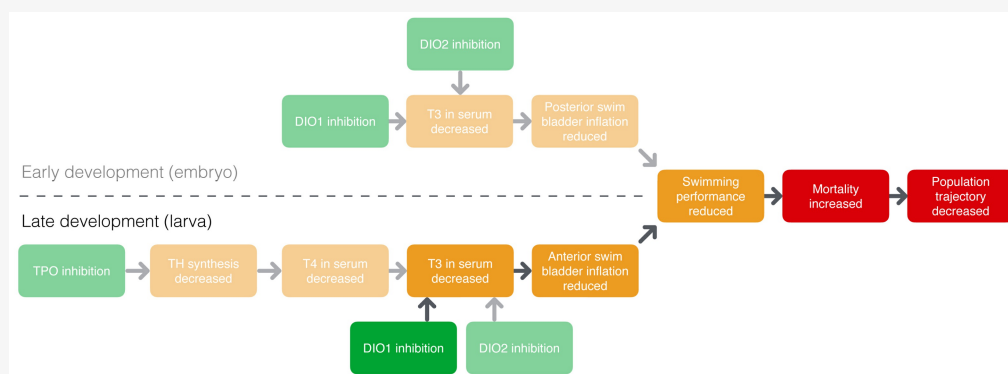


## AOP ID and Title:

AOP 158: Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation

**Short Title: DIO1i anterior swim bladder**

## Graphical Representation



## Authors

Lucia Vergauwen [1], [lucia.vergauwen(at)uantwerpen.be]

Evelyn Stinckens [1], [evelyn.stinckens(at)uantwerpen.be]

Dan Villeneuve [2], [villeneuve.dan(at)epa.gov]

Dries Knapen [1], [dries.knapen (at)uantwerpen.be]

[1] Zebrafishlab, Veterinary Physiology and Biochemistry, Department of Veterinary Sciences, University of Antwerp, Universiteitsplein 1, 2610 Wilrijk, Belgium

[2] United States Environmental Protection Agency, Mid-Continent Ecology Division, 6201 Congdon Blvd, Duluth, MN, USA.

## Status

Author status	OECD status	OECD project	SAAOP status
Open for adoption	EAGMST Under Review	1.35	Included in OECD Work Plan

## Abstract

Other than the difference in deiodinase (DIO) isoform, the current AOP is identical to the corresponding AOP leading from DIO2 inhibition to increased mortality via anterior swim bladder inflation (<https://aopwiki.org/aops/156>). The overall importance of DIO1 versus DIO2 in fish is not exactly clear. The current state of the art suggests that DIO2 is more important than DIO1 in regulating swim bladder inflation. Therefore AOP 156 may be of higher biological relevance compared to the AOP that is described here. Starting from reduced serum T3 levels, this AOP is also identical to the AOP leading from thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation (<https://aopwiki.org/aops/159>).

This AOP describes the sequence of events leading from deiodinase inhibition to increased mortality via reduced anterior swim bladder inflation. Thyroid hormones (THs) are critical during development and disruption of the TH system can interfere with normal development. Three types of iodothyronine deiodinases (DIO1-3) have been described in vertebrates that activate or inactivate THs and are therefore important mediators of TH action. While type II deiodinase (DIO2) has thyroxine (T4) as a preferred substrate and is mostly important for converting T4 to the more biologically active triiodothyronine (T3), type I deiodinase is capable of both converting T4 into T3 and converting rT3 to the inactive thyroid hormone 3,3' T2. Inhibition of DIO1 thus reduces T3 levels. However, partly because rT3, rather than T4, is the preferred substrate for DIO1, DIO1 inhibition is probably less important in causing reduced T3 levels when compared to DIO2 inhibition. Swim bladder inflation is known to be under TH control (Brown et al., 1988; Liu and Chan, 2002). Many fish species have a swim bladder which is a gas-filled organ that typically consists of two chambers (Robertson et al., 2007). The posterior chamber inflates during early development in the embryonic phase, while the anterior chamber inflates during late development in the larval phase. Both the posterior and the anterior chamber have an important role in regulating buoyancy, and the anterior chamber has an additional role in hearing (Robertson et al., 2017). This AOP describes how inhibition of DIO1 reduces levels of T3, thereby prohibiting proper inflation of the anterior chamber. Due to its role in regulating buoyancy, this results in reduced swimming performance. Since reduced swimming performance results in a decreased ability to forage and avoid predators, this reduces chances of survival. The final adverse outcome is a decrease of the

population trajectory. Since many AOPs eventually lead to this more general adverse outcome at the population level, the more specific and informative adverse outcome at the organismal level, increased mortality, is used in the AOP title. Support for this AOP is mainly based on chemical exposures in zebrafish and fathead minnows (Cavallin et al., 2017; Godfrey et al., 2017; Stinckens et al., 2020). This AOP is part of a larger AOP network describing how decreased synthesis and/or decreased biological activation of THs leads to incomplete or improper inflation of the swim bladder, leading to reduced swimming performance, increased mortality and decreased population trajectory (Knäpen et al., 2018; Knäpen et al., 2020; Villeneuve et al., 2018).

## Background

The larger AOP network describing the effect of deiodinase and thyroperoxidase inhibition on swim bladder inflation consists of 5 AOPs:

- Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation: <https://aopwiki.org/aops/155>
- Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation: <https://aopwiki.org/aops/156>
- Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation : <https://aopwiki.org/aops/157>
- Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation : <https://aopwiki.org/aops/158>
- Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation: <https://aopwiki.org/aops/159>

The development of these AOPs was mainly based on a series of dedicated experiments (using a set of reference chemicals as prototypical stressors) in zebrafish and fathead minnow that form the core of the empirical evidence. Specific literature searches were used to add evidence from other studies, mainly in zebrafish and fathead minnow. No systematic review approach was applied.

## Summary of the AOP

### Events

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

Sequence	Type	Event ID	Title	Short name
1	MIE	1009	<a href="#">Inhibition, Deiodinase 1</a>	Inhibition, Deiodinase 1
2	KE	1003	<a href="#">Decreased, Triiodothyronine (T3) in serum</a>	Decreased, Triiodothyronine (T3) in serum
3	KE	1007	<a href="#">Reduced, Anterior swim bladder inflation</a>	Reduced, Anterior swim bladder inflation
4	KE	1005	<a href="#">Reduced, Swimming performance</a>	Reduced, Swimming performance
5	AO	351	<a href="#">Increased Mortality</a>	Increased Mortality
6	AO	360	<a href="#">Decrease, Population trajectory</a>	Decrease, Population trajectory

### Key Event Relationships

Upstream Event	Relationship Type	Downstream Event	Evidence	Quantitative Understanding
<a href="#">Inhibition, Deiodinase 1</a>	adjacent	Decreased, Triiodothyronine (T3) in serum	Low	Low
<a href="#">Decreased, Triiodothyronine (T3) in serum</a>	adjacent	Reduced, Anterior swim bladder inflation	Moderate	Moderate
<a href="#">Reduced, Anterior swim bladder inflation</a>	adjacent	Reduced, Swimming performance	Moderate	Low
<a href="#">Reduced, Swimming performance</a>	adjacent	Increased Mortality	Moderate	Low
<a href="#">Increased Mortality</a>	adjacent	Decrease, Population trajectory	Moderate	Moderate

## Overall Assessment of the AOP

Upstream Event	Relationship Type	Downstream Event	Evidence	Quantitative Understanding
----------------	-------------------	------------------	----------	----------------------------

The attached document includes:

- Support for biological plausibility of KERs
- Support for essentiality of KEs
- Empirical support for KERs
- Dose and temporal concordance table covering the larger AOP network

Overall, the weight of evidence for the sequence of key events laid out in the AOP is moderate, and it should be noted that based on available evidence DIO2 seems to be more important than DIO1 in providing sufficient T3 for swim bladder inflation. The exact underlying mechanism of TH disruption leading to impaired swim bladder inflation is not exactly understood.

### Domain of Applicability

#### Life Stage Applicability

##### Life Stage Evidence

Larvae High

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	High	<a href="#">NCBI</a>
fathead minnow	Pimephales promelas	High	<a href="#">NCBI</a>

#### Sex Applicability

##### Sex Evidence

Unspecific Moderate

**Taxonomic:** Organogenesis of the swim bladder begins with an evagination from the gut. In physostomous fish, a connection between the swim bladder and the gut is retained. In physoclistous fish, once initial inflation by gulping atmospheric air at the water surface has occurred, the swim bladder is closed off from the digestive tract and swim bladder volume is regulated by gas secretion into the swim bladder (Woolley and Qin, 2010). This AOP is currently mainly based on experimental evidence from studies on zebrafish and fathead minnows, physostomous fish with a two-chambered swim bladder. This AOP is not applicable to fish that do not have a second swim bladder chamber that inflates during larval development, e.g., the Japanese rice fish (*Oryzias latipes*).

**Life stage:** The current AOP is only applicable to larval development, which is the period where the anterior swim bladder chamber inflates. In all life stages, the conversion of T4 into more biologically active T3 is essential. Inhibition of deiodinase (DIO) therefore impacts swim bladder inflation in both early (<https://aopwiki.org/aops/157>) and late developmental life stages.

**Sex:** All key events in this AOP are plausibly applicable to both sexes. Sex differences are not often investigated in tests using early life stages of fish. In Medaka, sex can be morphologically distinguished as soon as 10 days post fertilization. Females appear more susceptible to thyroid-induced swim bladder dysfunction compared with males (Godfrey et al., 2019). For zebrafish and fathead minnow, it is currently unclear whether sex-related differences are important in determining the magnitude of the changes across the sequence of events in this AOP. Different fish species have different sex determination and differentiation strategies. Zebrafish do not have identifiable heteromorphic sex chromosomes and sex is determined by multiple genes and influenced by the environment (Nagabhushana and Mishra, 2016). Zebrafish are undifferentiated gonochorists since both sexes initially develop an immature ovary (Maack and Segner, 2003). Immature ovary development progresses until approximately the onset of the third week. Later, in female fish immature ovaries continue to develop further, while male fish undergo transformation of ovaries into testes. Final transformation into testes varies among male individuals, however finishes usually around 6 weeks post fertilization. Since the anterior chamber inflates around 21 days post fertilization in zebrafish, sex differences are expected to play a minor role in the current AOP. Fathead minnow gonad differentiation also occurs during larval development. Fathead minnows utilize a XY sex determination strategy and markers can be used to genotype sex in life stages where the sex is not yet clearly defined morphologically (Olmstead et al., 2011). Ovarian differentiation starts at 10 dph followed by rapid development (Van Aerle et al., 2004). At 25 dph germ cells of all stages up to the primary oocytes stage were present and at 120 dph, vitellogenic oocytes were present. The germ cells (spermatogonia) of the developing testes only entered meiosis around 90–120 dph. Mature testes with spermatozoa are present around 150 dph. Since the anterior chamber inflates around 14 days post fertilization (9 dph) in fathead minnows, sex differences are expected to play a minor role in the current AOP.

### Essentiality of the Key Events

Overall, the support for essentiality of the KEs is low since there is limited direct evidence from specifically designed experimental studies illustrating essentiality. This includes evidence from combined DIO1 and DIO2 knockdown studies in zebrafish showing the link with reduced posterior chamber inflation, but anterior chamber inflation was not studied. There is additional indirect evidence that reduced thyroid hormone synthesis causes reduced anterior swim bladder inflation: Chopra et al. (2019) showed that

knockdown of dual oxidase, important for thyroid hormone synthesis, reduced anterior swim bladder inflation. It should be noted that dual oxidase also plays a role in oxidative stress. There is no specific evidence for the essentiality of DIO1 inhibition independent of DIO2 inhibition and DIO2 seems more important than DIO1 in providing sufficient T3 for proper swim bladder inflation. Therefore the overall evidence for essentiality is considered low.

## Weight of Evidence Summary

**Biological plausibility:** see Table. Overall, the weight of evidence for the biological plausibility of the KERs in the AOP is moderate since there is empirical support for an association between the sets of KEs and the KERs are plausible based on analogy to accepted biological relationships, but scientific understanding is not completely established.

**Empirical support:** see Table. Overall, the empirical support for the KERs in the AOP is moderate since dependent changes in sets of KEs following exposure to several specific stressors has been demonstrated, with limited evidence for dose and temporal concordance and some uncertainties.

## Quantitative Consideration

Quantitative understanding of this AOP is currently lacking.

## Considerations for Potential Applications of the AOP (optional)

A growing number of environmental pollutants are known to adversely affect the thyroid hormone system, and major gaps have been identified in the tools available for the identification, and the hazard and risk assessment of these thyroid hormone disrupting chemicals. Villeneuve et al. (2014) discussed the relevance of swim bladder inflation as a potential key event and endpoint of interest in fish tests. Knapen et al. (2020) provide an example of how the adverse outcome pathway (AOP) framework and associated data generation can address current testing challenges in the context of fish early-life stage tests, and fish tests in general. A suite of assays covering all the essential biological processes involved in the underlying toxicological pathways can be implemented in a tiered screening and testing approach for thyroid hormone disruption, using the levels of assessment of the OECD's Conceptual Framework for the Testing and Assessment of Endocrine Disrupting Chemicals as a guide. Specifically, for this AOP, deiodinase inhibition can be assessed using an in chemico assay, measurements of T3 levels could be added to the Fish Embryo Acute Toxicity (FET) test (OECD TG 236), the Fish Early Life Stage Toxicity (FELS) Test (OECD TG210) and the Fish Sexual Development Test (FSDT, OECD TG 234), and assessments of anterior chamber inflation and swimming performance could be added to the FELS Test and FSDT.

Thyroid hormone system disruption causes multiple unspecific effects. Addition of TH measurements could aid in increasing the diagnostic capacity of a battery of endpoints since they are specific to the TH system. A battery of endpoints would ideally include the MIE, the AO and TH levels as the causal link. It is also in this philosophy that TH measurements are currently being considered as one of the endpoints in project 2.64 of the OECD TG work plan, "Inclusion of thyroid endpoints in OECD fish Test Guidelines". While T3 measurements showed low levels of variation and were highly predictive of downstream effects in dedicated experiments to support this AOP, more variability may be present in other studies. Because of the rapid development in fish, it is important to compare T3 levels within specific developmental stages. For example, clear changes in T3 levels have been observed in zebrafish at 14, 21 and 32 dpf (Stinckens et al., 2020) and in fathead minnows at 4, 6, 10, 14, 18 and 21 dpf (Nelson et al., 2016; Cavallin et al., 2017) using liquid chromatography tandem mass spectrometry (LC-MS/MS).

The overall importance of DIO1 versus DIO2 in fish is not exactly clear. The current state of the art suggests that DIO2 is more important than DIO1 in regulating swim bladder inflation. Therefore AOP 156 may be more relevant for applications compared to the AOP that is described here.

## References

- Brown, C.L., Doroshov, S.I., Nunez, J.M., Hadley, C., Vaneenennaam, J., Nishioka, R.S., Bern, H.A., 1988. MATERNAL TRIIODOTHYRONINE INJECTIONS CAUSE INCREASES IN SWIMBLADDER INFLATION AND SURVIVAL RATES IN LARVAL STRIPED BASS, MORONE-SAXATILIS. *Journal of Experimental Zoology* 248, 168-176.
- Cavallin, J.E., Ankley, G.T., Blackwell, B.R., Blanksma, C.A., Fay, K.A., Jensen, K.M., Kahl, M.D., Knapen, D., Kosian, P.A., Poole, S.T., Randolph, E.C., Schroeder, A.L., Vergauwen, L., Villeneuve, D.L., 2017. Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry* 36, 2942-2952.
- Godfrey A, Hooser B, Abdelmoneim A, Sepulveda MS. 2019. Sex-specific endocrine-disrupting effects of three halogenated chemicals in japanese medaka. *Journal of Applied Toxicology*. 39(8):1215-1223.
- Godfrey, A., Hooser, B., Abdelmoneim, A., Horzmann, K.A., Freemanc, J.L., Sepulveda, M.S., 2017. Thyroid disrupting effects of halogenated and next generation chemicals on the swim bladder development of zebrafish. *Aquatic Toxicology* 193, 228-235.
- Knapen, D., Angrish, M.M., Fortin, M.C., Katsiadaki, I., Leonard, M., Margiotta-Casaluci, L., Munn, S., O'Brien, J.M., Pollesch, N., Smith, L.C., Zhang, X.W., Villeneuve, D.L., 2018. Adverse outcome pathway networks I: Development and applications. *Environmental Toxicology and Chemistry* 37, 1723-1733.
- Knapen, D., Stinckens, E., Cavallin, J.E., Ankley, G.T., Holbech, H., Villeneuve, D.L., Vergauwen, L., 2020. Toward an AOP

Network-Based Tiered Testing Strategy for the Assessment of Thyroid Hormone Disruption. Environmental Science & Technology 54, 8491-8499.

Liu, Y.W., Chan, W.K., 2002. Thyroid hormones are important for embryonic to larval transitory phase in zebrafish. Differentiation 70, 36-45.

Maack, G., Segner, H., 2003. Morphological development of the gonads in zebrafish. Journal of Fish Biology 62, 895-906.

Nagabhushana A, Mishra RK. 2016. Finding clues to the riddle of sex determination in zebrafish. Journal of Biosciences. 41(1):145-155.

Olmstead AW, Villeneuve DL, Ankley GT, Cavallin JE, Lindberg-Livingston A, Wehmas LC, Degitz SJ. 2011. A method for the determination of genetic sex in the fathead minnow, *pimephales promelas*, to support testing of endocrine-active chemicals. Environmental Science & Technology. 45(7):3090-3095.

Robertson, G.N., McGee, C.A.S., Dumbarton, T.C., Croll, R.P., Smith, F.M., 2007. Development of the swimbladder and its innervation in the zebrafish, *Danio rerio*. Journal of Morphology 268, 967-985.

Stinckens, E., Vergauwen, L., Blackwell, B.R., Anlley, G.T., Villeneuve, D.L., Knapen, D., 2020. Effect of Thyroperoxidase and Deiodinase Inhibition on Anterior Swim Bladder Inflation in the Zebrafish. Environmental Science & Technology 54, 6213-6223.

van Aerle R, Runnalls TJ, Tyler CR. 2004. Ontogeny of gonadal sex development relative to growth in fathead minnow. Journal of Fish Biology. 64(2):355-369.

Villeneuve, D., Angrish, M., Fortin, M., Katsiadaki, I., Leonard, M., Margiotta-Casaluci, L., Munn, S., O'Brien, J., Pollesch, N., Smith, L., Zhang, X., Knapen, D., 2018. Adverse Outcome Pathway Networks II: Network Analytics. Environ Toxicol Chem doi: 10.1002/etc.4124.

Villeneuve, D., Volz, D.C., Embry, M.R., Ankley, G.T., Belanger, S.E., Leonard, M., Schirmer, K., Tanguay, R., Truong, L., Wehmas, L., 2014. Investigating alternatives to the fish early-life stage test: a strategy for discovering and annotating adverse outcome pathways for early fish development. Environmental Toxicology and Chemistry 33, 158-169.

Woolley, L.D., Qin, J.G., 2010. Swimbladder inflation and its implication to the culture of marine finfish larvae. Reviews in Aquaculture 2, 181-190.

## Appendix 1

### List of MIEs in this AOP

#### [Event: 1009: Inhibition, Deiodinase 1](#)

**Short Name:** Inhibition, Deiodinase 1

#### Key Event Component

Process	Object	Action
catalytic activity	type I iodothyronine deiodinase	decreased

#### AOPs Including This Key Event

AOP ID and Name	Event Type
<a href="#">Aop:157 - Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	MolecularInitiatingEvent
<a href="#">Aop:158 - Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	MolecularInitiatingEvent
<a href="#">Aop:189 - Type I iodothyronine deiodinase (DIO1) inhibition leading to altered amphibian metamorphosis</a>	MolecularInitiatingEvent

#### Stressors

Name
iopanoic acid

Propylthiouracil

## Biological Context

### Level of Biological Organization

Molecular

## Evidence for Perturbation by Stressor

### Overview for Molecular Initiating Event

Propylthiouracil (PTU) is the prototypical DIO1 inhibitor in mammals, although teleostean and amphibian DIO1 enzymes are less sensitive to inhibition by PTU (Orozco et al., 2003; Kuiper et al., 2006). Olker et al. (2019) identified 22 DIO1-specific inhibitors using a human recombinant DIO1 enzyme (e.g., genistein, 6-methyl-2-thiouracil, sulfasalazine). Another well-known inhibitor of DIO1 (and DIO2 and 3) is iopanoic acid (IOP). Renko et al. (2003, 2015) pointed out that IOP is actually a substrate of DIO1 (and DIO2 and 3) which is in line with its action as a competitive inhibitor. In fact, many compounds inhibit all three DIO isoforms. Olker et al. (2019) identified 93 compounds that inhibit DIOs 1, 2 and 3.

## Domain of Applicability

### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
rat	<i>Rattus norvegicus</i>	High	<a href="#">NCBI</a>
mouse	<i>Mus musculus</i>	Moderate	<a href="#">NCBI</a>
pigs	<i>Sus scrofa</i>	Moderate	<a href="#">NCBI</a>
Ovis orientalis aries	<i>Ovis aries</i>	Moderate	<a href="#">NCBI</a>
fathead minnow	<i>Pimephales promelas</i>	Moderate	<a href="#">NCBI</a>
killifish	<i>Fundulus heteroclitus</i>	Moderate	<a href="#">NCBI</a>
gilthead bream	<i>Sparus aurata</i>	Moderate	<a href="#">NCBI</a>
African clawed frog	<i>Xenopus laevis</i>	Moderate	<a href="#">NCBI</a>
human	<i>Homo sapiens</i>	High	<a href="#">NCBI</a>
Oreochromis niloticus	<i>Oreochromis niloticus</i>	Moderate	<a href="#">NCBI</a>
zebrafish	<i>Danio rerio</i>	Moderate	<a href="#">NCBI</a>

### Life Stage Applicability

#### Life Stage Evidence

All life stages Moderate

### Sex Applicability

#### Sex Evidence

Unspecific Moderate

**Taxonomic:** Deiodination by DIO enzymes is known to exist in a wide range of vertebrates and invertebrates. Therefore, this KE is plausibly applicable across vertebrates. Studies reporting DIO1 inhibition have used human liver (Kuiper et al., 2006), human recombinant DIO1 enzyme (Olker et al., 2019), rat (*Rattus norvegicus*) liver (Klaren et al., 2005; Freyberger and Ahr, 2006; Kuiper et al., 2006; Pavelka, 2010) and thyroid gland (Ferreira et al., 2002), mouse (*Mus musculus*) brain (hernandez et al., 2006), hog (*Sus scrofa domestica*) liver (Stinckens et al., 2018), sheep (*Ovis orientalis aries*) fetal hepatic, renal and perirenal adipose tissue (Forhead et al., 2006), tadpole (*Xenopus laevis*) liver (Kuiper et al., 2006), fathead minnow (*Pimephales promelas*) whole fish (Noyes et al., 2011), Nile tilapia (*Oreochromis niloticus*) liver (Walpita et al., 2007), Gilthead Seabream (*Sparus aurata*) kidney (Klaren et al., 2005), and killifish (*Fundulus heteroclitus*) liver (Orozco et al., 2003) among others. The latter teleostean DIO1 enzymes as well as amphibian enzymes differ from other vertebrate DIO1 enzymes in their lower sensitivity to propylthiouracil (PTU), a typical DIO1 inhibitor in mammals.

Deiodinase 1 in liver is the main supplier of T3 to circulation in mammals (Marsili et al., 2011), and the same appears to be true for birds. By contrast, DIO1 function in teleostean and amphibian T3 plasma regulation is less clear (Finnson et al. 1999, Kuiper et al. 2006). The presence of DIO1 in the liver of teleosts has been a controversial issue, and both the high level of DIO2 activity and its

expression in the liver of teleosts are unique among vertebrates (Orozco and Valverde, 2005). This could explain why DIO2 inhibition seems to be more important than DIO1 inhibition in determining the adverse outcome in zebrafish (Stinckens et al., 2018).

**Life stage:** Deiodinase activity is important for all vertebrate life stages. Already during early embryonic development, deiodinase activity is needed to regulate thyroid hormone concentrations and coordinate developmental processes. However, the role of DIO1 and DIO2 seems to be distinct. The fact that DIO1 knockdown during zebrafish development only causes developmental defects when combined with DIO2 knockdown (Walpita et al., 2010), suggests that DIO1 is only important in cases of increased TH need during specific stages of development, as supported by increased expression during such stages (Vergauwen et al., 2018), and in cases of thyroid hormone depletion in fish.

**Sex:** This KE is plausibly applicable to both sexes. Deiodinases are important for TH homeostasis and identical in both sexes. Therefore inhibition of deiodinases is not expected to be sex-specific.

## Key Event Description

Disruption of the thyroid hormone system is increasingly being recognized as an important toxicity pathway, as it can cause many adverse outcomes. Thyroid hormones do not only play an important role in the adult individual, but they are also critical during embryonic development. Thyroid hormones (THs) play an important role in a wide range of biological processes in vertebrates including growth, development, reproduction, cardiac function, thermoregulation, response to injury, tissue repair and homeostasis. Numerous chemicals are known to disturb thyroid function, for example by inhibiting thyroperoxidase (TPO) or deiodinase (DIO), upregulating excretion pathways or modifying gene expression. The two major thyroid hormones are triiodothyronine (T3) and thyroxine (T4), both iodinated derivatives of tyrosine. Most TH actions depend on the binding of T3 to its nuclear receptors. Active and inactive THs are tightly regulated by enzymes called iodothyronine deiodinases (DIO). The activation occurs via outer ring deiodination (ORD), i.e. removing iodine from the outer, phenolic ring of T4 to form T3, while inactivation occurs via inner ring deiodination (IRD), i.e. removing iodine from the inner tyrosol ring of T4 or T3.

Three types of iodothyronine deiodinases (DIO1-3) have been described in vertebrates that activate or inactivate THs and are therefore important mediators of TH action. All deiodinases are integral membrane proteins of the thioredoxin superfamily that contain selenocysteine in their catalytic centre. Type I deiodinase is capable of both ORD and IRD, including the conversion of T4 into T3, as well as the conversion of rT3 to the inactive thyroid hormone 3,3'-T2. rT3, rather than T4, is the preferred substrate for DIO1. Furthermore, DIO1 has a very high  $K_m$  ( $\mu M$  range, compared to nM range for DIO2) (Darras and Van Herck, 2012). Type II deiodinase (DIO2) is only capable of ORD activity with T4 as a preferred substrate (i.e., activation of T4 to T3). DIO3 can inner ring deiodinate T4 and T3 to the inactive forms of THs, reverse T3, (rT3) and 3,3'-T2 respectively. DIO1 is a plasma membrane protein with its catalytic domain facing the cytosol.

## How it is Measured or Detected

At this time, there are no approved OECD or EPA guideline protocols for measurement of DIO inhibition. Deiodination is the major pathway regulating T3 bioavailability in mammalian tissues. In vitro assays can be used to examine inhibition of deiodinase 1 (DIO1) activity upon exposure to thyroid disrupting compounds.

Several methods for deiodinase activity measurements are available. A first in vitro assay measures deiodinase activities by quantifying the radioactive iodine release from iodine-labelled substrates, depending on the preferred substrates of the isoforms of deiodinases (Ferreira et al., 2002; Forhead et al., 2006; Freyberger and Ahr, 2006; Pavelka, 2010; Stinckens et al., 2018). Another assay uses a chromatography-based method coupled to mass spectroscopy to measure products of thyroxin resulting from deiodinase type-1 activity (Butt et al., 2011). A colorimetric method (Renko et al., 2012), the Sandell-Kolthoff method, that measures the release of iodine from T4 is also available. Each of these assays requires a source of deiodinase which can be obtained for example using unexposed pig liver tissue (available from slaughterhouses) or rat liver tissue. Hornung et al. (2018) and Olker et al. (2019) on the other hand used an adenovirus expression system to produce the DIO1 enzyme and developed an assay for nonradioactive measurement of iodide released using the Sandell-Kolthoff method in a 96-well plate format. This assay was then used to screen the ToxCast Phase 1 chemical library. The specific synthesis of DIO1 through the adenovirus expression system provides an important advantage over other methods where activity of the different deiodinase isoforms needs to be distinguished in other ways, such as based on differences in enzyme kinetics.

Measurements of in vivo deiodinase activity in tissues collected from animal experiments are scarce. Noyes et al. (2011) showed decreased rate of outer ring deiodination (mediated by DIO1 and DIO2) in whole fish microsomes after exposure to BDE-209. After incubation with the substrate, thyroid hormone levels were measured using LC-MS/MS. Houbrechts et al. (2016) confirmed decreased DIO1 activity in a DIO1-DIO2 knockdown zebrafish at the ages of 3 and 7 days post fertilization. Decreased T3 levels are often used as evidence of DIO inhibition, for example after exposure to iopanoic acid, in fish species such as zebrafish (Stinckens et al., 2020) and fathead minnow (Cavallin et al., 2017). It should be noted that it is difficult to make the distinction between decreased T3 levels caused by outer ring deiodination mediated by DIO2 inhibition or DIO1 inhibition.

## References

- Butt, C.M., Wang, D.L., Stapleton, H.M., 2011. Halogenated Phenolic Contaminants Inhibit the In Vitro Activity of the Thyroid-Regulating Deiodinases in Human Liver. *Toxicological Sciences* 124, 339-347.
- Cavallin JE, Ankley GT, Blackwell BR, Blanksma CA, Fay KA, Jensen KM, Kahl MD, Knapen D, Kosian PA, Poole ST et al. 2017.

Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry*. 36(11):2942-2952.

Darras, V.M., Van Herck, S.L.J., 2012. Iodothyronine deiodinase structure and function: from ascidians to humans. *Journal of Endocrinology* 215, 189-206.

Ferreira, A.C.F., Lisboa, P.C., Oliveira, K.J., Lima, L.P., Barros, I.A., Carvalho, D.P., 2002. Inhibition of thyroid type 1 deiodinase activity by flavonoids. *Food and Chemical Toxicology* 40, 913-917.

Finnsen, K.W., McLeese, J.M., Eales, J.G., 1999. Deiodination and deconjugation of thyroid hormone conjugates and type I deiodination in liver of rainbow trout, *Oncorhynchus mykiss*. *General and Comparative Endocrinology* 115, 387-397.

Forhead, A.J., Curtis, K., Kaptein, E., Visser, T.J., Fowden, A.L., 2006. Developmental control of iodothyronine deiodinases by cortisol in the ovine fetus and placenta near term. *Endocrinology* 147, 5988-5994.

Freyberger, A., Ahr, H.J., 2006. Studies on the goitrogenic mechanism of action of N,N,N',N'-tetramethylthiourea. *Toxicology* 217, 169-175.

Hernandez, A., Martinez, M.E., Fiering, S., Galton, V.A., St Germain, D., 2006. Type 3 deiodinase is critical for the maturation and function of the thyroid axis. *J Clin Invest* 116, 476-484.

Hornung, M.W., Korte, J.J., Olker, J.H., Denny, J.S., Knutsen, C., Hartig, P.C., Cardon, M.C., Degitz, S.J., 2018. Screening the ToxCast Phase 1 Chemical Library for Inhibition of Deiodinase Type 1 Activity. *Toxicological Sciences* 162, 570-581.

Houbrechts AM, Vergauwen L, Bagci E, Van Houcke J, Heijlen M, Kulemeka B, Hyde DR, Knapen D, Darras VM. 2016. Deiodinase knockdown affects zebrafish eye development at the level of gene expression, morphology and function. *Molecular and Cellular Endocrinology*. 424(C):81-93.

Klaren, P.H.M., Haasdijk, R., Metz, J.R., Nitsch, L.M.C., Darras, V.M., Van der Geyten, S., Flik, G., 2005. Characterization of an iodothyronine 5'-deiodinase in gilthead seabream (*Sparus auratus*) that is inhibited by dithiothreitol. *Endocrinology* 146, 5621-5630.

Kuiper, G., Klootwijk, W., Dubois, G.M., Destree, O., Darras, V.M., Van der Geyten, S., Demeneix, B., Visser, T.J., 2006. Characterization of recombinant *Xenopus laevis* type I iodothyronine deiodinase: substitution of a proline residue in the catalytic center by serine (Pro132Ser) restores sensitivity to 6-propyl-2-thiouracil. *Endocrinology* 147, 3519-3529.

Marsili, A., Zavacki, A.M., Harney, J.W., Larsen, P.R., 2011. Physiological role and regulation of iodothyronine deiodinases: A 2011 update. *Journal of Endocrinological Investigation* 34, 395-407.

Noyes, P.D., Hinton, D.E., Stapleton, H.M., 2011. Accumulation and Debromination of Decabromodiphenyl Ether (BDE-209) in Juvenile Fathead Minnows (*Pimephales promelas*) Induces Thyroid Disruption and Liver Alterations. *Toxicological Sciences* 122, 265-274.

Olker, J.H., Korte, J.J., Denny, J.S., Hartig, P.C., Cardon, M.C., Knutsen, C.N., Kent, P.M., Christensen, J.P., Degitz, S.J., Hornung, M.W., 2019. Screening the ToxCast Phase 1, Phase 2, and e1k Chemical Libraries for Inhibitors of Iodothyronine Deiodinases. *Toxicological Sciences* 168, 430-442.

Orozco, A., Valverde, R.C., 2005. Thyroid hormone deiodination in fish. *Thyroid* 15, 799-813.

Orozco, A., Villalobos, P., Jeziorski, M.C., Valverde, C., 2003. The liver of *Fundulus heteroclitus* expresses deiodinase type 1 mRNA. *General and Comparative Endocrinology* 130, 84-91.

Pavelka, S., 2010. Radiometric enzyme assays: development of methods for extremely sensitive determination of types 1, 2 and 3 iodothyronine deiodinase enzyme activities. *Journal of Radioanalytical and Nuclear Chemistry* 286, 861-865.

Renko, K., Hoefig, C.S., Hiller, F., Schomburg, L., Kohrle, J., 2012. Identification of Iopanoic Acid as Substrate of Type 1 Deiodinase by a Novel Nonradioactive Iodide-Release Assay. *Endocrinology* 153, 2506-2513.

Stinckens, E., Vergauwen, L., Ankley, G.T., Blust, R., Darras, V.M., Villeneuve, D.L., Witters, H., Volz, D.C., Knapen, D., 2018. An AOP-based alternative testing strategy to predict the impact of thyroid hormone disruption on swim bladder inflation in zebrafish. *Aquatic Toxicology* 200, 1-12.

Stinckens E, Vergauwen L, Blackwell BR, Anlley GT, Villeneuve DL, Knapen D. 2020. Effect of thyroperoxidase and deiodinase inhibition on anterior swim bladder inflation in the zebrafish. *Environmental Science & Technology*. 54(10):6213-6223.

Vergauwen, L., Cavallin, J.E., Ankley, G.T., Bars, C., Gabriels, I.J., Michiels, E.D.G., Fitzpatrick, K.R., Periz-Stanacev, J., Randolph, E.C., Robinson, S.L., Saari, T.W., Schroeder, A.L., Stinckens, E., Swintek, J., Van Cruchten, S.J., Verbueken, E., Villeneuve, D.L., Knapen, D., 2018. Gene transcription ontogeny of hypothalamic-pituitary-thyroid axis development in early-life stage fathead minnow and zebrafish. *General and Comparative Endocrinology* 266, 87-100.

Visser, T.J., Van Overmeeren, E., Fekkes, D., Docter, R., Hennemann, G. 1979. Inhibition of iodothyronine 5'-deiodinase by thioureylenes: structure-activity relationship. *FEBS Letters*, 103, 2.

Walpita, C.N., Crawford, A.D., Darras, V.M., 2010. Combined antisense knockdown of type 1 and type 2 iodothyronine deiodinases



disrupts embryonic development in zebrafish (*Danio rerio*). Gen Comp Endocrinol 166, 134-141.

Walpita, C.N., Grommen, S.V., Darras, V.M., Van der Geyten, S., 2007. The influence of stress on thyroid hormone production and peripheral deiodination in the Nile tilapia (*Oreochromis niloticus*). Gen Comp Endocrinol 150, 18-25.

## List of Key Events in the AOP

### [Event: 1003: Decreased, Triiodothyronine \(T3\) in serum](#)

**Short Name:** Decreased, Triiodothyronine (T3) in serum

### Key Event Component

Process	Object	Action
abnormal circulating hormone level	3,3',5'-triiodothyronine	decreased

### AOPs Including This Key Event

AOP ID and Name	Event Type
<a href="#">Aop:155 - Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:156 - Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:157 - Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:158 - Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:189 - Type I iodothyronine deiodinase (DIO1) inhibition leading to altered amphibian metamorphosis</a>	KeyEvent
<a href="#">Aop:159 - Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:363 - Thyroperoxidase inhibition leading to increased mortality via altered retinal layer structure</a>	KeyEvent
<a href="#">Aop:364 - Thyroperoxidase inhibition leading to increased mortality via decreased eye size</a>	KeyEvent
<a href="#">Aop:365 - Thyroperoxidase inhibition leading to increased mortality via altered photoreceptor patterning</a>	KeyEvent

## Biological Context

### Level of Biological Organization

Tissue

### Organ term

#### Organ term

serum

## Domain of Applicability

### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	<i>Danio rerio</i>	High	<a href="#">NCBI</a>
fathead minnow	<i>Pimephales promelas</i>	High	<a href="#">NCBI</a>
African clawed frog	<i>Xenopus laevis</i>	High	<a href="#">NCBI</a>

### Life Stage Applicability

Life Stage	Evidence
All life stages	High

### Sex Applicability

**Sex Evidence**

Unspecific Moderate

**Taxonomic:** The overall evidence supporting taxonomic applicability is strong. With few exceptions vertebrate species have circulating T3 and T4 that are bound to transport proteins in blood. Therefore, the current key event is plausibly applicable to vertebrates in general. Clear species differences exist in transport proteins (Yamauchi and Ishihara, 2009). Specifically, the majority of supporting data for TH decreases in serum come from rat studies, and the predominant iodothyronine binding protein in rat serum is transthyretin (TTR). TTR demonstrates a reduced binding affinity for T4 when compared with thyroxine binding globulin (TBG), the predominant serum binding protein for T4 in humans. This difference in serum binding protein affinity for THs is thought to modulate serum half-life for T4; the half-life of T4 in rats is 12-24 hr, whereas the half-life in humans is 5-9 days (Capen, 1997). While these species differences impact hormone half-life, possibly regulatory feedback mechanisms, and quantitative dose-response relationships, measurement of serum THs is still regarded as a measurable key event causatively linked to downstream adverse outcomes.

THs are evolutionarily conserved molecules present in all vertebrate species (Hulbert, 2000; Yen, 2001). Moreover, their crucial role in amphibian and larbean metamorphoses (Manzon and Youson, 1997; Yaoita and Brown, 1990) as well as fish development, embryo-to-larval transition and larval-to-juvenile transition (Thienpont et al., 2011; Liu and Chan, 2002) is well established. Their existence and importance has been also described in many different animal and plant kingdoms (Eales, 1997; Heyland and Moroz, 2005), while their role as environmental messenger via exogenous routes in echinoderms confirms the hypothesis that these molecules are widely distributed among the living organisms (Heyland and Hodin, 2004). However, the role of TH in the different species may differ depending on the expression or function of specific proteins (e.g receptors or enzymes) that are related to TH function, and therefore extrapolation between species should be done with caution.

**Life stage:** Thyroid hormones are essential in all life stages, but decreases of circulating levels are associated with specific developmental events. The earliest life stages of teleost fish rely on maternally transferred THs to regulate certain developmental processes until embryonic TH synthesis is active (Power et al., 2001). As a result, T4 levels are not expected to decrease in response to exposure to inhibitors of TH synthesis during these earliest stages of development. However, T3 levels are expected to decrease upon exposure to deiodinase inhibitors in any life stage, since maternal T4 needs to be activated to T3 by deiodinases similar to embryonically synthesized T4.

**Sex:** The KE is plausibly applicable to both sexes. Thyroid hormones are essential in both sexes and the components of the HPT-axis are identical in both sexes. There can however be sex-dependent differences in the sensitivity to the disruption of thyroid hormone levels and the magnitude of the response. In humans, females appear more susceptible to hypothyroidism compared to males when exposed to certain halogenated chemicals (Hernandez-Mariano et al., 2017; Webster et al., 2014). In adult zebrafish, Liu et al. (2019) showed sex-dependent changes in thyroid hormone levels and mRNA expression of regulatory genes including corticotropin releasing hormone (crh), thyroid stimulating hormone (tsh) and deiodinase 2 after exposure to organophosphate flame retardants. The underlying mechanism of any sex-related differences remains unclear.

**Key Event Description**

There are two biologically active thyroid hormones (THs), triiodothyronine (T3) and thyroxine (T4), and a few less active iodothyronines (rT3, 3,5-T2), which are all derived from the modification of tyrosine molecules (Hulbert, 2000). However, the plasma concentrations of the other iodothyronines are significantly lower than those of T3 and T4. The different iodothyronines are formed by the sequential outer or inner ring monodeiodination of T4 by the deiodinating enzymes, Dio1, Dio2, and Dio3 (Gereben et al., 2008). Deiodinase structure is considered to be unique, as THs are the only molecules in the body that incorporate iodide.

The circulatory system serves as the major transport and delivery system for THs from synthesis in the gland to delivery to tissues. The majority of THs in the blood are bound to transport proteins (Bartalena and Robbins, 1993). In **humans**, the major transport proteins are TBG (thyroxine binding globulin), TTR (transthyretin) and albumin. The percent bound to these proteins in adult humans is about 75, 15 and 10 percent, respectively (Schussler 2000). Unbound (free) hormones are approximately 0.03 and 0.3 percent for T4 and T3, respectively. In serum, it is the free form of the hormone that is active.

There are major species differences in the predominant binding proteins and their affinities for THs (see section below on Taxonomic applicability). However, there is broad agreement that changes in serum concentrations of THs is diagnostic of thyroid disease or chemical-induced disruption of thyroid homeostasis (Zoeller et al., 2007).

It is notable that the changes measured in the TH concentration reflect mainly the changes in the serum transport proteins rather than changes in the thyroid status. These thyroid-binding proteins serve as hormonal store which ensure their even and constant distribution in the different tissues, while they protect the most sensitive ones in the case of severe changes in thyroid availability, like in thyroidectomies (Obregon et al., 1981). Until recently, it was believed that all of the effects of TH were mediated by the binding of T3 to the thyroid nuclear receptors (TRa and TRb), a notion which is now questionable due to the increasing evidence that support the non-genomic action of TH (Davis et al., 2010; Moeller et al., 2006). Many non-nuclear TH binding sites have been identified to date and they usually lead to rapid cellular response in TH-effects (Bassett et al., 2003), but the specific pathways that are activated in this regard need to be elucidated.

The production of THs in the thyroid gland and the circulation levels in the bloodstream are self-controlled by an efficiently regulated

feedback mechanism across the Hypothalamus-Pituitary-Thyroid (HPT) axis. TH levels are regulated, not only in the plasma level, but also in the individual cell level, to maintain homeostasis. This is succeeded by the efficient regulatory mechanism of the thyroid hormone axis which consists of the following: (1) the hypothalamic secretion of the thyrotropin-releasing hormone (TRH), (2) the thyroid-stimulating hormone (TSH) secretion from the anterior pituitary, (3) hormonal transport by the plasma binding proteins, (4) cellular uptake mechanisms in the cell level, (5) intracellular control of TH concentration by the deiodinating mechanism (6) transcriptional function of the nuclear thyroid hormone receptor and (7) in the fetus, the transplacental passage of T4 and T3 (Cheng et al., 2010).

In regards to the brain, the TH concentration involves also an additional level of regulation, namely the hormonal transport through the Blood Brain Barrier (BBB) (Williams, 2008). The TRH and the TSH are actually regulating the production of pro-hormone T4 and in a lesser extent of T3, which is the biologically active TH. The rest of the required amount of T3 is produced by outer ring deiodination of T4 by the deiodinating enzymes D1 and D2 (Bianco et al., 2006), a process which takes place mainly in liver and kidneys but also in other target organs such as in the brain, the anterior pituitary, brown adipose tissue, thyroid and skeletal muscle (Gereben et al., 2008; Larsen, 2009). Both hormones exert their action in almost all tissues of mammals and they are acting intracellularly, and thus the uptake of T3 and T4 by the target cells is a crucial step of the overall pathway. The trans-membrane transport of TH is performed mainly through transporters that differ depending on the cell type (Hennemann et al., 2001; Friesema et al., 2005; Visser et al., 2008). Many transporter proteins have been identified up to date but the monocarboxylate transporters (Mct8, Mct10) and the anion-transporting polypeptide (OATP1c1) show the highest degree of affinity towards TH (Jansen et al., 2005).

T3 and T4 have significant effects on normal development, neural differentiation, growth rate and metabolism (Yen, 2001; Brent, 2012; Williams, 2008), with the most prominent ones to occur during the fetal development and early childhood. The clinical features of hypothyroidism and hyperthyroidism emphasize the pleiotropic effects of these hormones on many different pathways and target organs. The thyroidal actions though are not only restricted to mammals, as their high significance has been identified also for other vertebrates, with the most well-studied to be the amphibian metamorphosis (Furlow and Neff, 2006). The importance of the thyroid-regulated pathways becomes more apparent in iodine deficient areas of the world, where a higher rate of cretinism and growth retardation has been observed and linked to decreased TH levels (Gilbert et al., 2012). Another very common cause of severe hypothyroidism in human is the congenital hypothyroidism, but the manifestation of these effects is only detectable in the lack of adequate treatment and is mainly related to neurological impairment and growth retardation (Glinioer, 2001), emphasizing the role of TH in neurodevelopment in all above cases. In adults, the thyroid-related effects are mainly linked to metabolic activities, such as deficiencies in oxygen consumption, and in the metabolism of the vitamin, proteins, lipids and carbohydrates, but these defects are subtle and reversible (Oetting and Yen, 2007). Blood tests to detect the amount of thyroid hormone (T4) and thyroid stimulating hormone (TSH) are routinely done for newborn babies for the diagnosis of congenital hypothyroidism at the earliest stage possible.

Although the components of the thyroid hormone system as well as thyroid hormone synthesis and action are highly conserved across vertebrates, there are some taxon-specific considerations.

Although the HPT axis is highly conserved, there are some differences between fish and mammals (Blanton and Specker, 2007; Deal and Volkoff, 2020). For example, in **fish**, corticotropin releasing hormone (CRH) often plays a more important role in regulating thyrotropin (TSH) secretion by the pituitary and thus thyroid hormone synthesis compared to TSH-releasing hormone (TRH). TTRs from fish have low sequence identity with human TTR, for example seabream TTR has 54% sequence identity with human TTR but the only amino acid difference within the thyroxine-binding site is the conservative substitution of Ser117 in human TTR to Thr117 in seabream TTR (Santos and Power, 1999; Yamauchi et al., 1999; Eneqvist et al., 2004). In vitro binding experiments showed that TH disrupting chemicals bind with equal or weaker affinity to seabream TTR than to the human TTR with polar TH disrupting chemicals, in particular, showing a more than 500-fold lower affinity for seabream TTR compared to human TTR (Zhang et al., 2018).

Zebrafish and fathead minnows are oviparous fish species in which maternal thyroid hormones are transferred to the eggs and regulate early embryonic developmental processes during external (versus intra-uterine in mammals) development (Power et al., 2001; Campinho et al., 2014; Ruuskanen and Hsu, 2018) until embryonic thyroid hormone synthesis is initiated. Maternal transfer of thyroid hormones, both T4 and T3, to the eggs has been demonstrated in zebrafish (Walpita et al., 2007; Chang et al., 2012) and fathead minnows (Crane et al., 2004; Nelson et al., 2016).

Several studies have reported evidence of T3 decreases after exposure to TPO inhibitors and deiodinase inhibitors in early life stages of zebrafish (Stinckens et al., 2016; Stinckens et al., 2020; Wang et al., 2020) and fathead minnow (Nelson et al., 2016; Cavallin et al., 2017).

### How it is Measured or Detected

T3 and T4 can be measured as free (unbound) or total (bound + unbound). Free hormone are considered more direct indicators of T4 and T3 activities in the body. The majority of T3 and T4 measurements are made using either RIA or ELISA kits. In animal studies, total T3 and T4 are typically measured as the concentrations of free hormone are very low and difficult to detect. Historically, the most widely used method in toxicology is RIA. The method is routinely used in rodent endocrine and toxicity studies. The ELISA method has become more routine in rodent studies. The ELISA method is a commonly used as a human clinical test method.

Recently, analytical determination of iodothyronines (T3, T4, rT3, T2) and their conjugates through methods employing HPLC and mass spectrometry have become more common (DeVito et al., 1999; Miller et al., 2009; Hornung et al., 2015; Nelson et al., 2016;

Stinckens et al., 2016).

Any of these measurements should be evaluated for fit-for-purpose, relationship to the actual endpoint of interest, repeatability, and reproducibility. All three of the methods summarized above would be fit-for-purpose, depending on the number of samples to be evaluated and the associated costs of each method. Both RIA and ELISA measure THs by an indirect methodology, whereas analytical determination is the most direct measurement available. All of these methods, particularly RIA, are repeatable and reproducible.

In fish early life stages most evidence for the ontogeny of thyroid hormone synthesis comes from measurements of whole body thyroid hormone levels and using LC-MS techniques (Hornung et al., 2015) are increasingly used to accurately quantify whole body thyroid hormone levels as a proxy for serum thyroid hormone levels (Nelson et al., 2016; Stinckens et al., 2016; Stinckens et al., 2020).

## References

- Bartalena L, Robbins J. Thyroid hormone transport proteins. *Clin Lab Med*. 1993 Sep;13(3):583-98.
- Bassett JH, Harvey CB, Williams GR. (2003). Mechanisms of thyroid hormone receptor-specific nuclear and extra nuclear actions. *Mol Cell Endocrinol*. 213:1-11.
- Bianco AC, Kim BW. (2006). Deiodinases: implications of the local control of thyroid hormone action. *J Clin Invest*. 116: 2571–2579.
- Blanton ML, Specker JL. 2007. The hypothalamic-pituitary-thyroid (hpt) axis in fish and its role in fish development and reproduction. *Crit Rev Toxicol*. 37(1-2):97-115.
- Brent GA. (2012). Mechanisms of thyroid hormone action. *J Clin Invest*. 122: 3035-3043.
- Campinho MA, Saraiva J, Florindo C, Power DM. 2014. Maternal thyroid hormones are essential for neural development in zebrafish. *Molecular Endocrinology*. 28(7):1136-1149.
- Cavallin JE, Ankley GT, Blackwell BR, Blanksma CA, Fay KA, Jensen KM, Kahl MD, Knapen D, Kosian PA, Poole ST et al. 2017. Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry*. 36(11):2942-2952.
- Chang J, Wang M, Gui W, Zhao Y, Yu L, Zhu G. 2012. Changes in thyroid hormone levels during zebrafish development. *Zoological Science*. 29(3):181-184.
- Cheng SY, Leonard JL, Davis PJ. (2010). Molecular aspects of thyroid hormone actions. *Endocr Rev*. 31:139–170.
- Crane HM, Pickford DB, Hutchinson TH, Brown JA. 2004. Developmental changes of thyroid hormones in the fathead minnow, *pimephales promelas*. *General and Comparative Endocrinology*. 139(1):55-60.
- Davis PJ, Zhou M, Davis FB, Lansing L, Mousa SA, Lin HY. (2010). Mini-review: Cell surface receptor for thyroid hormone and nongenomic regulation of ion fluxes in excitable cells. *Physiol Behav*. 99:237–239.
- Deal CK, Volkoff H. 2020. The role of the thyroid axis in fish. *Frontiers in Endocrinology*. 11.
- DeVito M, Biegel L, Brouwer A, Brown S, Brucker-Davis F, Cheek AO, Christensen R, Colborn T, Cooke P, Crissman J, Crofton K, Doerge D, Gray E, Hauser P, Hurley P, Kohn M, Lazar J, McMaster S, McClain M, McConnell E, \*Meier C, Miller R, Tietge J, Tyl R. (1999). Screening methods for thyroid hormone disruptors. *Environ Health Perspect*. 107:407-415.
- Eales JG. (1997). Iodine metabolism and thyroid related functions in organisms lacking thyroid follicles: Are thyroid hormones also vitamins? *Proc Soc Exp Biol Med*. 214:302-317.
- Eneqvist T, Lundberg E, Karlsson A, Huang SH, Santos CRA, Power DM, Sauer-Eriksson AE. 2004. High resolution crystal structures of piscine transthyretin reveal different binding modes for triiodothyronine and thyroxine. *Journal of Biological Chemistry*. 279(25):26411-26416.
- Friesema EC, Jansen J, Milici C, Visser TJ. (2005). Thyroid hormone transporters. *Vitam Horm*. 70: 137–167.
- Furlow JD, Neff ES. (2006). A developmental switch induced by thyroid hormone: *Xenopus laevis* metamorphosis. *Trends Endocrinol Metab*. 17:40–47.
- Gereben B, Zavacki AM, Ribich S, Kim BW, Huang SA, Simonides WS, Zeöld A, Bianco AC. (2008). Cellular and molecular basis of deiodinase-regulated thyroid hormone signalling. *Endocr Rev*. 29:898–938.
- Gilbert ME, Rovet J, Chen Z, Koibuchi N. (2012). Developmental thyroid hormone disruption: prevalence, environmental contaminants and neurodevelopmental consequences. *Neurotoxicology*. 33: 842-852.
- Glinioer D. (2001). Potential consequences of maternal hypothyroidism on the offspring: evidence and implications. *Horm Res*. 55:109-114.
- Hennemann G, Docter R, Friesema EC, de Jong M, Krenning EP, Visser TJ. (2001). Plasma membrane transport of thyroid

hormones and its role in thyroid hormone metabolism and bioavailability. *Endocr Rev.* 22:451-476.

Hernandez-Mariano JA, Torres-Sanchez L, Bassol-Mayagoitia S, Escamilla-Nunez M, Cebrian ME, Villeda-Gutierrez EA, Lopez-Rodriguez G, Felix-Arellano EE, Blanco-Munoz J. 2017. Effect of exposure to p,p'-dDE during the first half of pregnancy in the maternal thyroid profile of female residents in a Mexican floriculture area. *Environmental Research.* 156:597-604.

Heyland A, Hodin J. (2004). Heterochronic developmental shift caused by thyroid hormone in larval sand dollars and its implications for phenotypic plasticity and the evolution of non-feeding development. *Evolution.* 58: 524-538.

Heyland A, Moroz LL. (2005). Cross-kingdom hormonal signaling: an insight from thyroid hormone functions in marine larvae. *J Exp Biol.* 208:4355-4361.

Hornung, M.W., Kosian, P.A., Haselman, J.T., Korte, J.J., Challis, K., Macherla, C., Nevalainen, E., Degitz, S.J., 2015. In Vitro, Ex Vivo, and In Vivo Determination of Thyroid Hormone Modulating Activity of Benzothiazoles. *Toxicological Sciences* 146, 254-264.

Hulbert A J. (2000). Thyroid hormones and their effects: A new perspective. *Biol Rev.* 75: 519-631.

Jansen J, Friesema EC, Milici C, Visser TJ. (2005). Thyroid hormone transporters in health and disease. *Thyroid.* 15: 757-768.

Larsen PR. (2009). Type 2 iodothyronine deiodinase in human skeletal muscle: new insights into its physiological role and regulation. *J Clin Endocrinol Metab.* 94:1893-1895.

Liu XS, Cai Y, Wang Y, Xu SH, Ji K, Choi K. 2019. Effects of tris(1,3-dichloro-2-propyl) phosphate (tdcpp) and triphenyl phosphate (tpp) on sex-dependent alterations of thyroid hormones in adult zebrafish. *Ecotoxicology and Environmental Safety.* 170:25-32.

Liu YW, Chan WK. 2002. Thyroid hormones are important for embryonic to larval transitory phase in zebrafish. *Differentiation.* 70(1):36-45.

Manzon RG, Youson JH. (1997). The effects of exogenous thyroxine (T4) or triiodothyronine (T3), in the presence and absence of potassium perchlorate, on the incidence of metamorphosis and on serum T4 and T3 concentrations in larval sea lampreys (*Petromyzon marinus* L.). *Gen Comp Endocrinol.* 106:211-220.

Miller MD, Crofton KM, Rice DC, Zoeller RT. (2009). Thyroid-disrupting chemicals: interpreting upstream biomarkers of adverse outcomes. *Environ Health Perspect.* 117:1033-1041.

Moeller LC, Dumitrescu AM, Seo H, Refetoff S. (2006). Thyroid hormone mediated changes in gene expression can be initiated by cytosolic action of the thyroid hormone receptor  $\beta$  through the phosphatidylinositol 3-kinase pathway. *NRS.* 4:1-4. Nelson, K., Schroeder, A., Ankley, G., Blackwell, B., Blanksma, C., Degitz, S., Flynn, K., Jensen, K., Johnson, R., Kahl, M., Knapen, D., Kosian, P., Misk, R., Randolph, E., Saari, T., Stinckens, E., Vergauwen, L., Villeneuve, D., 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part I: Fathead minnow. *Aquatic Toxicology* 173, 192-203. Obregon MJ, Mallol J, Escobar del Rey F, Morreale de Escobar G. (1981). Presence of L-thyroxine and 3,5,3-triiodo-L-thyronine in tissues from thyroidectomized rats. *Endocrinology* 109:908-913.

Nelson K, Schroeder A, Ankley G, Blackwell B, Blanksma C, Degitz S, Flynn K, Jensen K, Johnson R, Kahl M et al. 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part I: Fathead minnow. *Aquatic Toxicology.* 173:192-203.

Oetting A, Yen PM. (2007). New insights into thyroid hormone action. *Best Pract Res Clin Endocrinol Metab.* 21:193–208.

Power DM, Llewellyn L, Faustino M, Nowell MA, Bjornsson BT, Einarsdottir IE, Canario AV, Sweeney GE. 2001. Thyroid hormones in growth and development of fish. *Comp Biochem Physiol C Toxicol Pharmacol.* 130(4):447-459.

Ruuskanen S, Hsu BY. 2018. Maternal thyroid hormones: An unexplored mechanism underlying maternal effects in an ecological framework. *Physiological and Biochemical Zoology.* 91(3):904-916.

Santos CRA, Power DM. 1999. Identification of transthyretin in fish (*Sparus aurata*): Cdna cloning and characterisation. *Endocrinology.* 140(5):2430-2433.

Schussler, G.C. (2000). The thyroxine-binding proteins. *Thyroid* 10:141–149.

Stinckens E, Vergauwen L, Blackwell BR, Anlley GT, Villeneuve DL, Knapen D. 2020. Effect of thyroperoxidase and deiodinase inhibition on anterior swim bladder inflation in the zebrafish. *Environmental Science & Technology.* 54(10):6213-6223.

Stinckens, E., Vergauwen, L., Schroeder, A., Maho, W., Blackwell, B., Witters, H., Blust, R., Ankley, G., Covaci, A., Villeneuve, D., Knapen, D., 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part II: Zebrafish. *Aquatic Toxicology* 173, 204-217.

Thienpont B, Tingaud-Sequeira A, Prats E, Barata C, Babin PJ, Raldua D. 2011. Zebrafish eleutheroembryos provide a suitable vertebrate model for screening chemicals that impair thyroid hormone synthesis. *Environmental Science & Technology.* 45(17):7525-7532

Visser WE, Friesema EC, Jansen J, Visser TJ. (2008). Thyroid hormone transport in and out of cells. *Trends Endocrinol Metab.* 19:50-56.

Walpita CN, Van der Geyten S, Rurangwa E, Darras VM. 2007. The effect of 3,5,3'-triiodothyronine supplementation on zebrafish (danio rerio) embryonic development and expression of iodothyronine deiodinases and thyroid hormone receptors. *Gen Comp Endocrinol.* 152(2-3):206-214.

Wang JX, Shi GH, Yao JZ, Sheng N, Cui RN, Su ZB, Guo Y, Dai JY. 2020. Perfluoropolyether carboxylic acids (novel alternatives to pfoa) impair zebrafish posterior swim bladder development via thyroid hormone disruption. *Environment International.* 134.

Webster GM, Venners SA, Mattman A, Martin JW. 2014. Associations between perfluoroalkyl acids (pfass) and maternal thyroid hormones in early pregnancy: A population-based cohort study. *Environmental Research.* 133:338-347.

Williams GR. (2008). Neurodevelopmental and neurophysiological actions of thyroid hormone. *J Neuroendocrinol.* 20:784–794.

Yamauchi K, Nakajima J, Hayashi H, Hara A. 1999. Purification and characterization of thyroid-hormone-binding protein from masu salmon serum - a homolog of higher-vertebrate transthyretin. *European Journal of Biochemistry.* 265(3):944-949.

Yamauchi K1, Ishihara A. Evolutionary changes to transthyretin: developmentally regulated and tissue-specific gene expression. *FEBS J.* 2009 Oct;276(19):5357-66.

Yaoita Y, Brown DD. (1990). A correlation of thyroid hormone receptor gene expression with amphibian metamorphosis. *Genes Dev.* 4:1917-1924.

Yen PM. (2001). Physiological and molecular basis of thyroid hormone action. *Physiol Rev.* 81:1097-1142.

Zhang J, Grundstrom C, Brannstrom K, Iakovleva I, Lindberg M, Olofsson A, Andersson PL, Sauer-Eriksson AE. 2018. Interspecies variation between fish and human transthyretins in their binding of thyroid-disrupting chemicals. *Environmental Science & Technology.* 52(20):11865-11874.

Zoeller RT, Tan SW, Tyl RW. General background on the hypothalamic-pituitary-thyroid (HPT) axis. *Crit Rev Toxicol.* 2007 Jan-Feb;37(1-2):11-53

### [Event: 1007: Reduced, Anterior swim bladder inflation](#)

**Short Name: Reduced, Anterior swim bladder inflation**

### Key Event Component

Process	Object	Action
swim bladder inflation	anterior chamber swim bladder	decreased

### AOPs Including This Key Event

AOP ID and Name	Event Type
<a href="#">Aop:156 - Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:158 - Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:159 - Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent

### Biological Context

#### Level of Biological Organization

Organ

#### Organ term

##### Organ term

swim bladder

#### Domain of Applicability

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	High	<a href="#">NCBI</a>
fathead minnow	Pimephales promelas	High	<a href="#">NCBI</a>
<b>Life Stage Applicability</b>			
<b>Life Stage Evidence</b>			
Larvae	High		
<b>Sex Applicability</b>			
<b>Sex Evidence</b>			
Unspecific	Moderate		
<p><b>Taxonomic:</b> Teleost fish can be divided in two groups according to swim bladder morphology: physoclistous (e.g., yellow perch, sea bass, striped bass) and physostomous (e.g., zebrafish and fathead minnow). Physostomous fish retain a duct between the digestive tract and the swim bladder during adulthood allowing them to gulp air at the surface to fill the swim bladder. In contrast, in physoclistous fish, once initial inflation by gulping atmospheric air at the water surface has occurred, the swim bladder is closed off from the digestive tract and swim bladder volume is regulated by gas secretion into the swim bladder (Woolley and Qin, 2010). The evidence for impaired inflation of the anterior chamber of the swim bladder currently comes from work on zebrafish and fathead minnow (Stinckens et al., 2016; Nelson et al., 2016; Cavallin et al., 2017; Godfrey et al., 2017; Stinckens et al., 2020). While zebrafish and fathead minnows are physostomous fish with a two-chambered swim bladder, the Japanese rice fish (<i>Oryzias latipes</i>) is a physoclistous fish with a single chambered swim bladder that inflates during early development. The key event 'reduced anterior chamber inflation' is not applicable to such fish species. Therefore, the current key event is plausibly applicable to physostomous fish in general.</p>			
<p><b>Life stage:</b> The anterior chamber inflates during a specific developmental time frame. In zebrafish, the anterior chamber inflates around 21 days post fertilization (dpf) which is during the larval stage. In the fathead minnow, the anterior chamber inflates around 14 dpf, also during the larval stage. Therefore this KE is only applicable to the larval life stage.</p>			
<p><b>Sex:</b> This KE/KER plausibly applicable to both sexes. Sex differences are not often investigated in tests using early life stages of fish. In Medaka, sex can be morphologically distinguished as soon as 10 days post fertilization. Females appear more susceptible to thyroid-induced swim bladder dysfunction compared with males (Godfrey et al., 2019). For zebrafish and fathead minnow, it is currently unclear whether sex-related differences are important in determining the magnitude of the changes in this KE/KER. Different fish species have different sex determination and differentiation strategies. Zebrafish do not have identifiable heteromorphic sex chromosomes and sex is determined by multiple genes and influenced by the environment (Nagabhushana and Mishra, 2016). Zebrafish are undifferentiated gonochorists since both sexes initially develop an immature ovary (Maack and Segner, 2003). Immature ovary development progresses until approximately the onset of the third week. Later, in female fish immature ovaries continue to develop further, while male fish undergo transformation of ovaries into testes. Final transformation into testes varies among male individuals, however finishes usually around 6 weeks post fertilization. Since the anterior chamber inflates around 21 days post fertilization in zebrafish, sex differences are expected to play a minor role. Fathead minnow gonad differentiation also occurs during larval development. Fathead minnows utilize a XY sex determination strategy and markers can be used to genotype sex in life stages where the sex is not yet clearly defined morphologically (Olmstead et al., 2011). Ovarian differentiation starts at 10 dph followed by rapid development (Van Aerle et al., 2004). At 25 dph germ cells of all stages up to the primary oocytes stage were present and at 120 dph, vitellogenic oocytes were present. The germ cells (spermatogonia) of the developing testes only entered meiosis around 90–120 dph. Mature testes with spermatozoa are present around 150 dph. Since the anterior chamber inflates around 14 days post fertilization (9 dph) in fathead minnows, sex differences are expected to play a minor role in the current AOP.</p>			
<b>Key Event Description</b>			
<p>The swim bladder of bony fish is evolutionary homologous to the lung (Zheng et al., 2011). The teleost swim bladder is a gas-filled structure that consists of two chambers, the posterior and anterior chamber. In zebrafish, the posterior chamber inflates around 96 h post fertilization (hpf) which is 2 days post hatch, and the anterior chamber inflates around 21 dpf. In fathead minnow, the posterior and anterior chamber inflate around 6 and 14 dpf respectively. Inflation of the anterior swim bladder chamber is part of the larval-to-juvenile transition in fish, together with the development of adult fins and fin rays, ossification of the axial skeleton, formation of an adult pigmentation pattern, scale formation, maturation and remodeling of organs including the lateral line, nervous system, gut and kidneys (McMenamin and Parichy, 2013).</p>			
<p>The anterior chamber is formed by evagination from the cranial end of the posterior chamber (Robertson et al., 2007). Dumbarton et al. (2010) showed that the anterior chamber of zebrafish has particularly closely packed and highly organized bundles of muscle fibres, suggesting that contraction of these muscles would reduce swim bladder volume. While it had previously been suggested that the posterior chamber had a more important role as a hydrostatic organ, this implies high importance of the anterior chamber for buoyancy. The anterior chamber has an additional role in hearing (Bang et al., 2002). Weberian ossicles (the Weberian apparatus) connect the anterior chamber to the inner ear resulting in an amplification of sound waves. Reduced inflation of the anterior chamber may manifest itself as either a complete failure to inflate the chamber or reduced size of the chamber. Reduced size is often associated with a deviating morphology.</p>			

## How it is Measured or Detected

In several fish species, inflation of the anterior chamber can be observed using a stereomicroscope because the larvae are still transparent during the larval stage. This is for example true for zebrafish and fathead minnow. Anterior chamber size can then be measured based on photographs with a calibrator.

## References

- Bang, P.I., Yelick, P.C., Malicko, J.J., Sewell, W.F. 2002. High-throughput behavioral screening method for detecting auditory response defects in zebrafish. *Journal of Neuroscience Methods*. 118, 177-187.
- Cavallin, J.E., Ankley, G.T., Blackwell, B.R., Blanksma, C.A., Fay, K.A., Jensen, K.M., Kahl, M.D., Knapen, D., Kosian, P.A., Poole, S.T., Randolph, E.C., Schroeder, A.L., Vergauwen, L., Villeneuve, D.L., 2017. Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry* 36, 2942-2952.
- Dumbarton, T.C., Stoyek, M., Croll, R.P., Smith, F.M., 2010. Adrenergic control of swimbladder deflation in the zebrafish (*Danio rerio*). *J. Exp. Biol.* 213,2536–2546, <http://dx.doi.org/10.1242/jeb.039792>.
- Godfrey A, Hooser B, Abdelmoneim A, Sepulveda MS. 2019. Sex-specific endocrine-disrupting effects of three halogenated chemicals in japanese medaka. *Journal of Applied Toxicology*. 39(8):1215-1223.
- Godfrey, A., Hooser, B., Abdelmoneim, A., Horzmann, K.A., Freemanc, J.L., Sepulveda, M.S., 2017. Thyroid disrupting effects of halogenated and next generation chemicals on the swim bladder development of zebrafish. *Aquatic Toxicology* 193, 228-235.
- McMenamin, S.K., Parichy, D.M., 2013. Metamorphosis in Teleosts. *Animal Metamorphosis* 103, 127-165.
- Nagabhushana A, Mishra RK. 2016. Finding clues to the riddle of sex determination in zebrafish. *Journal of Biosciences*. 41(1):145-155.
- Nelson KR, Schroeder AL, Ankley GT, Blackwell BR, Blanksma C, Degitz SJ, Flynn KM, Jensen KM, Johnson RD, Kahl MD, Knapen D, Kosian PA, Misk RY, Randolph EC, Saari T, Stinckens E, Vergauwen L, Villeneuve DL. 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole – Part I: fathead minnow. *Aquatic Toxicology* 173: 192-203.
- Olmstead AW, Villeneuve DL, Ankley GT, Cavallin JE, Lindberg-Livingston A, Wehmas LC, Degitz SJ. 2011. A method for the determination of genetic sex in the fathead minnow, *pimephales promelas*, to support testing of endocrine-active chemicals. *Environmental Science & Technology*. 45(7):3090-3095.
- Roberston, G.N., McGee, C.A.S., Dumbarton, T.C., Croll, R.P., Smith, F.M., 2007. Development of the swim bladder and its innervation in the zebrafish, *Danio rerio*. *J. Morphol.* 268, 967–985, <http://dx.doi.org/10.1002/jmor>.
- Stinckens, E., Vergauwen, L., Blackwell, B.R., Anley, G.T., Villeneuve, D.L., Knapen, D., 2020. Effect of Thyroperoxidase and Deiodinase Inhibition on Anterior Swim Bladder Inflation in the Zebrafish. *Environmental Science & Technology* 54, 6213-6223.
- Stinckens, E., Vergauwen, L., Schroeder, A., Maho, W., Blackwell, B., Witters, H., Blust, R., Ankley, G., Covaci, A., Villeneuve, D., Knapen, D., 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part II: Zebrafish. *Aquatic Toxicology* 173, 204-217.
- van Aerle R, Runnalls TJ, Tyler CR. 2004. Ontogeny of gonadal sex development relative to growth in fathead minnow. *Journal of Fish Biology*. 64(2):355-369.
- Woolley, L.D., Qin, J.G., 2010. Swimbladder inflation and its implication to the culture of marine finfish larvae. *Reviews in Aquaculture* 2, 181-190.
- Zheng, W., Wang, Z., Collins, J.E., Andrews, R.M., Stemple, D., Gong, Z. 2011. Comparative transcriptome analyses indicate molecular homology of zebrafish swim bladder and mammalian lung. *PLoS One* 6, <http://dx.doi.org/10.1371/>

## Event: 1005: Reduced, Swimming performance

### Short Name: Reduced, Swimming performance

### Key Event Component

Process	Object	Action
aquatic locomotion		decreased

### AOPs Including This Key Event



AOP ID and Name	Event Type
<a href="#">Aop:155 - Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:156 - Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:157 - Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:158 - Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:159 - Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	KeyEvent
<a href="#">Aop:242 - Inhibition of lysyl oxidase leading to enhanced chronic fish toxicity</a>	KeyEvent
<a href="#">Aop:334 - Glucocorticoid Receptor Agonism Leading to Impaired Fin Regeneration</a>	KeyEvent

## Biological Context

### Level of Biological Organization

Individual

## Domain of Applicability

### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	High	<a href="#">NCBI</a>
teleost fish	teleost fish	High	<a href="#">NCBI</a>
fathead minnow	Pimephales promelas	High	<a href="#">NCBI</a>

### Life Stage Applicability

#### Life Stage Evidence

Larvae	Moderate
Juvenile	Moderate
Adult	Moderate

### Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Importance of swimming performance for natural behaviour is generally applicable to fish and the other taxa that rely on swimming to support vital behaviours.

**Life stage:** Importance of swimming performance for natural behaviour is generally applicable across all free-swimming life stages, i.e., post-embryonic life stages.

**Sex:** Importance of swimming performance for natural behaviour is generally applicable across sexes.

## Key Event Description

Adequate swimming performance in fish is essential for behaviour such as foraging, predator avoidance and reproduction.

## How it is Measured or Detected

For fish larvae, automated observation and tracking systems are commercially available and increasingly used for measuring swimming performance including distance travelled, duration of movements, swimming speed, etc. This kind of measurements is often included in publications describing effects of chemicals in zebrafish larvae (Hagenaars et al., 2014; Stinckens et al., 2016; Vergauwen et al., 2015).

For juvenile and adult fish, measurements of swim performance vary. However, in some circumstances, swim tunnels have been used to measure various data (Fu et al., 2013).

Little and Finger (1990) discussed swimming behavior as an indicator of sublethal toxicity in fish.

## References

Fu C, Cao ZD, Fu SJ. 2013. The effects of caudal fin loss and regeneration on the swimming performance of three cyprinid fish species with different swimming capacities. The Journal of Experimental Biology 216:3164-3174. doi:10.1242/jeb.084244

Hagenaars, A., Stinckens, E., Vergauwen, L., Bervoets, L., Knapen, D., 2014. PFOS affects posterior swim bladder chamber inflation and swimming performance of zebrafish larvae. Aquat. Toxicol. 157, 225–235.

Little EE, Finger SE. 1990. Swimming behavior as an indicator of sublethal toxicity in fish. Environmental Toxicology and Chemistry. 9(1):13-19.

Stinckens, E., Vergauwen, L., Schroeder, A.L., Maho, W., Blackwell, B., Witter, H., Blust, R., Ankley, G.T., Covaci, A., Villeneuve, D.L., Knapen, D., 2016. Disruption of thyroid hormone balance after 2-mercaptobenzothiazole exposure causes swim bladder inflation impairment—part II: zebrafish. Aquat. Toxicol. 173:204-17.

Vergauwen, Lucia; Nørgaard Schmidt, Stine; Maho, Walid; Stinckens, Evelyn; Hagenaars, An; Blust, Ronny; Mayer, Philipp; Covaci, Adrian; Knapen, Dries. 2014. A high throughput passive dosing format for the Fish Embryo Acute Toxicity test. Chemosphere. 139: 9-17.

## List of Adverse Outcomes in this AOP

### [Event: 351: Increased Mortality](#)

#### Short Name: Increased Mortality

#### Key Event Component

Process	Object	Action
mortality		increased

#### AOPs Including This Key Event

AOP ID and Name	Event Type
<a href="#">Aop:16 - Acetylcholinesterase inhibition leading to acute mortality</a>	AdverseOutcome
<a href="#">Aop:96 - Axonal sodium channel modulation leading to acute mortality</a>	AdverseOutcome
<a href="#">Aop:104 - Altered ion channel activity leading impaired heart function</a>	AdverseOutcome
<a href="#">Aop:113 - Glutamate-gated chloride channel activation leading to acute mortality</a>	AdverseOutcome
<a href="#">Aop:160 - Ionotropic gamma-aminobutyric acid receptor activation mediated neurotransmission inhibition leading to mortality</a>	AdverseOutcome
<a href="#">Aop:161 - Glutamate-gated chloride channel activation leading to neurotransmission inhibition associated mortality</a>	AdverseOutcome
<a href="#">Aop:138 - Organic anion transporter (OAT1) inhibition leading to renal failure and mortality</a>	AdverseOutcome
<a href="#">Aop:177 - Cyclooxygenase 1 (COX1) inhibition leading to renal failure and mortality</a>	AdverseOutcome
<a href="#">Aop:186 - unknown MIE leading to renal failure and mortality</a>	AdverseOutcome
<a href="#">Aop:312 - Acetylcholinesterase Inhibition leading to Acute Mortality via Impaired Coordination &amp; Movement</a>	AdverseOutcome
<a href="#">Aop:320 - Binding of viral S-glycoprotein to ACE2 receptor leading to acute respiratory distress associated mortality</a>	AdverseOutcome
<a href="#">Aop:155 - Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	AdverseOutcome
<a href="#">Aop:156 - Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	AdverseOutcome
<a href="#">Aop:157 - Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	AdverseOutcome
<a href="#">Aop:158 - Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	AdverseOutcome
<a href="#">Aop:159 - Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	AdverseOutcome
<a href="#">Aop:363 - Thyroperoxidase inhibition leading to increased mortality via altered retinal layer structure</a>	AdverseOutcome

AOP ID and Name	Event Type
<a href="#">Aop:377 - Dysregulated prolonged Toll Like Receptor 9 (TLR9) activation leading to Acute Respiratory Distress Syndrome (ARDS) and Multiple Organ Dysfunction (MOD)</a>	AdverseOutcome
<a href="#">Aop:364 - Thyroperoxidase inhibition leading to increased mortality via decreased eye size</a>	AdverseOutcome
<a href="#">Aop:365 - Thyroperoxidase inhibition leading to increased mortality via altered photoreceptor patterning</a>	AdverseOutcome
<a href="#">Aop:399 - Inhibition of Fyna leading to increased mortality via decreased eye size (Microphthalmos)</a>	AdverseOutcome
<a href="#">Aop:413 - Oxidation and antagonism of reduced glutathione leading to mortality via acute renal failure</a>	AdverseOutcome
<a href="#">Aop:410 - Repression of Gbx2 expression leads to defects in developing inner ear and consequently to increased mortality</a>	KeyEvent

## Biological Context

### Level of Biological Organization

Population

## Domain of Applicability

### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
all species	all species	High	<a href="#">NCBI</a>

### Life Stage Applicability

Life Stage	Evidence
All life stages	High

### Sex Applicability

Sex	Evidence
Unspecific	Moderate

All living things are susceptible to mortality.

## Key Event Description

Increased 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.

## How it is Measured or Detected

Mortality of animals is generally observed as cessation of the heart beat, breathing (gill or lung movement) and locomotory movements. Mortality is typically measured by observation. Depending on the size of the organism, instruments such as microscopes may be used. The reported metric is mostly the mortality rate: the number of deaths in a given area or period, or from a particular cause.

Depending on the species and the study setup, mortality can be measured:

- in the lab by recording mortality during exposure experiments
- in dedicated setups simulating a realistic situation such as mesocosms or drainable ponds for aquatic species
- in the field, for example by determining age structure after one capture, or by capture-mark-recapture efforts. The latter is a method commonly used in ecology to estimate an animal population's size where it is impractical to count every individual.

## Regulatory Significance of the AO

Increased mortality is one of the most common regulatory assessment endpoints, along with reduced growth and reduced reproduction.

### [Event: 360: Decrease, Population trajectory](#)

**Short Name:** Decrease, Population trajectory

## Key Event Component

Process	Object	Action
population growth rate	population of organisms	decreased
<b>AOPs Including This Key Event</b>		
AOP ID and Name		Event Type
<a href="#">Aop:23 - Androgen receptor agonism leading to reproductive dysfunction (in repeat-spawning fish)</a>		AdverseOutcome
<a href="#">Aop:25 - Aromatase inhibition leading to reproductive dysfunction</a>		AdverseOutcome
<a href="#">Aop:29 - Estrogen receptor agonism leading to reproductive dysfunction</a>		AdverseOutcome
<a href="#">Aop:30 - Estrogen receptor antagonism leading to reproductive dysfunction</a>		AdverseOutcome
<a href="#">Aop:100 - Cyclooxygenase inhibition leading to reproductive dysfunction via inhibition of female spawning behavior</a>		AdverseOutcome
<a href="#">Aop:122 - Prolyl hydroxylase inhibition leading to reproductive dysfunction via increased HIF1 heterodimer formation</a>		AdverseOutcome
<a href="#">Aop:123 - Unknown MIE leading to reproductive dysfunction via increased HIF-1alpha transcription</a>		AdverseOutcome
<a href="#">Aop:155 - Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>		AdverseOutcome
<a href="#">Aop:156 - Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>		AdverseOutcome
<a href="#">Aop:157 - Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>		AdverseOutcome
<a href="#">Aop:158 - Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>		AdverseOutcome
<a href="#">Aop:159 - Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>		AdverseOutcome
<a href="#">Aop:101 - Cyclooxygenase inhibition leading to reproductive dysfunction via inhibition of pheromone release</a>		AdverseOutcome
<a href="#">Aop:102 - Cyclooxygenase inhibition leading to reproductive dysfunction via interference with meiotic prophase I /metaphase I transition</a>		AdverseOutcome
<a href="#">Aop:63 - Cyclooxygenase inhibition leading to reproductive dysfunction</a>		AdverseOutcome
<a href="#">Aop:103 - Cyclooxygenase inhibition leading to reproductive dysfunction via interference with spindle assembly checkpoint</a>		AdverseOutcome
<a href="#">Aop:292 - Inhibition of tyrosinase leads to decreased population in fish</a>		AdverseOutcome
<a href="#">Aop:310 - Embryonic Activation of the AHR leading to Reproductive failure, via epigenetic down-regulation of GnRHR</a>		AdverseOutcome
<a href="#">Aop:16 - Acetylcholinesterase inhibition leading to acute mortality</a>		AdverseOutcome
<a href="#">Aop:312 - Acetylcholinesterase Inhibition leading to Acute Mortality via Impaired Coordination &amp; Movement</a>		AdverseOutcome
<a href="#">Aop:334 - Glucocorticoid Receptor Agonism Leading to Impaired Fin Regeneration</a>		AdverseOutcome
<a href="#">Aop:336 - DNA methyltransferase inhibition leading to population decline (1)</a>		AdverseOutcome
<a href="#">Aop:337 - DNA methyltransferase inhibition leading to population decline (2)</a>		AdverseOutcome
<a href="#">Aop:338 - DNA methyltransferase inhibition leading to population decline (3)</a>		AdverseOutcome
<a href="#">Aop:339 - DNA methyltransferase inhibition leading to population decline (4)</a>		AdverseOutcome
<a href="#">Aop:340 - DNA methyltransferase inhibition leading to transgenerational effects (1)</a>		AdverseOutcome
<a href="#">Aop:341 - DNA methyltransferase inhibition leading to transgenerational effects (2)</a>		AdverseOutcome
<a href="#">Aop:289 - Inhibition of 5α-reductase leading to impaired fecundity in female fish</a>		AdverseOutcome
<a href="#">Aop:297 - Inhibition of retinaldehyde dehydrogenase leads to population decline</a>		AdverseOutcome
<a href="#">Aop:346 - Aromatase inhibition leads to male-biased sex ratio via impacts on gonad differentiation</a>		AdverseOutcome
<a href="#">Aop:299 - Excessive reactive oxygen species production leading to population decline via reduced fatty acid beta-oxidation</a>		AdverseOutcome
<a href="#">Aop:311 - Excessive reactive oxygen species production leading to population decline via mitochondrial dysfunction</a>		AdverseOutcome
<a href="#">Aop:216 - Excessive reactive oxygen species production leading to population decline via follicular atresia</a>		AdverseOutcome

AOP ID and Name	Event Type
<a href="#">Aop:238 - Excessive reactive oxygen species production leading to population decline via lipid peroxidation</a>	AdverseOutcome
<a href="#">Aop:326 - Thermal stress leading to population decline (3)</a>	AdverseOutcome
<a href="#">Aop:325 - Thermal stress leading to population decline (2)</a>	AdverseOutcome
<a href="#">Aop:324 - Thermal stress leading to population decline (1)</a>	AdverseOutcome
<a href="#">Aop:363 - Thyroperoxidase inhibition leading to increased mortality via altered retinal layer structure</a>	AdverseOutcome
<a href="#">Aop:349 - Inhibition of 11<math>\beta</math>-hydroxylase leading to decreased population trajectory</a>	AdverseOutcome
<a href="#">Aop:348 - Inhibition of 11<math>\beta</math>-Hydroxysteroid Dehydrogenase leading to decreased population trajectory</a>	AdverseOutcome
<a href="#">Aop:376 - Androgen receptor agonism leading to male-biased sex ratio</a>	AdverseOutcome
<a href="#">Aop:386 - Increased reactive oxygen species production leading to population decline via inhibition of photosynthesis</a>	AdverseOutcome
<a href="#">Aop:387 - Increased reactive oxygen species production leading to population decline via mitochondrial dysfunction</a>	AdverseOutcome
<a href="#">Aop:388 - DNA damage leading to population decline via programmed cell death</a>	AdverseOutcome
<a href="#">Aop:389 - Oxygen-evolving complex damage leading to population decline via inhibition of photosynthesis</a>	AdverseOutcome
<a href="#">Aop:364 - Thyroperoxidase inhibition leading to increased mortality via decreased eye size</a>	AdverseOutcome
<a href="#">Aop:365 - Thyroperoxidase inhibition leading to increased mortality via altered photoreceptor patterning</a>	AdverseOutcome
<a href="#">Aop:399 - Inhibition of Fyna leading to increased mortality via decreased eye size (Microphthalmos)</a>	AdverseOutcome

## Biological Context

### Level of Biological Organization

Population

## Domain of Applicability

### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
all species	all species	High	<a href="#">NCBI</a>

### Life Stage Applicability

Life Stage	Evidence
All life stages	Not Specified

### Sex Applicability

Sex	Evidence
Unspecific	Not Specified

Consideration of population size and changes in population size over time is potentially relevant to all living organisms.

## Key Event Description

Population ecology is the study of the sizes (and to some extent also the distribution) of plant and animal populations and of the processes, mainly biological in nature, that determine these sizes. As such, it provides an integrated measure of events occurring at lower levels of biological organization (biochemical, organismal, etc.). The population size in turn determines community and ecosystem structure. For fish, maintenance of sustainable fish and wildlife populations (i.e., adequate to ensure long-term delivery of valued ecosystem services) is an accepted regulatory goal upon which risk assessments and risk management decisions are based.

## How it is Measured or Detected

Population trajectories, either hypothetical or site specific, can be estimated via population modeling based on measurements of vital rates or reasonable surrogates measured in laboratory studies. As an example, Miller and Ankley 2004 used measures of cumulative fecundity from laboratory studies with repeat spawning fish species to predict population-level consequences of

continuous exposure.

## Regulatory Significance of the AO

Maintenance of sustainable fish and wildlife populations (i.e., adequate to ensure long-term delivery of valued ecosystem services) is a widely accepted regulatory goal upon which risk assessments and risk management decisions are based.

## References

- Miller DH, Ankley GT. 2004. Modeling impacts on populations: fathead minnow (*Pimephales promelas*) exposure to the endocrine disruptor 17 $\beta$ -trenbolone as a case study. *Ecotoxicology and Environmental Safety* 59: 1-9.

## Appendix 2

### List of Key Event Relationships in the AOP

#### List of Adjacent Key Event Relationships

#### [Relationship: 1037: Inhibition, Deiodinase 1 leads to Decreased, Triiodothyronine \(T3\) in serum](#)

#### AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	adjacent	Low	Low
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Low	Low

#### Evidence Supporting Applicability of this Relationship

##### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	Low	<a href="#">NCBI</a>
fathead minnow	Pimephales promelas	Low	<a href="#">NCBI</a>

##### Life Stage Applicability

###### Life Stage Evidence

All life stages High

##### Sex Applicability

###### Sex Evidence

Unspecific Moderate

**Taxonomic:** Deiodinases are important for the activation of T4 to T3 across vertebrates. Therefore, this KER is plausibly applicable across vertebrates. There appear to be differences among vertebrate classes relative to the role of the different deiodinase isoforms in regulating thyroid hormone levels. It is generally assumed that deiodinase 1 in liver is the main supplier of T3 to circulation in mammals (Leonard et al., 1986), and the same appears to be true for birds (Freeman et al., 1991), while DIO2 is assumed to regulate intracellular concentrations of T3. In contrast to the general assumptions however, Maia et al. (2005) determined that in a normal physiological situation in humans the contribution of DIO2 to plasma T3 levels is twice that of DIO1. By contrast, DIO1 function in teleostean and amphibian T3 plasma regulation is less clear (Finnson et al. 1999, Kuiper et al. 2006). The presence of DIO1 in the liver of teleosts has been a controversial issue, and both the high level of DIO2 activity and its expression in the liver of teleosts are unique among vertebrates (Orozco and Valverde, 2005). These differences make it difficult to exactly evaluate the importance of DIO1 in regulating serum/tissue T3 levels across vertebrates. Mol et al. (1998) concluded that deiodinases in teleosts were more similar to mammalian deiodinases than had been generally accepted, based on the similarities in susceptibility to inhibition and the agreement of the Km values.

**Life stage:** Deiodinases are important for the activation of T4 to T3 across all life stages.

**Sex:** The KE is plausibly applicable to both sexes. Thyroid hormones are essential in both sexes and the components of the HPT-

axis are identical in both sexes. There can however be sex-dependent differences in the sensitivity to the disruption of thyroid hormone levels and the magnitude of the response. In humans, females appear more susceptible to hypothyroidism compared to males when exposed to certain halogenated chemicals (Hernandez-Mariano et al., 2017; Webster et al., 2014). In adult zebrafish, Liu et al. (2019) showed sex-dependent changes in thyroid hormone levels and mRNA expression of regulatory genes including corticotropin releasing hormone (crh), thyroid stimulating hormone (tsh) and deiodinase 2 after exposure to organophosphate flame retardants. The underlying mechanism of any sex-related differences remains unclear.

### Key Event Relationship Description

The two major thyroid hormones are thyroxine (T4) and the more biologically active triiodothyronine (T3), both iodinated derivatives of tyrosine. Active and inactive THs are tightly regulated by enzymes called iodothyronine deiodinases (DIO). The activation occurs via outer ring deiodination (ORD), i.e. removing iodine from the outer, phenolic ring of T4 to form T3, while inactivation occurs via inner ring deiodination (IRD), i.e. removing iodine from the inner tyrosol ring of T4 or T3.

Three types of iodothyronine deiodinases (DIO1-3) have been described in vertebrates that activate or inactivate THs and are therefore important mediators of TH action. All deiodinases are integral membrane proteins of the thioredoxin superfamily that contain selenocysteine in their catalytic centre. Type I deiodinase is capable of converting T4 into T3, as well as to convert rT3 to the inactive thyroid hormone 3,3'-T2, through outer ring deiodination. rT3, rather than T4, is the preferred substrate for DIO1. furthermore, DIO1 has a very high Km ( $\mu\text{M}$  range, compared to nM range for DIO2) (Darras and Van Herck, 2012). Type II deiodinase (DIO2) is only capable of ORD activity with T4 as a preferred substrate (i.e., activation of T4 to T3). DIO3 can inner ring deiodinate T4 and T3 to the inactive forms of THs, reverse T3, (rT3) and 3,3'-T2 respectively. (Darras and Van Herck, 2012)

Because of the high Km and preference for rT3 as a substrate, the importance of DIO1 in activating T4 to T3 in a physiological situation is likely limited.

### Evidence Supporting this KER

Inhibition of DIO1 activity is widely accepted to directly decrease T3 levels, since the conversion of T4 to T3 is inhibited. The importance of DIO1 inhibition in altering serum T3 levels depends on the relative role of different deiodinases in regulating serum versus tissue T3 levels and in negative feedback within the HPT axis. Both aspects appear to differ to some extent among vertebrate taxa.

### Biological Plausibility

Inhibition of DIO1 activity is widely accepted to directly decrease T3 levels, since the conversion of T4 to T3 is inhibited.

### Empirical Evidence

- In the study of Cavallin et al. (2017) fathead minnow larvae were exposed to iopanoic acid, a model iodothyronine deiodinase inhibitor that is assumed to inhibit all three deiodinase enzymes (DIO1,2,3) and pronounced decreases of whole body T3 concentrations were observed.
- Stinckens et al. (2020) showed that iopanoic acid reduced T3 levels in zebrafish in 21 and 32 day old larvae that had been exposed starting from fertilization.
- Stinckens et al. (2018) showed that perfluorooctanoic acid (PFOA) is a DIO1 and DIO2 inhibitor, and Wang et al. (2020) showed that T3 levels were decreased in zebrafish exposed continuously until the age of 5 days 250 or 500 mg/L. They also showed a T4 decrease, which is unexpected upon exposure to a DIO inhibitor. This is possibly due to one or more additional thyroid hormone disruption mechanisms of PFOA.

### Uncertainties and Inconsistencies

Since in fish early life stages THs are typically measured on a whole body level, it is currently uncertain whether T3 level changes occur at the serum and/or tissue level. Pending more dedicated studies, whole body TH levels are considered a proxy for serum TH levels.

The importance of DIO1 inhibition in altering serum T3 levels depends on the relative role of different deiodinases in regulating serum versus tissue T3 levels and in negative feedback within the HPT axis. Both aspects appear to differ to some extent among vertebrate taxa, but the details are not understood yet.

Another uncertainty lies in the relative importance of the different T4 activating iodothyronine deiodinases (DIO1, DIO2) in the conversion of T4 to T3. It has been previously suggested that DIO2 is the major contributor to TH activation in developing zebrafish embryos (Darras et al., 2015; Walpita et al., 2010). It has been shown that a morpholino knockdown targeting DIO1 mRNA alone did not affect embryonic development in zebrafish, while knockdown of DIO2 delayed progression of otic vesicle length, head-trunk angle and pigmentation index (Houbrechts et al., 2016; Walpita et al., 2010, 2009). DIO1 inhibition may only become essential in hypothyroidal circumstances, for example when DIO2 is inhibited or in case of iodine deficiency, in zebrafish (Walpita et al., 2010) and mice (Galton et al., 2009; Schneider et al., 2006).

In the study of Cavallin et al. (2017) fathead minnow larvae were exposed to IOP, a model iodothyronine deiodinase inhibitor that is assumed to inhibit all three deiodinase enzymes (DIO1,2,3). Transcriptional analysis showed that especially DIO2, but also DIO3 mRNA levels (in some treatments), were increased in 10 to 21 day old larvae exposed to IOP as of the age of 6 days. This suggests



that IOP effectively inhibited DIO2 and DIO3 in the larvae and that mRNA levels increased as a compensatory response. The authors also observed pronounced decreases of whole body T3 concentrations and increases of whole body T4 concentrations. It is not clear whether inhibition of DIO1 also played a role in the decrease of T3 levels.

### Quantitative Understanding of the Linkage

Since in fish enzyme activity and thyroid hormone levels are rarely measured in the same study, quantitative understanding of this linkage is limited.

### Known Feedforward/Feedback loops influencing this KER

Thyroid hormone levels are regulated via negative feedback, influencing this KER. Additionally, deiodinases regulate the activity of thyroid hormones, not only in serum and target organs, but also in the thyroid gland. Deiodinases themselves are known to be involved in the negative feedback system that results in increased TSH levels when the levels of T4 (and also T3) in serum are low (Schneider et al., 2001), resulting in an even more complicated impact on this KER. Increased TSH levels then stimulate increased T4 release from the thyroid gland, resulting in a compensatory increase of serum T4 levels. In DIO2 knockout mice it seemed that the negative feedback system was blocked resulting in increased levels of T4 and TSH and in normal rather than decreased T3 levels compared to WT. By inhibiting DIO1 using a PTU exposure, Schneider et al. (2001) showed that DIO2 played a role in the increased TSH levels in response to T3 or T4 injection.

### References

- Cavallin, J.E., Ankley, G.T., Blackwell, B.R., Blanksma, C.A., Fay, K.A., Jensen, K.M., Kahl, M.D., Knapen, D., Kosian, P.A., Poole, S.T., Randolph, E.C., Schroeder, A.L., Vergauwen, L., Villeneuve, D.L., 2017. Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry* 36, 2942-2952.
- Darras, V.M., Van Herck, S.L.J., 2012. Iodothyronine deiodinase structure and function: from ascidians to humans. *Journal of Endocrinology* 215, 189-206.
- Finsson, K.W., McLeese, J.M., Eales, J.G., 1999. Deiodination and deconjugation of thyroid hormone conjugates and type I deiodination in liver of rainbow trout, *Oncorhynchus mykiss*. *General and Comparative Endocrinology* 115, 387-397.
- Hernandez-Mariano JA, Torres-Sanchez L, Bassol-Mayagoitia S, Escamilla-Nunez M, Cebrian ME, Villeda-Gutierrez EA, Lopez-Rodriguez G, Felix-Arellano EE, Blanco-Munoz J. 2017. Effect of exposure to p,p'-dDE during the first half of pregnancy in the maternal thyroid profile of female residents in a Mexican floriculture area. *Environmental Research*. 156:597-604.
- Kuiper, G., Klootwijk, W., Dubois, G.M., Destree, O., Darras, V.M., Van der Geyten, S., Demeneix, B., Visser, T.J., 2006. Characterization of recombinant *Xenopus laevis* type I iodothyronine deiodinase: substitution of a proline residue in the catalytic center by serine (Pro132Ser) restores sensitivity to 6-propyl-2-thiouracil. *Endocrinology* 147, 3519-3529.
- Liu XS, Cai Y, Wang Y, Xu SH, Ji K, Choi K. 2019. Effects of tris(1,3-dichloro-2-propyl) phosphate (tdcpp) and triphenyl phosphate (tpp) on sex-dependent alterations of thyroid hormones in adult zebrafish. *Ecotoxicology and Environmental Safety*. 170:25-32.
- Mol, K.A., Van der Geyten, S., Burel, C., Kuhn, E.R., Boujard, T., Darras, V.M., 1998. Comparative study of iodothyronine outer ring and inner ring deiodinase activities in five teleostean fishes. *Fish Physiology and Biochemistry* 18, 253-266.
- Schneider, M.J., Fiering, S.N., Pallud, S.E., Parlow, A.F., St Germain, D.L., Galton, V.A., 2001. Targeted disruption of the type 2 selenodeiodinase gene (DIO2) results in a phenotype of pituitary resistance to T-4. *Molecular Endocrinology* 15, 2137-2148.
- Stinckens, E., Vergauwen, L., Ankley, G.T., Blust, R., Darras, V.M., Villeneuve, D.L., Witters, H., Volz, D.C., Knapen, D., 2018. An AOP-based alternative testing strategy to predict the impact of thyroid hormone disruption on swim bladder inflation in zebrafish. *Aquatic Toxicology* 200, 1-12.
- Stinckens, E., Vergauwen, L., Blackwell, B.R., Ankley, G.T., Villeneuve, D.L., Knapen, D., 2020. Effect of Thyroperoxidase and Deiodinase Inhibition on Anterior Swim Bladder Inflation in the Zebrafish. *Environmental Science & Technology* 54, 6213-6223.
- Wang, J.X., Shi, G.H., Yao, J.Z., Sheng, N., Cui, R.N., Su, Z.B., Guo, Y., Dai, J.Y., 2020. Perfluoropolyether carboxylic acids (novel alternatives to PFOA) impair zebrafish posterior swim bladder development via thyroid hormone disruption. *Environment International* 134.
- Webster GM, Venners SA, Mattman A, Martin JW. 2014. Associations between perfluoroalkyl acids (pfass) and maternal thyroid hormones in early pregnancy: A population-based cohort study. *Environmental Research*. 133:338-347.

**Relationship: 1035: Decreased, Triiodothyronine (T3) in serum leads to Reduced, Anterior swim bladder inflation**

### AOPs Referencing Relationship



AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
<a href="#">Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Moderate

### Evidence Supporting Applicability of this Relationship

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	Moderate	<a href="#">NCBI</a>
fathead minnow	Pimephales promelas	High	<a href="#">NCBI</a>

#### Life Stage Applicability

##### Life Stage Evidence

Larvae High

#### Sex Applicability

##### Sex Evidence

Unspecific Moderate

**Taxonomic:** Teleost fish can be divided in two groups according to swim bladder morphology: physoclistous (e.g., yellow perch, sea bass, striped bass) and physostomous (e.g., zebrafish and fathead minnow). Physostomous fish retain a duct between the digestive tract and the swim bladder during adulthood allowing them to gulp air at the surface to fill the swim bladder. In contrast, in physoclistous fish, once initial inflation by gulping atmospheric air at the water surface has occurred, the swim bladder is closed off from the digestive tract and swim bladder volume is regulated by gas secretion into the swim bladder (Woolley and Qin, 2010). The evidence for impaired inflation of the anterior chamber of the swim bladder currently comes from work on zebrafish and fathead minnow (Stinckens et al., 2016; Nelson et al., 2016; Cavallin et al., 2017; Godfrey et al., 2017; Stinckens et al., 2020). While zebrafish and fathead minnows are physostomous fish with a two-chambered swim bladder, the Japanese rice fish (*Oryzias latipes*) is a physoclistous fish with a single chambered swim bladder that inflates during early development. This KER is not applicable to such fish species. Therefore, the current key event is plausibly applicable to physostomous fish in general.

**Life stage:** The anterior chamber inflates during a specific developmental time frame. In zebrafish, the anterior chamber inflates around 21 days post fertilization (dpf) which is during the larval stage. In the fathead minnow, the anterior chamber inflates around 14 dpf, also during the larval stage. Therefore this KER is only applicable to the larval life stage.

**Sex:** This KE/KER plausibly applicable to both sexes. Sex differences are not often investigated in tests using early life stages of fish. In Medaka, sex can be morphologically distinguished as soon as 10 days post fertilization. Females appear more susceptible to thyroid-induced swim bladder dysfunction compared with males (Godfrey et al., 2019). For zebrafish and fathead minnow, it is currently unclear whether sex-related differences are important in determining the magnitude of the changes in this KE/KER. Different fish species have different sex determination and differentiation strategies. Zebrafish do not have identifiable heteromorphic sex chromosomes and sex is determined by multiple genes and influenced by the environment (Nagabhushana and Mishra, 2016). Zebrafish are undifferentiated gonochorists since both sexes initially develop an immature ovary (Maack and Segner, 2003). Immature ovary development progresses until approximately the onset of the third week. Later, in female fish immature ovaries continue to develop further, while male fish undergo transformation of ovaries into testes. Final transformation into testes varies among male individuals, however finishes usually around 6 weeks post fertilization. Since the anterior chamber inflates around 21 days post fertilization in zebrafish, sex differences are expected to play a minor role. Fathead minnow gonad differentiation also occurs during larval development. Fathead minnows utilize a XY sex determination strategy and markers can be used to genotype sex in life stages where the sex is not yet clearly defined morphologically (Olmstead et al., 2011). Ovarian differentiation starts at 10 dph followed by rapid development (Van Aerle et al., 2004). At 25 dph germ cells of all stages up to the primary oocytes stage were present and at 120 dph, vitellogenic oocytes were present. The germ cells (spermatogonia) of the developing testes only entered meiosis around 90–120 dph. Mature testes with spermatozoa are present around 150 dph. Since the anterior chamber inflates around 14 days post fertilization (9 dph) in fathead minnows, sex differences are expected to play a minor role in the current AOP.

#### Key Event Relationship Description

Thyroid hormones are known to be involved in development, especially in metamorphosis in amphibians and in embryonic-to-larval transition and larval-to-juvenile transition, including anterior chamber inflation in fish. Reduced T3 levels in serum prohibit local TH

action in the target tissues. Since swim bladder development and/or inflation is regulated by thyroid hormones, this results in impaired anterior chamber inflation.

### Evidence Supporting this KER

There is convincing evidence that decreased T3 levels result in impaired anterior chamber inflation, but the underlying mechanisms are not completely understood. A very convincing linear quantitative relationship between reduced T3 levels and reduced anterior chamber volume was shown in zebrafish across exposure to a limited set of three compounds. Therefore the evidence supporting this KER can be considered moderate.

### Biological Plausibility

Thyroid hormones are known to be involved in development, especially in metamorphosis in amphibians and in embryonic-to-larval transition (Liu and Chan, 2002) and larval-to-juvenile transition (Brown et al., 1997) in fish. Inflation of the anterior swim bladder chamber is part of the larval-to-juvenile transition in fish, together with the development of adult fins and fin rays, ossification of the axial skeleton, formation of an adult pigmentation pattern, scale formation, maturation and remodeling of organs including the lateral line, nervous system, gut and kidneys (Brown, 1997; Liu and Chan, 2002; McMenamin and Parichy, 2013).

### Empirical Evidence

Dedicated studies with two different experimental setups have been conducted to investigate the link between reduced T3 levels and reduced anterior chamber inflation:

#### 1. Studies applying larval exposures initiated after posterior chamber inflation

- In a study in which larval fathead minnows (*Pimephales promelas*) were exposed to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole (MBT), T3 concentrations measured at 14dpf were reduced at the same concentration (1 mg/L) that significantly reduced anterior swim bladder inflation at the same time-point (Nelson et al. 2016).
- In the study of Cavallin et al. (2017) fathead minnow larvae were exposed to IOP, a model iodothyronine deiodinase inhibitor that is assumed to inhibit all three deiodinase enzymes (DIO1,2,3). The authors observed pronounced decreases of whole body T3 concentrations and increases of whole body T4 concentrations, together with impaired inflation of the anterior swim bladder chamber. More specifically, inflation was delayed and the size of the swim bladder chamber was reduced until the end of the exposure experiment.

Since exposures were started after inflation of the posterior chamber, these studies show that DIO inhibition can directly affect anterior chamber inflation.

#### 2. Studies applying continuous exposure initiated immediately after fertilization and thus including both posterior and anterior chamber inflation

- In the study of Stinckens et al. (2020) exposure concentrations were chosen where the posterior chamber inflates. A strong correlation between reduced T3 levels and reduced anterior chamber inflation was observed in zebrafish exposed to iopanoic acid, a deiodinase inhibitor, as well as methimazole and propylthiouracil, both thyroperoxidase inhibitors, from fertilization until the age of 32 days. Anterior chamber inflation was delayed and a number of larvae did not manage to inflate the anterior chamber by the end of the 32 day exposure period. Additionally, exposed fish that had inflated the swim bladder had reduced anterior chamber sizes.

### Uncertainties and Inconsistencies

- Since in fish early life stages THs are typically measured on a whole body level, it is currently uncertain whether TH levels changes occur at the serum and/or tissue level. Pending more dedicated studies, whole body TH levels are considered a proxy for serum TH levels.
- The mechanism underlying the link between reduced T3 and reduced anterior chamber inflation remains unclear, but several hypotheses exist (Stinckens et al., 2020). For example, altered gas distribution between chambers could be the result of impaired development of smooth muscle fibers, delayed and/or impaired evagination of the anterior chamber, impaired anterior budding through altered Wnt and hedgehog signalling, etc. Reinwald et al. (2021) showed that T3 and propylthiouracil treatment of zebrafish embryos altered expression of genes involved in muscle contraction and functioning in an opposing fashion. The authors suggested impaired muscle function as an additional key event between decreased T3 levels and reduced swim bladder inflation.
- Increased T3 levels also seem to result in reduced swim bladder inflation. For example, Li et al. (2011) reported impairment of swim bladder inflation in Chinese rare minnows (*Gobiocypris rarus*) exposed to exogenous T3.

### References

Brown, D.D., 1997. The role of thyroid hormone in zebrafish and axolotl development. *Proceedings of the National Academy of Sciences of the United States of America* 94, 13011-13016.

Cavallin, J.E., Ankley, G.T., Blackwell, B.R., Blanksma, C.A., Fay, K.A., Jensen, K.M., Kahl, M.D., Knapen, D., Kosian, P.A., Poole, S.T., Randolph, E.C., Schroeder, A.L., Vergauwen, L., Villeneuve, D.L., 2017. Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry* 36, 2942-2952.

- Godfrey A, Hooser B, Abdelmoneim A, Sepulveda MS. 2019. Sex-specific endocrine-disrupting effects of three halogenated chemicals in Japanese medaka. *Journal of Applied Toxicology*. 39(8):1215-1223.
- Godfrey, A., Hooser, B., Abdelmoneim, A., Horzmann, K.A., Freeman, J.L., Sepulveda, M.S., 2017. Thyroid disrupting effects of halogenated and next generation chemicals on the swim bladder development of zebrafish. *Aquatic Toxicology* 193, 228-235.
- Li W, Zha J, Yang L, Li Z, Wang Z. Regulation of thyroid hormone related genes mRNA expression by exogenous T<sub>3</sub> in larvae and adult Chinese rare minnow (*Gobiocypris rarus*). *Environ Toxicol Pharmacol*. 2011 Jan;31(1):189-97. doi: 10.1016/j.etap.2010.10.007.
- Liu, Y.W., Chan, W.K., 2002. Thyroid hormones are important for embryonic to larval transitory phase in zebrafish. *Differentiation* 70, 36-45.
- McMenamin, S.K., Parichy, D.M., 2013. Metamorphosis in Teleosts. *Animal Metamorphosis* 103, 127-165.
- Nagabhushana A, Mishra RK. 2016. Finding clues to the riddle of sex determination in zebrafish. *Journal of Biosciences*. 41(1):145-155.
- Nelson KR, Schroeder AL, Ankley GT, Blackwell BR, Blanksma C, Degitz SJ, Flynn KM, Jensen KM, Johnson RD, Kahl MD, Knapen D, Kosian PA, Misk RY, Randolph EC, Saari T, Stinckens E, Vergauwen L, Villeneuve DL. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part I: Fathead minnow. *Aquat Toxicol*. 2016 Apr;173:192-203. doi: 10.1016/j.aquatox.2015.12.024.
- Olmstead AW, Villeneuve DL, Ankley GT, Cavallin JE, Lindberg-Livingston A, Wehmas LC, Degitz SJ. 2011. A method for the determination of genetic sex in the fathead minnow, *Pimephales promelas*, to support testing of endocrine-active chemicals. *Environmental Science & Technology*. 45(7):3090-3095.
- Reinwald H, König A, Ayobahan SU, Alvincz J, Sipos L, Gockener B, Bohle G, Shomroni O, Hollert H, Salinas G et al. 2021. Toxicogenomic fin(ger)prints for thyroid disruption aop refinement and biomarker identification in zebrafish embryos. *Science of the Total Environment*. 760.
- Stinckens, E., Vergauwen, L., Blackwell, B.R., Ankley, G.T., Villeneuve, D.L., Knapen, D., 2020. Effect of Thyroperoxidase and Deiodinase Inhibition on Anterior Swim Bladder Inflation in the Zebrafish. *Environmental Science & Technology* 54, 6213-6223.
- Stinckens, E., Vergauwen, L., Schroeder, A., Maho, W., Blackwell, B., Witters, H., Blust, R., Ankley, G., Covaci, A., Villeneuve, D., Knapen, D., 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part II: Zebrafish. *Aquatic Toxicology* 173, 204-217.
- Uchida, D., Yamashita, M., Kitano, T., Iguchi, T., 2002. Oocyte apoptosis during the transition from ovary-like tissue to testes during sex differentiation of juvenile zebrafish. *Journal of Experimental Biology* 205, 711-718.
- van Aerle R, Runnalls TJ, Tyler CR. 2004. Ontogeny of gonadal sex development relative to growth in fathead minnow. *Journal of Fish Biology*. 64(2):355-369.
- Zeng FX, Sherry JP, Bols NC. 2016. Evaluating the toxic potential of benzothiazoles with the rainbow trout cell lines, rtgill-w1 and rti-w1. *Chemosphere*. 155:308-318.

### **Relationship: 1034: Reduced, Anterior swim bladder inflation leads to Reduced, Swimming performance**

#### **AOPs Referencing Relationship**

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
<a href="#">Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Low
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Low
<a href="#">Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Low

#### **Evidence Supporting Applicability of this Relationship**

##### **Taxonomic Applicability**

Term	Scientific Term	Evidence	Links
zebrafish	<i>Danio rerio</i>	High	<a href="#">NCBI</a>
fathead minnow	<i>Pimephales promelas</i>	Low	<a href="#">NCBI</a>

##### **Life Stage Applicability**

**Life Stage Evidence**

Larvae High

**Sex Applicability****Sex Evidence**

Unspecific Moderate

**Taxonomic:** Importance of proper functioning of the swim bladder for supporting natural swimming behaviour can be plausibly assumed to be generally applicable to fish possessing an anterior chamber. Evidence exists for the role of the posterior chamber in swimming performance comes from a wide variety of freshwater and marine fish species. Evidence for the specific role of the anterior chamber is however less abundant.

**Life stage:** In zebrafish, the anterior chamber inflates around 21 days post fertilization (dpf) which is during the larval stage. In the fathead minnow, the anterior chamber inflates around 14 dpf, also during the larval stage. Therefore this KER is only applicable to the larval life stage. To what extent fish can survive and swim with partly inflated swim bladders during later life stages is unknown.

**Sex:** This KE/KER plausibly applicable to both sexes. Sex differences are not often investigated in tests using early life stages of fish. In Medaka, sex can be morphologically distinguished as soon as 10 days post fertilization. Females appear more susceptible to thyroid-induced swim bladder dysfunction compared with males (Godfrey et al., 2019). For zebrafish and fathead minnow, it is currently unclear whether sex-related differences are important in determining the magnitude of the changes in this KE/KER. Different fish species have different sex determination and differentiation strategies. Zebrafish do not have identifiable heteromorphic sex chromosomes and sex is determined by multiple genes and influenced by the environment (Nagabhushana and Mishra, 2016). Zebrafish are undifferentiated gonochorists since both sexes initially develop an immature ovary (Maack and Segner, 2003). Immature ovary development progresses until approximately the onset of the third week. Later, in female fish immature ovaries continue to develop further, while male fish undergo transformation of ovaries into testes. Final transformation into testes varies among male individuals, however finishes usually around 6 weeks post fertilization. Since the anterior chamber inflates around 21 days post fertilization in zebrafish, sex differences are expected to play a minor role. Fathead minnow gonad differentiation also occurs during larval development. Fathead minnows utilize a XY sex determination strategy and markers can be used to genotype sex in life stages where the sex is not yet clearly defined morphologically (Olmstead et al., 2011). Ovarian differentiation starts at 10 dph followed by rapid development (Van Aerle et al., 2004). At 25 dph germ cells of all stages up to the primary oocytes stage were present and at 120 dph, vitellogenic oocytes were present. The germ cells (spermatogonia) of the developing testes only entered meiosis around 90–120 dph. Mature testes with spermatozoa are present around 150 dph. Since the anterior chamber inflates around 14 days post fertilization (9 dph) in fathead minnows, sex differences are expected to play a minor role in the current AOP.

**Key Event Relationship Description**

Effects on swim bladder inflation can alter swimming performance and buoyancy of fish, which is essential for predator avoidance, energy sparing, migration, reproduction and feeding behaviour, resulting in increased mortality.

**Evidence Supporting this KER**

The weight of evidence supporting a direct linkage between these two KEs, i.e. reduced anterior swim bladder inflation and reduced swimming performance, is weak.

**Biological Plausibility**

The anterior chamber of the swim bladder has a function in regulating the buoyancy of fish, by altering the volume of the swim bladder (Roberston et al., 2007). Fish rely on the lipid and gas content in their body to regulate their position within the water column, with the latter being more efficient at increasing body buoyancy. Therefore, fish with functional swim bladders have no problem supporting their body (Brix 2002), while it is highly likely that impaired inflation severely impacts swimming performance. Fish with no functional swim bladder can survive, but are severely disadvantaged, making the likelihood of surviving smaller.

Several studies in zebrafish and fathead minnow showed that a smaller AC was associated with a larger posterior chamber (Nelson et al., 2016; Stinckens et al., 2016; Cavallin et al., 2017; Stinckens et al., 2020) suggesting a possible compensatory mechanism. As shown by Stoyek et al. (2011) however, the AC volume is highly dynamic under normal conditions due to a series of regular corrugations running along the chamber wall, and is in fact the main driver for adjusting buoyancy while the basic PC volume remains largely invariable. Therefore, it is plausible to assume that functionality of the swim bladder is affected when AC inflation is incomplete, even when the PC appears to fully compensate the gas volume of the swim bladder.

**Empirical Evidence**

- Lindsey et al. (2010) showed that zebrafish started swimming deeper down in the water column upon inflation of the anterior chamber, confirming a role of the anterior chamber in supporting swimming performance.
- After exposure to 2-mercaptobenzothiazole, a TPO inhibitor, from 0 to 32 days post fertilization (dpf) in zebrafish, the swimming activity of fish was impacted starting at 26 dpf if the inflation of the anterior chamber of the swim bladder was impaired or had no normal structure/size (Stinckens et al., 2016).

- Methimazole (MMI) and propylthiouracil (PTU), two thyroperoxidase inhibitors, and iopanoic acid (IOP), a deiodinase inhibitor, each reduced both anterior chamber inflation and swimming distance in zebrafish exposed from fertilization until the age of 32 days (Stinckens et al., 2020). Stinckens et al. (2020) showed a specific, direct link between reduced anterior chamber inflation and reduced swimming performance.
  - First, after 21 d of exposure to 111 mg/L propylthiouracil around 30% of anterior chambers were not inflated and swimming distance was reduced, while by 32 days post fertilization all larvae had inflated their anterior chamber (although chamber surface was still smaller) and the effect on swimming distance had disappeared.
  - The most direct way to assess the role of anterior chamber inflation in swimming performance, however, is to compare larvae with and without inflated anterior chamber at the same time point and within the same experimental treatment. Both in the propylthiouracil exposure at 21 days post fertilization and in the iopanoic acid exposure at 21 and 32 days post fertilization, swimming distance was clearly reduced in larvae lacking an inflated anterior chamber, while the swimming distance of larvae with inflated anterior chamber was equal to that of controls.
  - Exposure concentrations were selected where the posterior chamber inflates. Even though the posterior chamber was generally larger when anterior chamber inflation was reduced, this did not remove the effect on swimming performance, confirming a direct link between proper anterior chamber inflation and swimming performance.
  - No morphological effects were observed, but in some treatments reduced length and/or condition factor was observed. However, reduced swimming performance after 32 days of IOP exposure to medium concentrations was not accompanied by reduced length or condition factor. Therefore, at least in this study no evidence was found that the effect on swimming performance was an indirect consequence of effects other than reduced swim bladder inflation.
- It has also been reported that larvae that fail to inflate their swim bladder use additional energy to maintain buoyancy (Lindsey et al., 2010; Goodsell et al. 1996), possibly contributing to reduced swimming activity.

### Uncertainties and Inconsistencies

After exposure to 100 mg/L methimazole, 95% of the zebrafish larvae failed to inflate their anterior chamber at 32 dpf and swimming distance was reduced (Stinckens et al., 2020). On the other hand, there was no effect of impaired anterior chamber inflation on swimming distance in the methimazole exposure of 50 mg/L. Also, inflated but smaller anterior chambers did not result in a decreased swimming performance in this study. A similar result, where non-inflated anterior chambers did not consistently lead to reduced swimming performance, was previously found after exposure to 2-mercaptobenzothiazole (Stinckens et al., 2016). In summary, the precise relationship between these two KEs is not easy to determine and may be different for different chemicals. This is in part due to the complexity of the swim bladder system and the difficulty of distinguishing effects resulting from altered anterior chamber inflation from those resulting from altered posterior chamber inflation. Additionally, swimming capacity can be affected via other processes which may or may not depend on the HPT axis, such as general malformations, decreased cardiorespiratory function, energy metabolism and growth.

As Robertson et al., (2007) reported, the swim bladder only starts regulating buoyancy actively from 32 dpf onward in zebrafish, possibly explaining the lack of effect on swimming capacity in some cases.

The anterior chamber is also important for producing and transducing sound through the Weberian Apparatus (Popper, 1974; Lechner and Ladich, 2008). It is highly plausible that impaired inflation or size of the anterior swim bladder could lead to increased mortality as hearing loss would affect their ability to respond to their surrounding environment, thus impacting ecological relevant endpoints such as predator avoidance or prey seeking (Wisenden et al., 2008; Fay, 2009).

### References

- Brix O (2002) The physiology of living in water. In: Hart PJ, Reynolds J (eds) Handbook of Fish Biology and Fisheries, Vol. 1, pp. 70–96. Blackwell Publishing, Malden, USA.
- Cavallin, J.E., Ankley, G.T., Blackwell, B.R., Blanksma, C.A., Fay, K.A., Jensen, K.M., Kahl, M.D., Knapen, D., Kosian, P.A., Poole, S.T., Randolph, E.C., Schroeder, A.L., Vergauwen, L., Villeneuve, D.L., 2017. Impaired swim bladder inflation in early life stage fathead minnows exposed to a deiodinase inhibitor, iopanoic acid. *Environmental Toxicology and Chemistry* 36, 2942-2952.
- Czesny, S.J., Graeb, B.D.S., Dettmersn, J.M., 2005. Ecological consequences of swimbladder noninflation for larval yellow perch. *Trans. Am. Fish. Soc.* 134,1011–1020, <http://dx.doi.org/10.1577/T04-016.1>.
- Fay, R., 2009. Soundscapes and the sense of hearing of fishes. *Integrative Zool.* 4,26–32.
- Godfrey A, Hooser B, Abdelmoneim A, Sepulveda MS. 2019. Sex-specific endocrine-disrupting effects of three halogenated chemicals in japanese medaka. *Journal of Applied Toxicology.* 39(8):1215-1223.
- Goodsell, D.S., Morris, G.M., Olsen, A.J. 1996. Automated docking of flexible ligands. *Applications of Autodock.* *J. Mol. Recognition*, 9:1-5.
- Lechner, W., Ladich, F., 2008. Size matters: diversity in swimbladders and Weberian ossicles affects hearing in catfishes. *J. Exp. Biol.* 211, 1681–1689.
- Lindsey, B.W., Smith, F.M., Croll, R.P., 2010. From inflation to flotation: contribution of the swimbladder to whole-body density and

swimming depth during development of the zebrafish (*Danio rerio*). *Zebrafish* 7, 85–96, <http://dx.doi.org/10.1089/zeb.2009.0616>.

Maack, G., Segner, H., 2003. Morphological development of the gonads in zebrafish. *Journal of Fish Biology* 62, 895-906.

Nagabhushana A, Mishra RK. 2016. Finding clues to the riddle of sex determination in zebrafish. *Journal of Biosciences*. 41(1):145-155.

Nelson, K., Schroeder, A., Ankley, G., Blackwell, B., Blanksma, C., Degitz, S., Flynn, K., Jensen, K., Johnson, R., Kahl, M., Knapen, D., Kosian, P., Milsik, R., Randolph, E., Saari, T., Stinckens, E., Vergauwen, L., Villeneuve, D., 2016. Impaired anterior swim bladder inflation following exposure to the thyroid peroxidase inhibitor 2-mercaptobenzothiazole part I: Fathead minnow. *Aquatic Toxicology* 173, 192-203.

Olmstead AW, Villeneuve DL, Ankley GT, Cavallin JE, Lindberg-Livingston A, Wehmas LC, Degitz SJ. 2011. A method for the determination of genetic sex in the fathead minnow, *pimephales promelas*, to support testing of endocrine-active chemicals. *Environmental Science & Technology*. 45(7):3090-3095.

Roberston, G.N., McGee, C.A.S., Dumbarton, T.C., Croll, R.P., Smith, F.M., 2007. Development of the swim bladder and its innervation in the zebrafish, *Danio rerio*. *J. Morphol.* 268, 967–985, <http://dx.doi.org/10.1002/jmor>.

Stinckens, E., Vergauwen, L., Blackwell, B.R., Ankley, G.T., Villeneuve, D.L., Knapen, D., 2020. Effect of Thyroperoxidase and Deiodinase Inhibition on Anterior Swim Bladder Inflation in the Zebrafish. *Environmental Science & Technology* 54, 6213-6223.

Stinckens, E., Vergauwen, L., Schroeder, A.L., Maho, W., Blackwell, B., Witter, H., Blust, R., Ankley, G.T., Covaci, A., Villeneuve, D.L., Knapen, D., 2016. Disruption of thyroid hormone balance after 2-mercaptobenzothiazole exposure causes swim bladder inflation impairment—part II: zebrafish. *Aquat. Toxicol.* 173:204-17.

Stoyek, M.R., Smith, F.M., Croll, R.P., 2011. Effects of altered ambient pressure on the volume and distribution of gas within the swimbladder of the adult zebrafish, *Danio rerio*. *Journal of Experimental Biology* 214, 2962-2972.

van Aerle R, Runnalls TJ, Tyler CR. 2004. Ontogeny of gonadal sex development relative to growth in fathead minnow. *Journal of Fish Biology*. 64(2):355-369.

Wisenden, B.D., Pogatschnik, J., Gibson, D., Bonacci, L., Schumacher, A., Willet, A., 2008. Sound the alarm: learned association of predation risk with novel auditory stimuli by fathead minnows (*Pimephales promelas*) and glowlight tetras (*Hemigrammus erythrozonus*) after single simultaneous pairings with conspecific chemical alarm cues. *Environ. Biol. Fish* 81, 141–147.

Woolley, L.D., Qin, J.G., 2010. Swimbladder inflation and its implication to the culture of marine finfish larvae. *Rev. Aquac.* 2, 181–190, <http://dx.doi.org/10.1111/j.1753-5131.2010.01035.x>.

### **Relationship: 2212: Reduced, Swimming performance leads to Increased Mortality**

#### **AOPs Referencing Relationship**

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
<a href="#">Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	adjacent	Moderate	Low
<a href="#">Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Low
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	adjacent	Moderate	Low
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Low
<a href="#">Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Low

#### **Evidence Supporting Applicability of this Relationship**

##### **Taxonomic Applicability**

Term	Scientific Term	Evidence	Links
zebrafish	<i>Danio rerio</i>	Moderate	<a href="#">NCBI</a>
fathead minnow	<i>Pimephales promelas</i>	Moderate	<a href="#">NCBI</a>

##### **Life Stage Applicability**

**Life Stage Evidence**

Adult	Moderate
-------	----------

Juvenile	Moderate
----------	----------

Larvae	Moderate
--------	----------

**Sex Applicability**

Sex	Evidence
-----	----------

Unspecific	Moderate
------------	----------

Importance of swimming performance on survival is generally applicable to all hatched fish across life stages and sexes and to other taxa that rely on swimming to support vital behaviours.

**Key Event Relationship Description**

Reduced swimming performance is likely to affect essential endpoints such as predator avoidance, feeding behaviour and reproduction in taxa that rely on swimming to support these vital behaviours. These parameters are biologically plausible to affect survival, especially in a non-laboratory environment where food is scarce and predators are abundant.

**Evidence Supporting this KER**

A direct relationship between reduced swimming performance and reduced survival is difficult to establish. There is however a lot of indirect evidence linking reduced swim bladder inflation to reduced survival (<https://aopwiki.org/relationships/2213>), which can be plausibly assumed to be related to reduced swimming performance.

For example, all zebrafish larvae that failed to inflate the posterior chamber after exposure to 2 mg/L iopanoic acid (IOP), died by the age of 9 dpf (Stinckens et al., 2020). Since larvae from the same group that were able to inflate the posterior chamber survived and the test was performed in the laboratory in optimal conditions, it is plausible to assume that the cause of death was the inability to swim and find food due to the failure to inflate the posterior swim bladder chamber.

**Biological Plausibility**

Reduced swimming performance is likely to affect essential endpoints such as predator avoidance, feeding behaviour and reproduction. These parameters are biologically plausible to affect survival, especially in a non-laboratory environment where food is scarce and predators are abundant.

**Empirical Evidence**

A direct relationship between reduced swimming performance and reduced survival is difficult to establish. There is however a lot of indirect evidence linking reduced swim bladder inflation to reduced survival (see non-adjacent KER 1041), which can be plausibly assumed to be related to reduced swimming performance.

For example, all zebrafish larvae that failed to inflate the posterior chamber after exposure to 2 mg/L iopanoic acid (IOP), died by the age of 9 dpf (Stinckens et al., 2020). Since larvae from the same group that were able to inflate the posterior chamber survived and the test was performed in the laboratory in optimal conditions, it is plausible to assume that the cause of death was the inability to swim and find food due to the failure to inflate the posterior swim bladder chamber.

**Uncertainties and Inconsistencies**

A direct relationship between reduced swimming performance and reduced survival is difficult to establish in a laboratory environment where food is abundant and there are no predators.

**Quantitative Understanding of the Linkage**

Quantitative understanding of this linkage is currently limited.

**Time-scale**

Reduced swimming performance is not expected to immediately lead to mortality. Depending on the extent of the reduction in swimming performance and depending on the cause of death (e.g., starvation due to the inability to find food, being caught by a predator) the lag time may vary.

As an example, Stinckens et al. (2020) found that zebrafish larvae that failed to inflate the swim bladder at 5 dpf and did not manage to inflate it during the days afterwards died by the age of 9 dpf. Since zebrafish initiate exogenous feeding around 5 dpf when the yolk is almost completely depleted, there was a lag period of around 4 days after which reduced feeding resulted in mortality. Obviously, in a laboratory setup there is no increased risk of being caught by a predator.

## References

Stinckens, E., Vergauwen, L., Blackwell, B.R., Anlley, G.T., Villeneuve, D.L., Knapen, D., 2020. Effect of Thyroperoxidase and Deiodinase Inhibition on Anterior Swim Bladder Inflation in the Zebrafish. *Environmental Science & Technology* 54, 6213-6223.

## Relationship: 2013: Increased Mortality leads to Decrease, Population trajectory

### AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
<a href="#">Acetylcholinesterase Inhibition leading to Acute Mortality via Impaired Coordination &amp; Movement</a>	adjacent		
<a href="#">Acetylcholinesterase inhibition leading to acute mortality</a>	adjacent	Moderate	Moderate
<a href="#">Deiodinase 2 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Deiodinase 2 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced posterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Deiodinase 1 inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Thyroperoxidase inhibition leading to increased mortality via reduced anterior swim bladder inflation</a>	adjacent	Moderate	Moderate
<a href="#">Thyroperoxidase inhibition leading to increased mortality via altered retinal layer structure</a>	adjacent	High	Moderate
<a href="#">Thyroperoxidase inhibition leading to increased mortality via decreased eye size</a>	adjacent		
<a href="#">Thyroperoxidase inhibition leading to increased mortality via altered photoreceptor patterning</a>	adjacent		
<a href="#">Inhibition of Fyna leading to increased mortality via decreased eye size (Microphthalmos)</a>	adjacent	High	High

### Evidence Supporting Applicability of this Relationship

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
zebrafish	Danio rerio	High	<a href="#">NCBI</a>
fathead minnow	Pimephales promelas	High	<a href="#">NCBI</a>

#### Life Stage Applicability

##### Life Stage Evidence

All life stages High

#### Sex Applicability

##### Sex Evidence

Unspecific Moderate

**Taxonomic:** All organisms must survive to reproductive age in order to reproduce and sustain populations. The additional considerations related to survival made above are applicable to other fish species in addition to zebrafish and fathead minnows with the same reproductive strategy (r-strategist as described in the theory of MaxArthur and Wilson (1967). The impact of reduced survival on population size is even greater for k-strategists that invest more energy in a lower number of offspring.

**Life stage:** Density dependent effects start to play a role in the larval stage of fish when free-feeding starts (Hazlerigg et al., 2014).

**Sex:** This linkage is independent of sex.



## Key Event Relationship Description

Increased mortality in the reproductive population may lead to a declining population. This depends on the excess mortality due to the applied stressor and the environmental parameters such as food availability and predation rate. Most fish species are r-strategist, meaning they produce a lot of offspring instead of investing in parental care. This results in natural high larval mortality causing only a small percentage of the larvae to survive to maturity. If the excess larval mortality due to a stressor is small, the population dynamics might result in constant population size. Should the larval excess be more significant, or last on the long-term, this will affect the population. To calculate the long-term persistence of the population, population dynamic models should be used.

## Evidence Supporting this KER

Survival rate is an obvious determinant of population size and is therefore included in population modeling (e.g., Miller et al., 2020).

### Biological Plausibility

- Survival to reproductive maturity is a parameter of demographic significance. Assuming resource availability (i.e., food, habitat, etc.) is not limiting to the extant population, sufficient mortality in the reproductive population may ultimately lead to declining population trajectories.
- Under some conditions, reduced larval survival may be compensated by reduced predation and increased food availability, and therefore not result in population decline (Stige et al., 2019).

### Empirical Evidence

- According to empirical data, combined with population dynamic models, feeding larvae are the crucial life stage in zebrafish (and other r-strategists) for the regulation of the population. (Schäfers et al., 1993)
- In fathead minnow, natural survival of early life stages has been found to be highly variable and influential on population growth (Miller and Ankley, 2004)
- Rearick et al. (2018) used linked data from behavioural assays to survival trials and applied a modelling approach to quantify changes in antipredator escape performance of larval fathead minnows in order to predict changes in population abundance. This work was done in the context of exposure to an environmental oestrogen. Exposed fish had delayed response times and slower escape speeds, and were more susceptible to predation. Population modelling showed that this can result in population decline.
- In the context of fishing and fisheries, ample evidence of a link between increased mortality and a decrease of population size has been given. Important insights can result from the investigation of optimum modes of fishing that allow for maintaining a population (Alekseeva and Rudenko, 2018). Jacobsen and Essington (2018) showed the impact of varying predation mortality on forage fish populations.
- Boreman (1997) reviewed methods for comparing the population-level effects of mortality in fish populations induced by pollution or fishing.

### Uncertainties and Inconsistencies

- The extent to which larval mortality affects population size could depend on the fraction of surplus mortality compared to a natural situation.
- There are scenarios in which individual mortality may not lead to declining population size. These include instances where populations are limited by the availability of habitat and food resources, which can be replenished through immigration. Effects of mortality in the larvae can be compensated by reduced competition for resources (Stige et al., 2019).
- The direct impact of pesticides on migration behavior can be difficult to track in the field, and documentation of mortality during migration is likely underestimated (Eng 2017).

## References

- Alekseeva SM, Rudenko AI. 2018. Modeling of optimum fishing population. *Marine Intellectual Technologies*. 3(4):142-146.
- Beaudouin, R., Goussen, B., Piccini, B., Augustine, S., Devillers, J., Brion, F., Pery, A.R., 2015. An individual-based model of zebrafish population dynamics accounting for energy dynamics. *PloS one* 10, e0125841.
- Boreman J. 1997. Methods for comparing the impacts of pollution and fishing on fish populations. *Transactions of the American Fisheries Society*. 126(3):506-513.
- Caswell, H., 2000. *Matrix population models*. Sinauer Sunderland, MA, USA.
- Eng, M.L., Stutchbury, B.J.M. & Morrissey, C.A. Imidacloprid and chlorpyrifos insecticides impair migratory ability in a seed-eating songbird. *Sci Rep* 7, 15176 (2017)
- Hazlerigg, C.R., Lorenzen, K., Thorbek, P., Wheeler, J.R., Tyler, C.R., 2012. Density-dependent processes in the life history of

fishes: evidence from laboratory populations of zebrafish *Danio rerio*. PLoS One 7, e37550.

Jacobsen NS, Essington TE. 2018. Natural mortality augments population fluctuations of forage fish. *Fish and Fisheries*. 19(5):791-797.

MacArthur, R., Wilson, E., 1967. *The Theory of Island Biogeography*. Princeton: Princeton Univ. Press. 203 p.

Miller, D.H., Ankley, G.T., 2004. Modeling impacts on populations: fathead minnow (*Pimephales promelas*) exposure to the endocrine disruptor 17 $\beta$ -trenbolone as a case study. *Ecotoxicology and Environmental Safety* 59, 1-9.

Miller, D.H., Clark, B.W., Nacci, D.E. 2020. A multidimensional density dependent matrix population model for assessing risk of stressors to fish populations. *Ecotoxicology and environmental safety* 201, 110786

Pinceel, T., Vanschoenwinkel, B., Brendonck, L., Buschke, F., 2016. Modelling the sensitivity of life history traits to climate change in a temporary pool crustacean. *Scientific reports* 6, 29451.

Rearick, D.C., Ward, J., Venturelli, P., Schoenfuss, H., 2018. Environmental oestrogens cause predation-induced population decline in a freshwater fish. *Royal Society open science* 5, 181065.

Schäfers, C., Oertel, D., Nagel, R., 1993. Effects of 3, 4-dichloroaniline on fish populations with differing strategies of reproduction. *Ecotoxicology and Ecophysiology*, 133-146.

Stige, L.C., Rogers, L.A., Neuheimer, A.B., Hunsicker, M.E., Yaragina, N.A., Ottersen, G., Ciannelli, L., Langangen, Ø., Durant, J.M., 2019. Density- and size-dependent mortality in fish early life stages. *Fish and Fisheries* 20, 962-976. Hazlerigg, C.R.E., Tyler, C.R., Lorenzen, K., Wheeler, J.R., Thorbek, P., 2014. Population relevance of toxicant mediated changes in sex ratio in fish: An assessment using an individual-based zebrafish (*Danio rerio*) model. *Ecological Modelling* 280, 76-88.

Stige, L.C., Rogers, L.A., Neuheimer, A.B., Hunsicker, M.E., Yaragina, N.A., Ottersen, G., Ciannelli, L., Langangen, O., Durant, J.M., 2019. Density- and size-dependent mortality in fish early life stages. *Fish and Fisheries* 20, 962-976.