhR across developmental stages is warranted.

Consistency:

- There are no known AhR-mediated effects that occur at concentrations below those that cause alteration in cardiovascular development and function that result in early life stage mortality in fishes, amphibians, reptiles, or birds.
- There are no studies in which COX-2 and altered cardiovascular development or function were co-investigated in which altered cardiovascular development or function occurred without an up-regulation in COX-2.
- In TCDD exposure groups, some individuals do not manifest alterations in cardiovascular development or function (Dong et al 2010). TCDD exposed individuals of Japanese medaka that did not manifest alterations in cardiovascular development or function had expression of COX-2 that was not statistically different than controls, while individuals that did manifest alterations in cardiovascular development or function had increased expression of COX-2 (Dong et al 2010).
- There is also consistency in the TCDD-induced alterations in cardiovascular phenotype between distantly related oviparous taxa, namely fish and birds (Teraoka et al 2008; Fujisawa et al 2014). Likewise, COX-2 is known to be up-regulated in both these taxa (Teraoka et al 2008; Fujisawa et al 2014). Cardiovascular development and function and COX-2 have not been investigated in amphibians or reptiles.

Uncertainties, inconsistencies, and data gaps:

- There are several other pathways by which activation of the AhR could result in altered cardiovascular development and function in developing embryos. These include, but are not limited to, down-regulation in Sox9b, BMP-4, and genes in the cell cycle gene cluster (Hofsteen et al 2013; Jonsson et al 2007), oxidative stress (Goldstone & Stegeman 2008), and AhR cross-talk with hypoxia inducible factor 1 α (HIF1 α) (Goldstone & Stegeman 2008).
- Investigations of knockdown and null strains for Sox9b in zebrafish do not result in the complete phenotype of altered cardiovascular development recorded in embryos following exposure to planar aromatic hydrocarbons (Hofsteen et al 2013). Specifically, knockdown or knockout of Sox9b is associated with mild pericardial edema, unlooping, loss of proepicardium, and failure to form epicardium and endocardial cushions, but does not result in typical TCDD-mediated effects of a compacted ventricle or an elongated string-like atrium (Hofsteen et al 2013). Altered cardiovascular development as a result of complete knockout of Sox9b is not severe enough to cause complete cardiac failure and early life stage mortality in zebrafish (Hofsteen et al 2013). Injection of TCDD exposed embryos with Sox9b mRNA was able to prevent the Sox9b phenotype of cardiovascular development, however it did not prevent altered cardiovascular development altogether (Hofsteen et al 2013). Considering, TCDD is only able to decrease expression of Sox9b in the heart by up to about 50% and complete knockout of Sox9b expression is not lethal suggests that Sox9b is not essential to TCDD-mediated alteration in cardiovascular development and function (Hofsteen et al 2013).
- Oxidative stress as a result of induction in CYP1A has commonly been proposed as the mechanism of altered cardiovascular development and function and CYP1A follows dose- and temporal concordance with mortality across numerous investigations in fishes and birds (Goldstone & Stegeman 2008). Early studies of CYP1A knockdown in zebrafish demonstrated protection against alteration in cardiovascular development and function induced by exposure to TCDD (Teraoka et al 2003). However, more recent investigations have observed no protection (Carney et al 2006). This inconsistency has been proposed to result from the earlier studies only recording alteration in cardiovascular development and function at early stages when adverse effects are difficult to accurately observe (Carney et al 2006). In birds, COX-2 inhibitors have no effect on expression of CYP1A but protect against TCDD induced alteration in cardiovascular development and function suggesting that CYP1A is not involved in toxicities (Fujisawa et al 2014).
- For cross-species and cross-taxa extrapolation, there is uncertainty in whether COX-2 is up-regulated by AhR through genomic or non-genomic mechanisms. Specifically, there is no detailed analysis regarding how widespread COX-2 genes which contain DREs in the promoter region are among species and among taxa and whether non-genomic or genomic mechanisms of up-regulation in COX-2 are more ubiquitous.
- All mechanistic investigations into mechanisms of AhR-mediated alteration in cardiovascular development and function have been conducted in zebrafish, Japanese medaka, and chicken. Therefore, no mechanistic information is available to conclude cross-species extrapolation outside of a shared phenotype of altered cardiovascular development and function. There is no information about AhR-mediated alteration in cardiovascular development or function or up-regulation of COX-2 in early fishes (Petromyzontiformes; Myxiniiformes; Chondrichthyes), amphibians, or reptiles.
- Despite these uncertainties, the strong, quantitative link between activation of the AhR and early life stage mortality means that elucidating the precise series of key events is less critical. Therefore, the evidence suggesting COX-2 as a primary mechanism might be all that is

necessary, although multiple mechanisms acting together is the most likely true mechanism.

Quantitative Consideration

- The majority of the quantitative understanding and the strongest quantitative understanding is for the indirect relationship between activation of the AhR and early life stage mortality.
- There is a strong quantitative understanding between quantitative structure-activity relationship (QSAR) or binding affinity for the AhR and potency among PCDDs, PCDFs, and planar PCBs (Van den Berg et al 1998; 2006). Specifically, these studies have demonstrated that congeners with greater binding affinity have greater potency (Van den Berg et al 1998; 2006). This has partially contributed to the successful development of the toxic equivalency factor (TEF) methodology in risk assessment (Van den Berg et al 1998; 2006).
- There is also a strong quantitative understanding of differences in binding affinity of the AhR among species of birds and differences in sensitivity to early life stage mortality (Karchner et al 2006; Farmahin et al 2012; 2013; Manning et al 2013). Specifically, these studies demonstrate that species of birds with AhRs with greater affinity for DLCs have greater sensitivity than species with AhRs with lesser affinity for DLCs (Karchner et al 2006). These differences in sensitivity range by more than 40-fold for TCDD (Cohen-Barnhouse et al 2011). However, a quantitative understanding between differences in binding affinity of the AhR among species and differences in sensitivity to early life stage mortality is not yet available for other taxa (Doering et al 2013).
- There is some quantitative understanding between up-regulation of COX-2 and incidence of and severity of cardiac deformities for medakafish exposed to TCDD (Dong et al 2010). This quantitative understanding includes a strong linear relationship ($R^2 = 0.88$) between abundance of COX-2 transcript and heart area (Dong et al 2010). However, this information is not available with regards to multiple investigations, species, taxonomic groups, or chemicals.
- There is strong quantitative understanding between incidence of and severity of cardiovascular deformities and mortality. However, numerous different cardiovascular endpoints are investigated among studies making side-by-side comparisons difficult.

Considerations for Potential Applications of the AOP (optional)

There are great differences in sensitivity to agonists of the AhR among species and among taxa and great differences in potency among agonists of the AhR. Therefore, this AOP has utility towards the mechanistic understanding of adverse effects of agonists of the AhR with regard to cross-chemical, cross-species, and cross-taxa extrapolations. This is particularly true regarding ongoing development of a quantitative AOP.

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Appendix 1

List of MIEs in this AOP

Event: 18: Activation, AhR (<https://aopwiki.org/events/18>)

Short Name: Activation, AhR

Key Event Component

Process	Object	Action
aryl hydrocarbon receptor activity	aryl hydrocarbon receptor	increased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:21 - aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	MolecularInitiatingEvent
Aop:57 - AhR activation leading to hepatic steatosis (https://aopwiki.org/aops/57)	MolecularInitiatingEvent
Aop:131 - Aryl hydrocarbon receptor activation leading to uroporphyrin (https://aopwiki.org/aops/131)	MolecularInitiatingEvent
Aop:150 - Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	MolecularInitiatingEvent

Stressors

Name
Benzidine
Dibenzo-p-dioxin
Polychlorinated biphenyl
Polychlorinated dibenzofurans
Hexachlorobenzene
Polycyclic aromatic hydrocarbons (PAHs)

Biological Context

Level of Biological Organization

Molecular

Evidence for Perturbation by Stressor

Overview for Molecular Initiating Event

The AHR can be activated by several structurally diverse chemicals, but binds preferentially to planar halogenated aromatic hydrocarbons and polycyclic aromatic hydrocarbons. Dioxin-like compounds (DLCs), which include polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and certain polychlorinated biphenyls (PCBs), are among the most potent AHR ligands^[38]. Only a subset of PCDD, PCDF and PCB congeners has been shown to bind to the AHR and cause toxic effects to those elicited by TCDD. Until recently, TCDD was considered to be the most potent DLC in birds^[39]; however, recent reports indicate that 2,3,4,7,8-pentachlorodibenzofuran (PeCDF) is more potent than TCDD in some species of birds.^{[40][13][41][21][42][43]} When screened for their ability to induce aryl hydrocarbon hydroxylase (AHH) activity, dioxins with chlorine atoms at a minimum of three out of the four lateral ring positions, and with at least one non-chlorinated ring position are the most active^[44]. Of the dioxin-like PCBs, non-ortho congeners are the most toxicologically active, while mono-ortho PCBs are generally less potent^{[45][9]}. Chlorine

- Contrary to studies of birds and mammals, even the most potent mono-ortho PCBs bind to AhRs of fishes with very low affinity, if at all (Abnet et al 1999; Doering et al 2014; 2015; Eisner et al 2016; Van den Berg et al 1998).

The role of the AHR in mediating the toxic effects of planar hydrophobic contaminants has been well studied, however the endogenous role of the AHR is less clear^[1]. Some endogenous and natural substances, including prostaglandin PGG2 and the tryptophan derivatives indole-3-carbinol, 6-formylindolo[3,2-b]carbazole (FICZ) and kynurenic acid can bind to and activate the AHR.^{[6][46][47][48][49]} The AHR is thought to have important endogenous roles in reproduction, liver and heart development, cardiovascular function, immune function and cell cycle regulation^{[50][38][51][52][53]}^{[54][46][55][56][57]} and activation of the AHR by DLCs may therefore adversely affect these processes.

Dibenzo-p-dioxin

Denison, M. S., Soshilov, A. A., He, G., DeGroot, D. E., and Zhao, B. (2011). Exactly the same but different: promiscuity and diversity in the molecular mechanisms of action of the aryl hydrocarbon (dioxin) receptor. *Toxicol.Sci.* **124**, 1-22.

Polychlorinated biphenyl

Of the dioxin-like PCBs, non-ortho congeners are the most toxicologically active, while mono-ortho PCBs are generally less potent (McFarland and Clarke 1989; Safe 1994). Chlorine substitution at ortho positions increases the energetic costs of assuming the coplanar conformation required for binding to the AHR (McFarland and Clarke 1989). Thus, a smaller proportion of mono-ortho PCB molecules are able to bind to the AHR and elicit toxic effects, resulting in reduced potency of these congeners. Other PCB congeners, such as di-ortho substituted PCBs, are very weak AHR agonists and do not likely contribute to dioxin-like effects (Safe 1994).

Safe, S. (1994). Polychlorinated biphenyls (PCBs): Environmental impact, biochemical and toxic responses, and implications for risk assessment. *Critical Reviews in Toxicology* **24**, 87-149.

McFarland, V. A., and Clarke, J. U. (1989). Environmental occurrence, abundance, and potential toxicity of polychlorinated biphenyl congeners: Considerations for a congener-specific analysis. *Environ.Health Perspect.* **81**, 225-239.

Polychlorinated dibenzofurans

Denison, M. S., Soshilov, A. A., He, G., DeGroot, D. E., and Zhao, B. (2011). Exactly the same but different: promiscuity and diversity in the molecular mechanisms of action of the aryl hydrocarbon (dioxin) receptor. *Toxicol.Sci.* **124**, 1-22.

Hexachlorobenzene

Cripps, D. J., Peters, H. A., Gocmen, A., and Dogramici, I. (1984) Porphyria turcica due to hexachlorobenzene: a 20 to 30 year follow-up study on 204 patients. *Br. J Dermatol.* **111** (4), 413-422.

Polycyclic aromatic hydrocarbons (PAHs)

PAHs are potent AHR agonists, but due to their rapid metabolism, they cause a transient alteration in AHR-mediated gene expression; this property results in a very different toxicity profile relative to persistent AHR-agonists such as dioxin-like compounds (Denison et al. 2011).

Denison, M. S., Soshilov, A. A., He, G., DeGroot, D. E., and Zhao, B. (2011). Exactly the same but different: promiscuity and diversity in the molecular mechanisms of action of the aryl hydrocarbon (dioxin) receptor. *Toxicol.Sci.* **124**, 1-22.

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebra danio	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
Gallus gallus	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)
Pagrus major	Pagrus major	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=143350)
Acipenser transmontanus	Acipenser transmontanus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7904)
Acipenser fulvescens	Acipenser fulvescens	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=41871)
rainbow trout	Oncorhynchus mykiss	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8022)
Salmo salar	Salmo salar	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8030)
Xenopus laevis	Xenopus laevis	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8355)
Ambystoma mexicanum	Ambystoma mexicanum	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8296)
Phasianus colchicus	Phasianus colchicus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9054)
Coturnix japonica	Coturnix japonica	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=93934)
mouse	Mus musculus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10090)
rat	Rattus norvegicus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10116)
human	Homo sapiens	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9606)
Microgadus tomcod	Microgadus tomcod	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=34823)

Life Stage Applicability

Life Stage	Evidence
Embryo	High
Development	High
All life stages	High

Sex Applicability

Sex	Evidence
Unspecific	High

The AHR structure has been shown to contribute to differences in species sensitivity to DLCs in several animal models. In 1976, a 10-fold difference was reported between two strains of mice (non-responsive DBA/2 mouse, and responsive C57BL/6 14 mouse) in CYP1A induction, lethality and teratogenicity following TCDD exposure^[3]. This difference in dioxin sensitivity was later attributed to a single nucleotide polymorphism at position 375 (the equivalent position of amino acid residue 380 in chicken) in the AHR LBD^{[30][19][31]}. Several other studies reported the importance of this amino acid in birds and mammals^{[32][30][22][33][34][35][31][36]}. It has also been shown that the amino acid at position 319 (equivalent to 324 in chicken) plays an important role in ligand-binding affinity to the AHR and transactivation ability of the AHR, due to its involvement in LBD cavity volume and its steric effect^[35]. Mutation at position 319 in the mouse eliminated AHR DNA binding^[35].

The first study that attempted to elucidate the role of avian AHR1 domains and key amino acids within avian AHR1 in avian differential sensitivity was performed by Karchner *et al.*^[22]. Using chimeric AHR1 constructs combining three AHR1 domains (DBD, LBD and TAD) from the chicken (highly sensitive to DLC toxicity) and common tern (resistant to DLC toxicity), Karchner and colleagues^[22], showed that amino acid differences within the LBD were responsible for differences in TCDD sensitivity between the chicken and common tern. More specifically, the amino acid residues found at positions 324 and 380 in the AHR1 LBD were associated with differences in TCDD binding affinity and transactivation between the chicken (Ile324_Ser380) and common tern (Val324_Ala380) receptors^[22]. Since the Karchner *et al.* (2006) study was conducted, the predicted AHR1 LBD amino acid sequences were been obtained for over 85 species of birds and 6 amino acid residues differed among species^{[14][37]}. However, only the amino acids at positions 324 and 380 in the AHR1 LBD were associated with differences in DLC toxicity in ovo and AHR1-mediated gene expression in vitro^{[14][37][16]}. These results indicate that avian species can be divided into one of three AHR1 types based on the amino acids found at positions 324 and 380 of the AHR1 LBD: type 1 (Ile324_Ser380), type 2 (Ile324_Ala380) and type 3 (Val324_Ala380)^{[14][37][16]}.

- Little is known about differences in binding affinity of AhRs and how this relates to sensitivity in non-avian taxa.
- Low binding affinity for DLCs of AhR1s of African clawed frog (*Xenopus laevis*) and axolotl (*Ambystoma mexicanum*) has been suggested as a mechanism for tolerance of these amphibians to DLCs (Lavine *et al* 2005; Shoots *et al* 2015).
- Among reptiles, only AhRs of American alligator (*Alligator mississippiensis*) have been investigated and little is known about the sensitivity of American alligator or other reptiles to DLCs (Oka *et al* 2016).
- Among fishes, great differences in sensitivity to DLCs are known both for AhRs and for embryos among species that have been tested (Doering *et al* 2013; 2014).
- Differences in binding affinity of the AhR2 have been demonstrated to explain differences in sensitivity to DLCs between sensitive and tolerant populations of Atlantic Tomcod (*Microgadus tomcod*) (Wirgin *et al* 2011).
 - This was attributed to the rapid evolution of populations in highly contaminated areas of the Hudson River, resulting in a 6-base pair deletion in the AHR sequence (outside the LBD) and reduced ligand binding affinity, due to reduces AHR protein stability.
- Information is not yet available regarding whether differences in binding affinity of AhRs of fishes are predictive of differences in sensitivity of embryos, juveniles, or adults (Doering *et al* 2013).

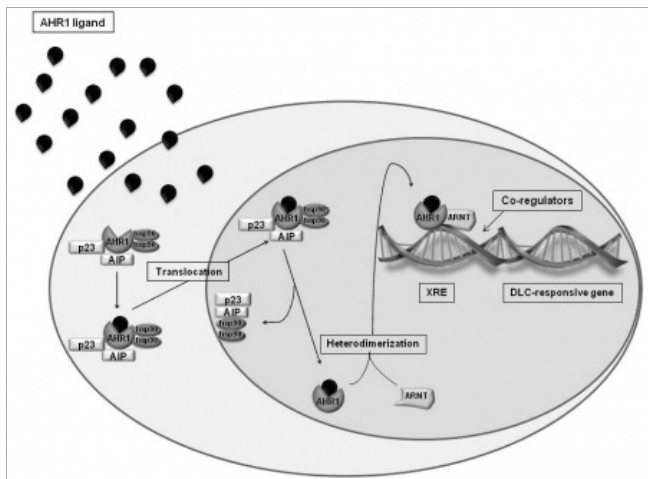
Key Event Description

The AHR Receptor

The aryl hydrocarbon receptor (AHR) is a ligand-activated transcription factor that belongs to the basic helix-loop-helix Per-ARNT-Sim (bHLH-PAS) superfamily and consists of three domains: the DNA-binding domain (DBD), ligand binding domain (LBD) and transactivation domain (TAD)^[1]. Other members of this superfamily include the AHR nuclear translocator (ARNT), which acts as a dimerization partner of the AHR^{[2][3]}; Per, a circadian transcription factor; and Sim, the “single-minded” protein involved in neuronal development^{[4][5]}. This group of proteins shares a highly conserved PAS domain and is involved in the detection of and adaptation to environmental change^[4].

Investigations of invertebrates possessing early homologs of the AhR suggest that the AhR evolutionarily functioned in regulation of the cell cycle, cellular proliferation and differentiation, and cell-to-cell communications (Hahn *et al* 2002). However, critical functions in angiogenesis, regulation of the immune system, neuronal processes, metabolism, development of the heart and other organ systems, and detoxification have emerged sometime in early vertebrate evolution (Duncan *et al.*, 1998; Emmons *et al.*, 1999; Lahvis and Bradfield, 1998).

The molecular Initiating Event



(https://aopwiki.org/wiki/index.php/File:AHR_mechanism.jpeg)

Figure 1: The molecular mechanism of activation of gene expression by AHR.

The molecular mechanism for AHR-mediated activation of gene expression is presented in Figure 1. In its unliganded form, the AHR is part of a cytosolic complex containing heat shock protein 90 (HSP90), the HSP90 co-chaperone p23 and AHR-interacting protein (AIP)^[6]. Upon ligand binding, the AHR migrates to the nucleus where it dissociates from the cytosolic complex and forms a heterodimer with ARNT^[7]. The AHR-ARNT complex then binds to a xenobiotic response element (XRE) found in the promoter of an AHR-regulated gene and recruits co-regulators such as CREB binding protein/p300, steroid receptor co-activator (SRC) 1, SRC-2, SRC-3 and nuclear receptor interacting protein 1, leading to induction or repression of gene expression^[6]. Expression levels of several genes, including phase I (e.g. cytochrome P450 (CYP) 1A, CYP1B, CYP2A) and phase II enzymes (e.g. uridine diphosphate glucuronosyl transferase (UDP-GT), glutathione S-transferases (GSTs)), as well as genes involved in cell proliferation (transforming growth factor-beta, interleukin-1 beta), cell cycle regulation (p27, jun-B) and apoptosis (Bax), are regulated through this mechanism^{[6][8][7][9]}.

AHR Isoforms

- Over time the AhR has undergone gene duplication and diversification in vertebrates, which has resulted in multiple clades of AhR, namely AhR1, AhR2, and AhR3 (Hahn 2002).
- Fishes and birds express AhR1s and AhR2s, while mammals express a single AhR that is homologous to the AhR1 (Hahn 2002; Hahn et al 2006).
- The AhR3 is poorly understood and known only from some cartilaginous fishes (Hahn 2002).
- Little is known about diversity of AhRs in reptiles and amphibians (Hahn et al 2002).
- In some taxa, subsequent genome duplication events have further led to multiple isoforms of AhRs in some species, with up to four isoforms of the AhR (α , β , δ , γ) having been identified in Atlantic salmon (*Salmo salar*) (Hansson et al 2004).
- Although homologs of the AhR have been identified in some invertebrates, compared to vertebrates these AhRs have differences in binding of ligands in the species investigated to date (Hahn 2002; Hahn et al 1994).

Roles of isoforms in birds:

Two AHR isoforms (AHR1 and AHR2) have been identified in the black-footed albatross (*Phoebastria nigripes*), great cormorant (*Phalacrocorax carbo*) and domestic chicken (*Gallus gallus domesticus*)^[10]. AHR1 mRNA levels were similar in the kidney, heart, lung, spleen, brain, gonad and intestine from the great cormorant but were lower in muscle and pancreas. AHR2 expression was mainly observed in the liver, but was also detected in gonad, brain and intestine. AHR1 levels represented a greater proportion (80%) of total AHR levels than AHR2 in the cormorant liver^[10], and while both AHR isoforms bound to TCDD, AHR2 was less effective at inducing TCDD-dependent transactivation compared to AHR1 in black-

- AhR1 and AhR2 both bind and are activated by TCDD *in vitro* (Yasui et al 2007).
- AhR1 has greater binding affinity and sensitivity to activation by TCDD relative to AhR2 (Yasui et al 2007).
- AhR1 is believed to mediate toxicities of DLCs, while AhR2 has no known role in toxicities (Farmahin et al 2012; Farmahin et al 2013; Manning et al 2012).

Roles of isoforms in fishes:

- AhR1 and AhR2 both bind and are activated by TCDD *in vitro* (Bak et al 2013; Doering et al 2014; 2015; Karchner et al 1999; 2005).
- AhR1 has greater sensitivity to activation by TCDD than AhR2 in red seabream (*Pagrus major*), white sturgeon (*Acipenser transmontanus*), and lake sturgeon (*Acipenser fulvescens*) (Bak et al 2013; Doering et al 2014; 2015).
- AhR2 has greater binding affinity or activation by TCDD than AhR1 in zebrafish (*Danio rerio*) and mummichog (*Fundulus heteroclitus*) (Karchner et al 1999; 2005).
- AhR2 is believed to mediate toxicities in fishes, while AhR1 has no known role in toxicities. Specifically, knockdown of AhR2 protects against toxicities of dioxin-like compounds (DLCs) and polycyclic aromatic hydrocarbons (PAHs) in zebrafish (*Danio rerio*) and mummichog (*Fundulus heteroclitus*), while knockdown of AhR1 offers no protection (Clark et al 2010; Prasch et al 2003; Van Tiem & Di Giulio 2011).

Roles of isoforms in amphibians and reptiles:

- Less is known about AhRs of amphibians or reptiles.
- AhR1 is believed to mediate toxicities in amphibians (Hahn 2002; Lavine et al 2005; Oka et al 2016; Shoots et al 2015). However, all AhRs of amphibians that have been investigated have very low affinity for TCDD (Hahn 2002; Lavine et al 2005; Oka et al 2016; Shoots et al

2015).

- Both AhR1s and AhR2 of American alligator (*Alligator mississippiensis*) are activated by agonists with comparable sensitivities (Oka et al 2016). AhRs of no other reptiles have been investigated.

How it is Measured or Detected

Methods that have been previously reviewed and approved by a recognized authority should be included in the Overview section above. All other methods, including those well established in the published literature, should be described here. Consider the following criteria when describing each method: 1. Is the assay fit for purpose? 2. Is the assay directly or indirectly (i.e. a surrogate) related to a key event relevant to the final adverse effect in question? 3. Is the assay repeatable? 4. Is the assay reproducible?

Transactivation Reporter Gene Assays (recommended approach)

Transient transfection transactivation

Transient transfection transactivation is the most common method for evaluating nuclear receptor activation^[12]. Full-length AHR cDNAs are cloned into an expression vector along with a reporter gene construct (chimeric luciferase, P-lactamase or CAT reporter vectors containing the appropriate response elements for the gene of interest). There are a number of commercially available cell lines that can serve as recipients for these vectors (CV-1, HuH7, FLC-7, LS174T, LS180 MCF-7, HEC1, LLC-PK1, HEK293, HepG2, and Caco-2 cells)^[12]. The greatest advantage of using transfected cells, rather than primary cell cultures, is the assurance that the nuclear receptor of interest is responsible for the observed induction. This would not be possible in a primary cell culture due to the co-regulation of different receptors for the same target genes. This model makes it easy to compare the responsiveness of the AHR across multiple species under the same conditions simply by switching out the AHR clone. One disadvantage to the transient transfection assay is the inherent variability associated with transfection efficiency, leading to a movement towards the use of stable cell lines containing the nuclear receptor and reporter gene linked to the appropriate response elements^[12].

Luciferase reporter gene (LRG) assay

The described luciferase reporter gene (LRG) assays have been used to investigate activation of AhRs of:

- Humans (*Homo sapiens*) (Abnet et al 1999)
- Species of birds, namely chicken (*Gallus gallus*), ring-necked pheasant (*Phasianus colchicus*), Japanese quail (*Coturnix japonica*), and common tern (*Sterna hirundo*) (Farmahin et al 2012; Manning et al 2013). Mutant AhR1s with ligand binding domains resembling those of at least 86 avian species have also been investigated (Farmahin et al 2013). AhR2s of birds have only been investigated in black-footed albatross (*Phoebastria nigripes*) and common cormorant (*Phalacrocorax carbo*) (Yasio et al 2007).
- American alligator (*Alligator mississippiensis*) is the only reptile for which AhR activation has been investigated (Oka et al 2016). AhR1A, AhR1B, and AhR2 of American alligator were assayed (Oka et al 2016).
- AhR1 of two amphibians have been investigated, namely African clawed frog (*Xenopus laevis*) and salamander (*Ambystoma mexicanum*) (Lavine et al 2005; Shoots et al 2015; Ohi et al 2003).
- AhR1s and AhR2s of several species of fish have been investigated, namely Atlantic salmon (*Salmo salar*), Atlantic tomcod (*Microgadus tomcod*), white sturgeon (*Acipenser transmontanus*), rainbow trout (*Oncorhynchus mykiss*), red seabream (*Pagrus major*), lake sturgeon (*Acipenser fulvescens*), and zebrafish (*Danio rerio*) (Andreasen et al 2002; Abnet et al 1999; Bak et al 2013; Doering et al 2014; 2015; Evans et al 2005; Hansson & Hahn 2008; Karchner et al 1999; Tanguay et al 1999; Wirgin et al 2011).

For demonstrative purposes, a luciferase reporter gene assay used to measure AHR1-mediated transactivation for avian species is described here. However, comparable assays are utilized for investigating AHR1s and AHR2s of all taxa. A monkey kidney cell line (Cos-7) that has low endogenous AHR1 expression was transfected with the appropriate avian AHR1 clone, cormorant ARNT1, a CYP1A5 firefly luciferase reporter construct and a *Renilla* luciferase vector to control for transfection efficiency. After seeding, the cells were exposed to DLC and luciferase activity was measured using a luminometer. Luminescence, which is proportional to the extent of AHR activation, is expressed as the ratio of firefly luciferase units to *Renilla* luciferase units^[13]. This particular assay was modified from its original version to increase throughput efficiency; (a) cells were seeded in 96-well plates rather than Petri dishes or 48-well plates, (b) DLCs were added directly to the wells without changing the cell culture medium, and (c) the same 96-well plates were used to measure luminescence without lysing the cells and transferring to another plate. Similar reporter gene assays have been used to measure AHR1 activation in domestic and wild species of birds, including the chicken, ring-necked pheasant (*Phasianus colchicus*), Japanese quail (*Coturnix japonica*), great cormorant, black-footed albatross and peregrine falcon (*Falco peregrinus*).^{[14][13][15][11][16][17]}

Transactivation in stable cell lines

Stable cell lines have been developed and purified to the extent that each cell contains both the nuclear receptor and appropriate reporter vector, eliminating the variability associated with transfection^[12]. A stable human cell line containing a luciferase reporter driven by multiple dioxin response elements has been developed that is useful in identifying AhR agonists and antagonists^[18]. An added benefit of this model is the potential to multiplex 3 assays in a single well: receptor activation, cell viability and enzyme activity^[12]. Such assays are used extensively in drug discovery due to their high throughput efficiency, and may serve just as useful for risk assessment purposes.

Ligand-Binding Assays

Ligand binding assays measure the ability of a test compound to compete with a labeled, high-affinity reference ligand for the LBD of a nuclear receptor. It is important to note that ligand binding does not necessitate receptor activation and therefore cannot distinguish between agonists and antagonists; however, binding affinities of AHR ligands are highly correlated with chemical potencies^[19] and can explain differences in species sensitivities to DLCs^{[20][21][22]}; they are therefore worth mentioning. Binding affinity and efficacy have been used to develop structure-activity relationships for AHR disruption^{[20][23]} that are potentially useful in risk-assessment. There has been tremendous progress in the development of

ligand-binding assays for nuclear receptors that use homogenous assay formats (no wash steps) allowing for the detection of low-affinity ligands, many of which do not require a radiolabel and are amenable to high throughput screening^{[24][12]}. This author however was unable to find specific examples of such assays in the context of AHR binding and therefore some classic radioligand assays are described instead.

Hydroxyapatite (HAP) binding assay

The HAP binding assay makes use of an *in vitro* transcription/translation method to synthesize the AHR protein, which is then incubated with radiolabeled TDCPP and a HAP pellet. The occupied protein adsorbs to the HAP and the radioactivity is measured to determine saturation binding. An additional ligand can also be included in the mixture in order to determine its binding affinity relative to TCDD (competitive binding)^{[25][22]}. This assay is simple, repeatable and reproducible; however, it is insensitive to weak ligand-receptor interactions^{[22][21][26]}.

Whole cell filtration binding assay

Dold and Greenlee^[27] developed a method to detect specific binding of TCDD to whole mammalian cells in culture and was later modified by Farmahin et al.^[21] for avian species. The cultured cells are incubated with radiolabeled TCDD with or without the presence of a competing ligand and filtered. The occupied protein adsorbs onto the filter and the radioactivity is measured to determine saturation binding and/or competitive binding. This assay is able to detect weak ligand-receptor interactions that are below the detection limit of the HAP assay^[21].

Protein-DNA Interaction Assays

The active AHR complexed with ARNT can be measured using protein-DNA interaction assays. Two methods are described in detail by Perez-Romero and Imperiale^[28]. Chromatin immunoprecipitation measures the interaction of proteins with specific genomic regions *in vivo*. It involves the treatment of cells with formaldehyde to crosslink neighboring protein-protein and protein-DNA molecules. Nuclear fractions are isolated, the genomic DNA is sheared, and nuclear lysates are used in immunoprecipitations with an antibody against the protein of interest. After reversal of the crosslinking, the associated DNA fragments are sequenced. Enrichment of specific DNA sequences represents regions on the genome that the protein of interest is associated with *in vivo*. Electrophoretic mobility shift assay (EMSA) provides a rapid method to study DNA-binding protein interactions *in vitro*. This relies on the fact that complexes of protein and DNA migrate through a nondenaturing polyacrylamide gel more slowly than free DNA fragments. The protein-DNA complex components are then identified with appropriate antibodies. The EMSA assay was found to be consistent with the LRG assay in chicken hepatoma cells dosed with dioxin-like compounds^[29].

In silico Approaches

In silico homology modeling of the ligand binding domain of the AHR in combination with molecular docking simulations can provide valuable insight into the transactivation-potential of a diverse array of AHR ligands. Such models have been developed for multiple AHR isoforms and ligands (high/low affinity, endogenous and synthetic, agonists and antagonists), and can accurately predict ligand potency based on their structure and physicochemical properties (Bonati et al 2017; Hirano et al 2015; Sovadinova et al 2006).

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List of Key Events in the AOP

Event: 944: dimerization, AHR/ARNT (<https://aopwiki.org/events/944>)

Short Name: dimerization, AHR/ARNT

Key Event Component

Process	Object	Action
protein dimerization activity	aryl hydrocarbon receptor	increased
protein dimerization activity	aryl hydrocarbon receptor nuclear translocator	increased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:150 - Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	KeyEvent

AOP21

AOP ID and Name	Event Type
Aop:21 - aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	KeyEvent

Stressors

Name
2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)
Stressor:147 Dibenzo-p-dioxin
Polychlorinated biphenyl
Polychlorinated dibenzofurans
Polycyclic aromatic hydrocarbons

Biological Context

Level of Biological Organization
Molecular

Cell term

Cell term
eukaryotic cell

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
chicken	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)
zebrafish	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
mouse	Mus musculus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10090)
Coturnix japonica	Coturnix japonica	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=93934)
Phasianus colchicus	Phasianus colchicus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9054)
rainbow trout	Oncorhynchus mykiss	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8022)
Pagrus major	Pagrus major	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=143350)
Acipenser fulvescens	Acipenser fulvescens	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=41871)

Term	Scientific Term	Evidence	Links
Acipenser transmontanus	Acipenser transmontanus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7904)
Salmo salar	Salmo salar	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8030)
Xenopus laevis	Xenopus laevis	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8355)
human	Homo sapiens	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9606)
Ambystoma mexicanum	Ambystoma mexicanum	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8296)
Microgadus tomcod	Microgadus tomcod	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=34823)

Life Stage Applicability

Life Stage	Evidence
Embryo	High
Development	High
All life stages	High

Sex Applicability

Sex	Evidence
Unspecific	High

Taxonomic Presence of ARNT genes:

- ARNTs have been identified in all tetrapods investigated to date (Drutel et al 1996; Hirose et al 1996; Hoffman et al 1991; Lee et al 2007; Lee et al 2011).
- ARNTs have been identified in a great phylogenetic diversity of fishes, including early fishes (Doering et al 2014; 2016).
- ARNT has been identified in investigated invertebrates (Powell-Coffman et al 1998).

Taxonomic Applicability of Heterodimerization of ARNT isoforms with AhR isoforms:

- In mouse (*Mus mus*) and chicken (*Gallus gallus*) both the ARNT1 and ARNT2 were capable of heterodimerizing with AHR and interacting with dioxin-responsive elements on the DNA *in vitro* (Hirose et al 1996; Lee et al 2007; Lee et al 2011; Prasch et al 2004). However, no studies have yet confirmed involvement of both ARNT1 and ARNT2 *in vivo*.
- In zebrafish, all adverse effects of DLCs so far examined *in vivo* are mediated solely by ARNT1 based on knockdown studies, although ARNT2 is capable of heterodimerizing with AHR2 and interacting with dioxin-responsive elements on the DNA *in vitro* (Prasch et al 2004; Prasch et al 2006). In addition to AHRs of zebrafish, AHRs of Atlantic salmon (*Salmo salar*), Atlantic tomcod (*Microgadus tomcod*), mummichog, rainbow trout, and red seabream (*Pagrus major*) have been demonstrated to heterodimerize with ARNT1 *in vitro* (Abnet et al 1999; Bak et al 2013; Hansson & Hahn 2008; Karchner et al 1999; Virgin et al 2011), while AHRs of white sturgeon (*Acipenser transmontanus*), and lake sturgeon (*Acipenser fulvescens*) have been demonstrated to heterodimerize with ARNT2 *in vitro* (Doering et al 2014b; 2015b; Prasch et al 2004; 2006).

This mechanism is conserved across species. Mammals possess a single AHR, whereas birds and fish express multiple isoforms, and all three express multiple ARNT isoforms. Not all of the isoforms identified are functionally active. For example, killifish AHR1 and AHR2 are active and display different transcription profiles, whereas zebrafish AHR2 and ARNT2 are active in mediating xenobiotic-mediated toxicity and AHR1 is inactive (Hahn et al. 2006; Prasch et al. 2006).

Key Event Description

Structure and Function of ARNT

- The aryl hydrocarbon receptor nuclear translocator (ARNT) is a member of the Per-Arnt-Sim (PAS) family of proteins (Gu et al 2000).
- PAS proteins share highly conserved PAS domains (Gu et al 2000).
- PAS proteins act as transcriptional regulators in response to environmental and physiological cues (Gu et al 2000).
- ARNTs have numerous key roles in vertebrates related to responses to developmental and environmental cues.

Isoforms of ARNT:

- Over time ARNT has undergone gene duplication and diversification in vertebrates, which has resulted in three clades of ARNT, namely ARNT1, ARNT2, and ARNT3.
- Each clade can include multiple isoforms and splice variants (Hill et al 2009; Lee et al 2007; Lee et al 2011; Powel & Hahn 2000; Tanguay et al 2000).
- ARNT1s have been demonstrated to function predominantly through heterodimerization with the aryl hydrocarbon receptor (AhR) and hypoxia inducible factor 1 α (HIF1 α) (Prasch et al 2004; 2006; Wang et al 1995).
- ARNT2s are believed to function predominantly through heterodimerization with Single Minded (SIM) (Hirose et al 1996).
- ARNT3s, which are also known as ARNT-like (ARNTL), Brain and Muscle ARNT-like-1 (BMAL1), or Morphine Preference 3 (MOP3), are believed to function predominantly through heterodimerization with Circadian Locomotor Output Cycles Kaput (CLOCK) (Gekakis et al 1998).

Roles of ARNTs in mammals:

- ARNT1 functions in normal vascular and hematopoietic development (Kozak et al 1997; Maltepe et al 1997; Abbott & Buckalew 2000).
- ARNT2 functions in development of the hypothalamus and nervous system (Hosoya et al 2001; Keith et al 2001).
- ARNT3 functions in biological rhythms (Gekakis et al 1998).

Roles of ARNTs in other taxa:

- ARNTs have been demonstrated to have roles in development of the heart, brain, liver, and possibly the peripheral nervous system in zebrafish (*Danio rerio*) (Hill et al 2009).
- Roles of ARNTs in other taxa have not been sufficiently investigated to date.

Interaction with AHR

- Both ARNT1s and ARNT2s are able to heterodimerize with AhR and interact with dioxin-responsive elements on the DNA in *in vitro* systems (Hirose et al 1996; Lee et al 2007; Lee et al 2011; Prasch et al 2004).
- Selective knockdown of ARNTs in zebrafish (*Danio rerio*) demonstrates that ARNT1s, but not ARNT2s, are required for activation of the AhR *in vivo* (Prasch et al 2004; 2006).
- In limited investigations ARNT3 has not been demonstrated to interact with the AHR either *in vivo* or *in vitro* (Jain et al 1998).

Upon ligand binding, the aryl hydrocarbon receptor (AHR) migrates to the nucleus where it dissociates from the cytosolic complex and forms a heterodimer with AHR nuclear translocator (ARNT) (Mimura and Fujii-Kuriyama 2003). The AHR-ARNT complex then binds to a xenobiotic response element (XRE) found in the promoter of an AHR-regulated gene and recruits co-regulators such as CREB binding protein/p300, steroid receptor co-activator (SRC) 1, SRC-2, SRC-3 and nuclear receptor interacting protein 1, leading to induction or repression of gene expression (Fujii-Kuriyama and Kawajiri 2010). Expression levels of several genes, including phase I (e.g. cytochrome P450 (CYP) 1A, CYP1B, CYP2A) and phase II enzymes (e.g. uridine diphosphate glucuronosyl transferase (UDP-GT), glutathione S-transferases (GSTs)), as well as genes involved in cell proliferation (transforming growth factor-beta, interleukin-1 beta), cell cycle regulation (p27, jun-B) and apoptosis (Bax), are regulated through this mechanism (Fujii-Kuriyama and Kawajiri 2010; Giesy et al. 2006; Mimura and Fujii-Kuriyama 2003; Safe 1994).

How it is Measured or Detected

AHR/ARNT heterodimerization can be measured in several ways:

1) The active AHR complexed with ARNT can be measured using protein-DNA interaction assays. Two methods are described in detail by Perez-Romero and Imperiale (Perez-Romero and Imperiale 2007). Chromatin immunoprecipitation measures the interaction of proteins with specific genomic regions *in vivo*. It involves the treatment of cells with formaldehyde to crosslink neighboring protein-protein and protein-DNA molecules. Nuclear fractions are isolated, the genomic DNA is sheared, and nuclear lysates are used in immunoprecipitations with an antibody against the protein of interest. After reversal of the crosslinking, the associated DNA fragments are sequenced. Enrichment of specific DNA sequences represents regions on the genome that the protein of interest is associated with *in vivo*. Electrophoretic mobility shift assay (EMSA) provides a rapid method to study DNA-binding protein interactions *in vitro*. This relies on the fact that complexes of protein and DNA migrate through a non-denaturing polyacrylamide gel more slowly than free DNA fragments. The protein-DNA complex components are then identified with appropriate antibodies. The EMSA assay was found to be consistent with the luciferase reporter gene assay (in chicken hepatoma cells dosed with dioxin-like compounds (Heid et al. 2001).

2) Species-specific differences in dimerization and differences in dimerization between ARNT isoform and AhR isoform combinations have been assessed through luciferase reporter gene (LRG) assays utilizing COS-7 cells transfected with expression constructs of AhR and ARNT isoforms of mammals, birds, and fishes (Abnet et al 1999; Bak et al 2013; Doering et al 2014; 2015; Hansson & Hahn 2008; Hirose et al 1996; Karchner et al 1999; Lee et al 2007; Lee et al 2011; Prasch et al 2004; Wirgin et al 2011). However, this method is indirect as it also includes binding of a ligand to the AhR, and interaction of the AhR/ARNT heterodimer with dioxin-responsive elements on the DNA.

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Event: 1269: Increase, COX-2 expression (<https://aopwiki.org/events/1269>)

Short Name: Increase, COX-2 expression

Key Event Component

AOP21

Process	Object	Action
gene expression	prostaglandin G/H synthase 2	increased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:21 - aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	KeyEvent

Stressors

Name
2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)
Aristolochic acid
Doxorubicin

Biological Context

Level of Biological Organization
Molecular

Cell term

Cell term
eukaryotic cell

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Danio rerio	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
Oryzias latipes	Oryzias latipes	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8090)
Gallus gallus	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)
mouse	Mus musculus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10090)
human	Homo sapiens	Moderate	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9606)

Life Stage Applicability

Life Stage	Evidence
Embryo	High

Sex Applicability

Sex	Evidence
Unspecific	High

COX-2 Structure and Function:

- There is a high level of conservation of COX-2, as well as its function, especially across vertebrates (Havird et al 2008; 2015), indicating that numerous vertebrate taxa might be susceptible to up-regulation in COX-2.
- Typically, teleost fish genomes contain more than one COX-2 gene, likely a result of genome duplication after divergence of teleosts from tetrapods (Ishikawa et al 2007; Havird et al 2015). In zebrafish there are two isoforms, COX-2a and COX-2b (Teraoka et al 2014).
- In invertebrates, COX is found in most crustaceans, the majority of molluscs, but only in specific lineages within Cnidaria and Annelida. COX genes are not found in Hemichordata, Echinodermata, or Platyhelminthes. Insecta COX genes lack in homology, but might function as COX enzymes based on structural analyses (Havird et al 2015).

Key Event Description

COX Pathway:

https://aopwiki.org/system/dragonfly/production/2017/05/08/7vmvnr8r73_COX_pathway.pdf

(https://aopwiki.org/system/dragonfly/production/2017/05/08/7vmvnr8r73_COX_pathway.pdf)

- Prostaglandin-endoperoxide synthase (PTGS; KEGG ID E.C. 1.14.99.1) is an enzyme that has two catalytic sites.
- Cyclooxygenase site (COX) catalyzes conversion of arachidonic acid into endoperoxide prostaglandin G2 (Simmons et al 2004 (https://aopwiki.org/wiki/index.php?title=Simmons_et_al.,_2004&action=edit&redlink=1)).
- Peroxidase active site converts PGG2 to PGH2 (KEGG reactions 1599, 1590). PGH2 is a precursor for synthesis of other prostaglandins (PGEs, PGFs), prostacyclin, and thromboxanes (Simmons et al 2004; Botting & Botting 2011).
- There are two isoforms, COX-1 and COX-2
- COX-2 is inducible by certain chemical exposures, inflammation, during discrete stages of gamete maturation, and more (Green et al 2012).
- However, COX biology is complex and important details of the pathway remain unknown (Grosser 2006).

COX Cardiovascular Roles:

- Prostaglandins which are catalyzed by COX and have roles in cellular homeostasis and in promoting inflammatory responses (Chien et al 2015; Smith et al 2000; Tilley et al 2001; Vane et al 1994).
- Significant evidence suggests a link between COX-2 mediated inflammatory responses and progression of alterations in cardiovascular development and function in murine models, humans, and zebrafish (*Danio rerio*) (Delgado et al 2004; Gullestad & Aukrust 2005; Hocherl et al 2002; Huang et al 2007; Wong et al 1998).
- However, the precise mechanism by which prostaglandins produce alterations in cardiovascular development have not been clearly elucidated (Hocherl & Dreher 2002).

How it is Measured or Detected

- COX-2 can be measured as abundance of transcript by use of quantitative real-time polymerase chain reaction (q-RT PCR). Transcript abundance of COX-2 has been measured in whole embryos of fishes (Dong et al 2010; Huang et al 2007; Teraoka et al 2008; 2014) and embryonic hepatic and cardiac tissue of birds (Fujisawa et al 2014).
- COX-2 could be measured by use of ELISA or Western Blot, but commercial kits are not currently available for fishes or birds.

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AOP21

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Event: 317: Altered, Cardiovascular development/function (<https://aopwiki.org/events/317>)

Short Name: Altered, Cardiovascular development/function

Key Event Component

Process	Object	Action
abnormal cardiovascular system physiology		morphological change
cardiovascular system development	cardiovascular system	abnormal

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:150 - Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	KeyEvent
Aop:21 - aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	KeyEvent

Stressors

Name
2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)

Biological Context

Level of Biological Organization
Organ

Organ term

Organ term
heart

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Vertebrates	Vertebrates	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)
Invertebrates	Invertebrates	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)

Life Stage Applicability

Life Stage	Evidence
Embryo	High

Sex Applicability

Sex	Evidence
Unspecific	High

- Some form of cardiovascular system is present in members of the clade Bilateria (Bishopric 2005). This clade includes most animal phyla, except for sponges (Porifera), jellyfishes and corals (Cnidaria), placozoans (Placozoa), and comb jellies (Ctenophora).
- Differences in cardiovascular systems are present among taxa. Vertebrates have closed circulatory systems, while some invertebrate taxa have open circulatory systems (Kardong 2006).

Key Event Description

This key event applies to the disruption of cardiogenesis early enough in embryogenesis to result in gross morphological alterations leading to reduced cardiac function.

How it is Measured or Detected

Altered cardiovascular development/function can be measured in numerous ways:

- 1) As blood flow in the mesencephalic vein by use of time-lapse recording using a digital video camera (Teraoka et al 2008; 2014). Blood flow is measured as the number of red blood cells passing the mesencephalic vein per second (Teraoka et al 2008; 2014). This method is described in detail by Teraoka et al (2002). However, some studies have assessed blood flow through visualized scoring techniques by use of a microscope as (1) same rate as control, (2) slower rate than control, or (3) no flow (Henry et al 1997).
- 2) As heart area, pericardial edema area, or yolk sac edema area quantified with area analysis by use of a microscope linked digital camera and conventional image software (Dong et al 2010; Teraoka et al 2008; 2014; Yamauchi et al 2006). Images at the same magnification are used to obtain the area measured as number of pixels (Teraoka et al 2008; 2014). This method can use either live individuals or histologic samples. This method is described in detail by Teraoka et al (2003).
- 3) As basic physical measurements such as heart weight, heart aspect ratio (horizontal length versus vertical length), heart weight to body weight ratio (Fujisawa et al 2014).
- 4) As incidence of malformation measured as percent occurrence among individuals (Buckler et al 2015; Dong et al 2010; Park et al 2014; Yamauchi et al 2006). This method is described in detail by Dong et al (2010).
- 5) As heartbeat rate measured by direct observation by use of a microscope (Park et al 2014). This method is described in detail by Park et al (2014).

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AOP21

Zabel, E.W; Cook, P.M.; Peterson, R.E. Toxic equivalency factors of polychlorinated dibenzo-p-dioxin, dibenzofuran and biphenyl congeners based on early-life stage mortality in rainbow trout (*Oncorhynchus mykiss*). *Aquat Toxicol.* **1995**. 31, 315-328.

Event: 947: Increase, Early Life Stage Mortality (<https://aopwiki.org/events/947>)

Short Name: Increase, Early Life Stage Mortality

Key Event Component

Process	Object	Action
embryonic lethality		increased
mortality		increased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:150 - Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	AdverseOutcome
Aop:21 - aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	KeyEvent

Stressors

Name
2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)

Biological Context

Level of Biological Organization
Individual

Evidence for Perturbation by Stressor

2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)

Exposure of embryos to 2,3,7,8-TCDD causes early life stage mortality in all studied species of fishes (Doering et al 2013).

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Vertebrates	Vertebrates	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)

Life Stage Applicability

Life Stage	Evidence
Embryo	High

Life Stage	Evidence
Foetal	High
Development	High

Sex Applicability

Sex	Evidence
Unspecific	High

All members of the subphylum vertebrata are susceptible to early life stage death (Weinstein 1999).

Key Event Description

Increased early life stage mortality refers to an increase in the number of individuals dying in an experimental replicate group or in a population over a specific period of time.

In Birds:

Early life stage mortality occurs at any stage in development prior to birth/hatch and is considered embryo/lethal.

In Fishes:

Early Life Stage Mortality refers to death prior to yolk sac adsorption and swim-up.

How it is Measured or Detected

In birds it may be identified as failure to hatch or lack of movement within the egg when candled; heartbeat monitors are available for identifying viable avian and reptilian eggs (ex. Avitronic's Buddy monitor). In mammals, stillborn or mummified offspring, or an increased rate of resorptions early in pregnancy are all considered embryo/lethal, and can be detected using ultra-high frequency ultrasound (30-70 MHz; a.k.a. ultrasound biomicroscopy) (Flores *et al.* 2014). In fishes, mortality is typically measured by observation. Lack of any heart beat, gill movement, and body movement are typical signs of death used in the evaluation of mortality.

Regulatory Significance of the AO

Poor early life stage survival is an endpoint of major relevance to environmental regulators, as it is likely to lead to population decline. Early-life stage, acute and chronic test guidelines have been established by the Organisation for Economic Co-operation and Development (OECD), U.S. Environmental Protection Agency (EPA) and Environment and Climate Change Canada (ECCC), and are currently used in risk assessments to set limits for safe exposures. Aquatic test guidelines are most prevalent and include OECD210, OECD229, EPA850.1400 and ECCC EPS 1/RM/28 for fish and OECD241 for frogs.

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Appendix 2

List of Key Event Relationships in the AOP

List of Adjacent Key Event Relationships

Relationship: 972: Activation, AhR leads to dimerization, AHR/ARNT (<https://aopwiki.org/relationships/972>)

AOPs Referencing Relationship

AOP21

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	adjacent	High	Moderate
aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	adjacent	High	Moderate

Evidence Supporting Applicability of this Relationship

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Mus musculus	Mus musculus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10090)
Danio rerio	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
rainbow trout	Oncorhynchus mykiss	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8022)
Pagrus major	Pagrus major	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=143350)
Acipenser fulvescens	Acipenser fulvescens	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=41871)
Salmo salar	Salmo salar	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8030)
Acipenser transmontanus	Acipenser transmontanus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7904)
Xenopus laevis	Xenopus laevis	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8355)
Ambystoma mexicanum	Ambystoma mexicanum	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8296)
Microgadus tomcod	Microgadus tomcod	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=34823)
human	Homo sapiens	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9606)
Gallus gallus	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)
Phasianus colchicus	Phasianus colchicus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9054)
Coturnix japonica	Coturnix japonica	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=93934)

Life Stage Applicability

Life Stage	Evidence
All life stages	High

Sex Applicability

Sex	Evidence
Unspecific	High

- The aryl hydrocarbon receptor (AhR) and aryl hydrocarbon receptor nuclear translocator (ARNT) are highly conserved and ancient proteins with homologs having been identified in most major animal groups, apart from the most ancient lineages, such as sponges (Porifera) (Hahn et al 2002).
- *In vitro* dimerization of AhRs and ARNTs have been demonstrated in mammals, birds, reptiles, amphibians, teleost and non-teleost fishes, and some invertebrates (Butler et al 2001; Emmons et al 1999; Hahn et al 2002; Powell-Coffman et al 1998).

Key Event Relationship Description

In its unliganded form, the AHR is part of a cytosolic complex containing heat shock protein 90 (HSP90), the HSP90 co-chaperone p23 and AHR-interacting protein (AIP) (Fujii-Kuriyama *et al.* 2010). Upon ligand binding, the aryl hydrocarbon receptor (AHR) migrates to the nucleus where it dissociates from the cytosolic complex and forms a heterodimer with AHR nuclear translocator (ARNT) (Mimura and Fujii-Kuriyama 2003).

AhRs can heterodimerize with ARNT1 and ARNT2 isoforms in order to activate reporter constructs in transfected cells and recognize response elements in gel shift assays in all investigated vertebrates, including birds, fishes, and reptiles (Abnet et al 1999; Andreassen et al 2002a; 2002b; Bak et al 2013; Doering et al 2014; Doering et al 2015; Farmahin et al 2012; 2013; Hansson & Hahn 2008; Karchner et al 1999; 2006; Lavine et al 2005; Shoots et al 2015; Tanguay et al 1999; 2000; Wirgin et al 2011).

Evidence Supporting this KER

Biological Plausibility

The mechanism of AHR-mediated transcriptional regulation is well understood (Fujii-Kuriyama and Kawajiri 2010).

Numerous PAS proteins are known to interact with each other in response to environmental and developmental cues through dimerization at their PAS domains (Pohjanvirta 2012).

Empirical Evidence

ARNT is a necessary dimerization partner for the transcriptional activation of AHR regulated genes (Hoffman et al. 1991; Poland et al. 1976). The AHR/ARNT complex was confirmed following *in vitro* exposure to halogenated aromatic hydrocarbons using an electrophoretic mobility shift assay; a dose-dependent supershift in DNA-binding was observed using specific antibodies in chicken and human cell lines (Heid et al. 2001).

- Unliganded AhR exists as a cytosolic 9S form, while in the presence of a ligand the AhR exists as a nuclear 6S form. ARNT exists as a nuclear 6S form (Okey 2007).
- The 6S form of AhR is approximately 210 kDa. Liganded AhR is approximately 100 kDa and ARNT is approximately 110 kDa (Elferink et al 1990; Swanson et al 1993).
- Dimerization of AhRs with ARNTs has been demonstrated in all invertebrate and vertebrate species so far investigated (Butler et al 2001; Emmons et al 1999; Hahn et al 2002; Powell-Coffman et al 1998).
- Heterodimers are not formed on response elements in gel shift assays in the absence of AhR and/or ARNT (Tanguay et al 2000).

Uncertainties and Inconsistencies

- There are uncertainties in the precise physiological and toxicological roles of different AhR clades (AhR1, AhR2, AhR3) and isoforms (α , β , δ , γ).
- There are uncertainties in the precise physiological and toxicological roles of different ARNT clades (ARNT1, ARNT2, ARNT3) and isoforms (a, b, c).
- Nothing is known about differences in binding affinity of AhR for ARNT and of the AhR/ARNT heterodimer for DNA among species and taxa.
- There is uncertainty in whether anthropogenic contaminants that act as ligands of the AhR and lead to dimerization of AhR with ARNT in vertebrates also act as ligands in invertebrates.

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Relationship: 1350: dimerization, AHR/ARNT leads to Increase, COX-2 expression
(<https://aopwiki.org/relationships/1350>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	adjacent	High	Moderate

Evidence Supporting Applicability of this Relationship

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Danio rerio	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
Oryzias latipes	Oryzias latipes	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8090)
Gallus gallus	Gallus gallus	Low	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)

Life Stage Applicability

Life Stage	Evidence
Embryo	High
Development	High

Sex Applicability

Sex	Evidence
Unspecific	High

- Dimerization of AhR/ARNT leading to increased expression of COX-2 has only been investigated in zebrafish, Japanese medaka, and chicken (Dong et al 2010; Teraoka et al 2008; 2014; Fugisawa et al 2014).
- Due to the presence of a functional AhR/ARNT pathway and COX-2 genes among all vertebrate taxa, it is acknowledged that this key event relationship is likely applicable to vertebrates in general and possibly some invertebrates.

Key Event Relationship Description

- The AhR/ARNT heterodimer is able to interact with dioxin-responsive elements (DREs) on the DNA causing the up-regulation in dioxin-responsive genes (Whitlock et al 1996).
- DREs in the promoter region of COX-2 allow the AhR/ARNT heterodimer to up-regulate expression of COX-2 (Degner et al 2007; Jonsson et al 2012).

Evidence Supporting this KER**Biological Plausibility**

- Putative DREs have been identified in the promoter region of COX-2 in zebrafish and presumably exist in other species and taxa (Degner et al 2007; Jonsson et al 2012).
- DREs are well characterized and numerous other genes that have DREs in their promoter region are known to be up-regulated by the AhR/ARNT heterodimer (Denison et al 1988).

Empirical Evidence

- Expression of COX-2 is up-regulated in response to exposure to ligands that activate AhR causing dimerization with ARNT (Dong et al 2010; Teraoka et al 2008; 2014).
- Knockdown of ARNT1 prevents interaction of AhR with DREs and the up-regulation in dioxin-responsive genes (Antkiewicz et al 2006; Prasch et al 2004).
- Depletion of ARNT lessens or prevents interaction of AhR with DREs and the up-regulation in dioxin-responsive genes (Prasch et al 2004).
- However, expressions of COX-2 have not yet been investigated following targeted knockdown of either AhR or ARNT1 preventing dimerization and interaction with DREs.

Uncertainties and Inconsistencies

- In chicken (*Gallus gallus*), and presumably other species of birds, COX-2 is believed to be up-regulated by the AhR through non-genomic mechanisms that are independent of the AhR/ARNT heterodimer (Fujisawa et al 2014). DREs are not believed to be present in the promoter region of COX-2 in chicken (Fujisawa et al 2014).
- However, nothing is known regarding the presence or absence of DREs in the promoter region of COX-2 in species or taxa other than zebrafish.
- Amounts of COX-2 protein have not been investigated and therefore only increases in expressions of transcript are known.

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Teraoka, H.; Okuno, Y.; Nijoukubo, D.; Yamakoshi, A.; Peterson, R.E.; Stegeman, J.J.; Kitazawa, T.; Hiraga, T.; Kubota, A. (2014). Involvement of COX2-thromboxane pathway in TCDD-induced pericardial edema in developing zebrafish. *Aquat. Toxicol.* 154, 19-25.

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Relationship: 1351: Increase, COX-2 expression leads to Altered, Cardiovascular development/function (<https://aopwiki.org/relationships/1351>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	adjacent	Moderate	Moderate

Evidence Supporting Applicability of this Relationship

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Danio rerio	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
Oryzias latipes	Oryzias latipes	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8090)
Gallus gallus	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)

Life Stage Applicability

Life Stage	Evidence
Embryo	High
Development	High

Sex Applicability

Sex	Evidence
Unspecific	High

- Links between induction of COX-2 and alteration of cardiovascular development and function has only been demonstrated in zebrafish, Japanese medaka, and chicken (Dong et al 2010; Teraoka et al 2008; 2014).
- However, it is acknowledged that this key event relationship could be applicable to all vertebrate taxa and some invertebrate taxa based on presence of COX-2 genes and a cardiovascular system.

Key Event Relationship Description

- The precise role that COX-2 plays in altered cardiovascular development/function has not been investigated. However, the prostaglandin synthesis pathway, of which COX-2 is a rate limiting step, is known to have roles in development of the heart (Dong et al 2010; Huang et al 2007; Teraoka et al 2008; 2014).

Evidence Supporting this KER

Biological Plausibility

- The prostaglandin synthesis pathway, of which COX-2 is a rate limiting step, is known to have roles in development of the heart and therefore altered levels of expression of COX-2 could be expected to result in altered development of the heart.

Empirical Evidence

- Blocking induction of COX-2 through knockdown of COX-2 or through selective antagonists of COX-2 in zebrafish, Japanese medaka (*Oryzias latipes*), and chicken (*Gallus gallus*) prevents alteration in cardiovascular development and function by 2,3,7,8-TCDD, including prevention of pericardial edema, changes in heart size, and reduction in blood flow (Dong et al 2010; Teraoka et al 2008; 2014).
- Knockdown of and selective antagonists of thromboxane synthase 1 (CYP5A), which is down-stream of COX-2 in the prostaglandin

synthesis pathway, prevents alteration in cardiovascular development and function by 2,3,7,8-TCDD (Teraoka et al 2008).

COX-2 Cardiovascular Development Roles:

- Transgenic mice (*Mus musculus*) that over express COX-2 display altered cardiac remodeling that results in cardiomyocyte hypertrophy (Streicher et al 2010). However, significantly impaired cardiac function was not observed in the strain of transgenic mice investigated in this study (Streicher et al 2010).
- Embryos of zebrafish (*Danio rerio*) exposed to the COX-2 inducers, aristolochic acid and doxorubicin, develop hypertrophy of the heart, disorganization of cardiomyocytes, and loss of endocardium (Huang et al 2007). These effects result in reduced function of the heart and eventually cause death in zebrafish (Huang et al 2007).
- COX-2 has also been demonstrated to have roles in cardiovascular development in humans, chicken (*Gallus gallus*), and Japanese medaka (*Oryzias latipes*) (Fujisawa et al 2014; Gullestad & Aukrust 2005; Hoehnerl et al 2002; Huang et al 2007; Wong et al 1998).

Uncertainties and Inconsistencies

- Intermediary steps between increased expression of COX-2 and altered heart development and function have not been investigated.
- The precise role of COX-2 and the prostaglandin synthesis pathway in early development of the heart is not known.

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- Dong, W.; Matsumura, F.; Kullman, S.W. (2010). TCDD induced pericardial edema and relative COX-2 expression in medaka (*Oryzias latipes*) embryos. *Toxicol. Sci.* 118 (1), 213-223.
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Relationship: 1567: Altered, Cardiovascular development/function leads to Increase, Early Life Stage Mortality (<https://aopwiki.org/relationships/1567>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	adjacent	High	Low
aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	adjacent	High	Low

Evidence Supporting Applicability of this Relationship

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
mammals	mammals	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)
fish	fish	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)
chicken	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)

Life Stage Applicability

Life Stage	Evidence
Embryo	High

Sex Applicability

Sex	Evidence
Unspecific	High

Cardiovascular remodelling and cardiac failure leading to embryo death has been observed in mammals (Kopf and Walker 2009, Thakur et al. 2013), fish (Kopf and Walker 2009) and chickens (Kopf and Walker 2009). Although the chick is preferentially used as a lab model for developmental studies, this KER likely extends to other avian species as well.

Key Event Relationship Description

Changes in heart morphology can result in decreased cardiac output and are associated with myocardial disease, abnormalities in cardiac loading, rhythm disorders, ischemia (restriction in blood supply to tissues, causing a shortage of oxygen and glucose needed for cellular metabolism), and cardiac compression. Severe cardiac dysfunction can result in congestive fetal heart failure (inability of the heart to deliver adequate blood flow to organs) leading to fluid build-up in tissues and cavities (edema and effusion, respectively). Fluid buildup exerts a positive pressure on fetal cardiac chambers, which further limits the diastolic ventricular filling reserve, potentiating the diminished cardiac output and leading to fetal death (Thakur et al. 2013).

It remains unclear whether edema plays an essential role in causing fetal death, or whether it simply accelerates the rate of deterioration; nonetheless, it is a reliable indicator of cardiotoxicity.

Evidence Supporting this KER

Biological Plausibility

The connection between altered cardiovascular development during embryogenesis, diminished cardiac output and embryonic death have been well studied (Thakur et al. 2013; Kopf and Walker 2009)

Empirical Evidence

- The most common cause of infant death due to birth defects is congenital cardiovascular malformation (Kopf and Walker 2009)
- At low doses of dioxin-like compounds, disrupted heart looping (Henshel et al. 1993), congenital heart defects, (Cheung et al. 1981) and impaired contraction of cardiac myocytes (Canga et al. 1993) were observed in chick embryos without the onset of edema. Whereas at higher doses edema and embryo death are increased (Walker et al. 1997).
- Changes in heart morphology consistent with dilated cardiomyopathy (decreased cardiac output and ventricular cavity expansion) were observed in chick embryos exposed to 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) followed by progression to congestive heart failure.
- Changes in heart morphology and decreases in cardiac output and peripheral blood flow precede heart failure in Zebrafish (Antkiewicz et al. 2005; Belair et al. 2001; Henry et al. 1997; Plavicki et al. 2013)
- When mannitol is used as a protective agent against chemical-induced edema in zebrafish, cardiotoxic effects are still observed; therefore, edema is secondary to cardiotoxicity (Antkiewicz et al. 2005; Plavicki et al. 2013)
- Edema is a hallmark sign of cardio-developmental toxicity in fish, chick, and mammalian species exposed to strong AHR agonists early in embryogenesis (Carney et al. 2006)
 - Note that it presents as pericardial and yolk sac edema in fish, pericardial, peritoneal and subcutaneous edema on chicks, and peritoneal and subcutaneous edema in mice.

Uncertainties and Inconsistencies

There is no doubt that severely altered cardiovascular development early in embryogenesis causes embryonic death, however the precise sequence of events leading to heart failure remains to be elucidated.

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List of Non Adjacent Key Event Relationships

Relationship: 984: Activation, AhR leads to Increase, Early Life Stage Mortality (<https://aopwiki.org/relationships/984>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Aryl hydrocarbon receptor activation leading to early life stage mortality, via reduced VEGF (https://aopwiki.org/aops/150)	non-adjacent	High	Moderate
aryl hydrocarbon receptor activation leading to early life stage mortality, via increased COX-2 (https://aopwiki.org/aops/21)	non-adjacent	High	Moderate

Evidence Supporting Applicability of this Relationship

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
chicken	Gallus gallus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9031)
Japanese quail	Coturnix japonica	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=93934)
Ring-necked pheasant	Phasianus colchicus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9054)
turkey	Meleagris gallopavo	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9103)
bobwhite quail	Colinus virginianus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=9014)
American kestrel	Falco sparverius	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=56350)
Double-crested cormorant	Double-crested cormorant	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)
Eastern bluebird	Eastern bluebird	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=0)
zebrafish	Danio rerio	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=7955)
Fundulus heteroclitus	Fundulus heteroclitus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8078)
Mus musculus	Mus musculus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10090)
Oncorhynchus mykiss	Oncorhynchus mykiss	Moderate	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8022)

Term	Scientific Term	Evidence	Links
Xenopus laevis	Xenopus laevis	Low	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=8355)
rat	Rattus norvegicus	High	NCBI (http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&id=10116)

Life Stage Applicability

Life Stage	Evidence
Embryo	High
Development	High

Sex Applicability

Sex	Evidence
Unspecific	High

- Overall, this KER is believed to be applicable to all vertebrates based on mortality as a result of exposure to known agonists of the AhR (Buckler et al 2015; Cohen-Barnhouse et al 2011; Elonen et al 1998; Johnson et al 1998; Jung et al 1997; Kopf & Walker 2009; Park et al 2014; Tillitt et al 2016; Toomey et al 2001; Walker et al 1991; Wang et al 2013; Yamauchi et al 2006; Zabel et al 1995).
- The correlation between AHR-mediated reporter gene activity and embryo death has been demonstrated in avian species as described above.
- Little is known about differences in binding affinity of AhRs and how this relates to sensitivity in non-avian taxa.
- Low binding affinity for DLCs of AhR1s of African clawed frog (*Xenopus laevis*) and axolotl (*Ambystoma mexicanum*) has been suggested as a mechanism for tolerance of these amphibians to DLCs (Lavine et al 2005; Shoots et al 2015).
- Among reptiles, only AhRs of American alligator (*Alligator mississippiensis*) have been investigated and little is known about the sensitivity of American alligator or other reptiles to DLCs (Oka et al 2016).
- Among fishes, great differences in sensitivity to DLCs are known both for AhRs and for embryos among species that have been tested (Doering et al 2013; 2014).
- Differences in binding affinity of the AhR2 have been demonstrated to explain differences in sensitivity to DLCs between sensitive and tolerant populations of Atlantic Tomcod (*Microgadus tomcod*) (Wirgin et al 2011).
- Information is not yet available regarding whether differences in binding affinity of AhRs of fishes are predictive of differences in sensitivity of embryos, juveniles, or adults (Doering et al 2013).

Key Event Relationship Description

The aryl hydrocarbon receptor is commonly known for its involvement in xenobiotic metabolism and clearance, but it also regulates a number of endogenous processes including angiogenesis, immune responses, neuronal processes, metabolism, and development of numerous organ systems (Duncan et al., 1998; Emmons et al., 1999; Hahn et al 2002; Lahvis and Bradfield, 1998). Strong AHR agonists that cause sustained AHR activation interfere with the receptor's endogenous role in embryogenesis, which causes numerous developmental abnormalities and ultimately leads to embryonic death (Kopf and Walker 2009; Carreira et al 2015).

It's important to note that this relationship only applies to AHR agonists that cause sustained AHR activation. Strong AHR agonists that are rapidly metabolized, such as polycyclic aromatic hydrocarbons, only cause transient AHR activation leading to an alternate mode of toxicity.

This Key Event Relationship describes the indirect link between the Molecular Initiating Event (activation of the AhR) and the Adverse Outcome (increased early life stage mortality).

Evidence Supporting this KER**Biological Plausibility****AHR Ligand Binding Domain**

- Mammalian and avian sensitivity to DLCs ultimately comes down to the identity of two particular amino acids in the ligand binding domain (LBD) of the AHR: positions 375 and 319 in mice and 380 and 324 in birds.
 - A 10-fold difference between two strains of mice (non-responsive DBA/2 mouse, and responsive C57BL/6 14 mouse) in CYP1A induction, lethality and teratogenicity following TCDD exposure (Poland et al. 1976), was attributed to a single nucleotide polymorphism at position 375 (Ema et al. 1994; Poland et al. 1994; Poland and Knutson 1982).
 - Several other studies reported the importance of this amino acid in birds and mammals (Backlund and Ingelman-Sundberg 2004; Ema et al. 1994; Karchner et al. 2006; Murray et al. 2005; Pandini et al. 2007; Pandini et al. 2009; Poland et al. 1994; Ramadoss and Perdev 2004).
- The amino acid at position 319 plays an important role in ligand-binding affinity to the AHR and transactivation ability of the AHR, due to its involvement in LBD cavity volume and its steric effect (Pandini et al. 2009).
 - Mutation at position 319 in the mouse eliminated AHR DNA binding (Pandini et al. 2009).

Using AHR LBD Constructs to Determine Avian Sensitivity

- Using chimeric AHR1 constructs combining three AHR1 domains (DBD, LBD and TAD) from the chicken (highly sensitive to DLC toxicity) and common tern (resistant to DLC toxicity), Karchner and colleagues (2006), showed that amino acid differences within the LBD were responsible for differences in TCDD sensitivity between the chicken and common tern.
 - They specifically attributed positions 324 and 380 with differences in TCDD binding affinity and transactivation between the chicken (Ile324_Ser380) and common tern (Val324_Ala380) receptors.
- The LBD of over 85 bird species have since been analyzed to find that 6 amino acid residues differed among species (Farmahin et al. 2013; Head et al. 2008), but only positions 324 and 380 in the AHR1 LBD were associated with differences in DLC toxicity in ovo and AHR1-mediated gene expression in vitro (Farmahin et al. 2013; Head et al. 2008; Manning et al. 2012).
 - Based on these results, avian species can be divided into one of three AHR1 types based on the amino acids found at positions 324 and 380 of the AHR1 LBD: type 1 (Ile324_Ser380; most sensitive), type 2 (Ile324_Ala380; moderately sensitive) and type 3 (Val324_Ala380; least sensitive) (Farmahin et al. 2013; Head et al. 2008; Manning et al. 2012).
 - A sampling of bird species and their AHR LBD category is described in table 1. A list of 86 species and their subtype can be found in Farmahin et al. (2013).

Table 1

AHR1 subtypes identified based on predicted amino acid sequences of the avian AHR1 ligand binding domain (LBD). Avian AHR1 LBD sequences from 86 species were obtained from GenBank or were determined from liver or blood samples obtained from the National Wildlife Research Centre, Ottawa, ON, commercial suppliers near Ottawa, ON, or the Tittabawassee River basin, Michigan, USA

AHR 1 subtype	LBD amino acid residues						Examples ^b
	256	257	297	324 ^a	337	380 ^a	
1A	A	A	T	I	V	S	Domestic chicken (<i>Gallus gallus domesticus</i>)
1B	A	A	T	I	I	S	European starling (<i>Sturnus vulgaris</i>)
1C	A	T	T	I	I	S	Gray catbird (<i>Dumetella carolinensis</i>)
2A	A	A	I	I	V	A	Wild turkey (<i>Meleagris gallopavo</i>)
2B	A	A	T	I	I	A	Indigo bunting (<i>Passerina cyanea</i>)
2C	A	A	V	I	V	A	Rock ptarmigan (<i>Lagopus muta</i>)
2D	A	P	T	I	V	A	Spotted sandpiper (<i>Actitis macularius</i>)
2E	A	T	T	I	I	A	Tree swallow (<i>Tachycineta bicolor</i>)
2F	A	T	T	I	V	A	Black-footed albatross (<i>Phoebastria nigripes</i>)
2G	T	A	I	I	V	A	Ring-necked pheasant (<i>Phasianus colchicus</i>)
3A	A	A	T	V	V	A	Japanese quail (<i>Coturnix japonica</i>)
3B	A	T	T	V	V	A	Herring gull (<i>Larus argentatus</i>)
3C	T	T	T	V	V	A	Wood duck (<i>Aix sponsa</i>)

^aAmino acid residues at positions 324 and 380 were used to classify species into three major AHR1 types, which are indicated by white (type 1), light grey (type 2), and dark grey (type 3) shading.

^bThe full list of 86 species is presented in (Farmahin, R. et al. (2013). *Toxicol. Sci.* **131**(1), 139-152)

(Source: Manning, G. E. et al. (2012). *Toxicol. Appl. Pharmacol.* **263**(3), 390-399)

(https://aopwiki.org/wiki/index.php/File:AHR1_LBD_Types.png)

Empirical Evidence

Mammals:

- AhR deficient strains of mice (*Mus musculus*) are unaffected by exposure to agonists of the AhR (Fernandez-Salguero et al 1996).
- Strains of mice that express AhRs with lesser affinity for agonists are more tolerant to adverse effects of exposure relative to strains of mice that express AhRs with greater affinity for agonists (Bisson et al 2009; Ema et al 1993).

Birds:

Binding of dioxin-like compounds (DLCs) to avian AHR1 (Farmahin et al. 2014; Karchner et al. 2006) and AHR1-mediated transactivation measured using luciferase reporter gene (LRG) assays have been demonstrated in domestic and wild species of birds (Farmahin et al. 2012; Farmahin et al. 2013b; Fujisawa et al. 2012; Lee et al. 2009; Manning et al. 2012; Mol et al. 2012), and binding affinity was found to be strongly correlated with embryotoxicity (Manning et al. 2012).

Fish:

- Knockdown of the AhR2 prevents mortality following exposure to agonist of the AhR in fishes (Clark et al 2010; Hanno et al 2010; Prasch et al 2003; Van Tiem & Di Giulio 2011). Relative potencies of dioxin-like compounds for activation of AHR2 alpha of rainbow trout (*Oncorhynchus mykiss*) is predictive of relative potencies for early life stage mortality (Abnet et al 1999).

Amphibians:

- AhR1s of amphibians studied to date are insensitive to activation by dioxin-like compounds *in vitro*, while amphibians studies to date are extremely tolerant to adverse effects of exposure to dioxin-like compounds *in vivo* (Jung et al 1997; Lavine et al 2005; Shoots et al 2015).

Invertebrates:

- Chemicals that activate the AhR of vertebrates are not known to bind AhRs of invertebrates and increased mortality in invertebrates has never been observed as a result of exposure to these agonists (Hahn 2002; Hahn et al 1994).

Uncertainties and Inconsistencies

Interestingly, interference with endogenous AHR functions, either by knock-out or by agonist exposure during early development, causes similar cardiac abnormalities (Carreira et al 2015). Although this is counterintuitive, it demonstrates that the AHR has an optimal window of activity, and deviation either above or below this range results in toxicity.

Uncertainties:

- Only limited AhR activation information is currently available for fishes.
- Only limited AhR activation information and mortality information is currently available for reptiles and amphibians.
- Despite decades of research into the molecular initiating event (i.e., binding of chemicals to the AhR) and resulting adverse outcomes (i.e. mortality), less is known about the precise cascade of key events that link activation of the AhR to the adverse outcome (Doering et al 2016).
- However, hundreds to thousands of different genes are regulated, either directly or indirectly, by activation of the AhR, which presents major uncertainties in the precise pathway of key events or whether perturbation to multiple pathways is the cause of mortality (Brinkmann et al 2016; Doering et al 2016; Huang et al 2014; Li et al 2013; Whitehead et al 2010).
- Despite these uncertainties in the AOP, considerable research has investigated the indirect relationship between activation of the AhR and increased mortality among different chemicals, species, and taxa (Doering et al 2013).

Inconsistencies:

- There are no currently known inconsistencies between AhR activation and increased mortality among vertebrates.

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