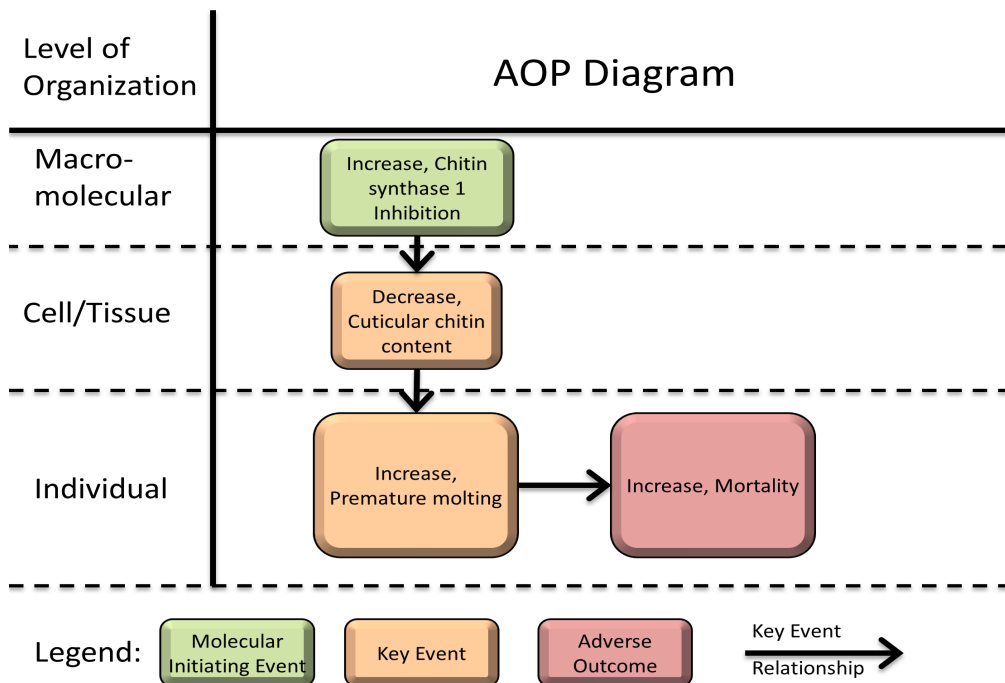


**AOP 360: Chitin synthase 1 inhibition leading to mortality**

Short Title: CHS-1 inhibition leading to mortality

## Graphical Representation



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## Abstract

Arthropods heavily rely on chitin synthesis as chitin is one of the main constituents of the cuticle. Successful molting, and therefore a successful development necessitates stability and integrity of the cuticle. The cuticular chitin synthase (CHS1) is the key enzyme in the biosynthetic pathway and arthropods are therefore especially dependent on its proper function.

The present AOP describes the effects of chemical inhibition of the cuticular chitin synthase (CHS1) on the molting process leading to increased mortality in arthropods. Inhibition of CHS1 is the molecular initiating event and leads to a decreased chitin content in the arthropod cuticle which leaves the organism immature at the stage for ecdysis. This phenomenon can be described as premature molting. The organism eventually dies due to being stuck in the old cuticle or due to the consequences of a weak exoskeleton after ecdysis.

The AOP is considered to be very consistent. Essentiality of key events was rated as high for every key event and the biological plausibility was rated as high for the whole AOP. However, there does not exist very much empirical evidence that allows to draw a representative conclusion on

dose and time concordance along the AOP. Therefore, empirical evidence and also the quantitative understanding was considered to be low. The overall confidence in the AOP was valued as moderate.

The present AOP will guide assay development for further experimental studies by revealing data and knowledge gaps. One of its primary applications will also be providing guidance in screening strategies in order to broaden its chemical applicability domain.

## Background

Arthropods need to shed their exoskeleton in order to grow and reproduce. This process, also called molting or ecdysis, is mediated by behavioural mechanisms which involve the skeletal muscles (Ayali 2009; Song et al. 2017a). In order to properly shed its cuticle, the organism needs to possess a newly synthesized cuticle that possesses a certain integrity to support this process. Since chitin is a major constituent of the cuticle, it contributes substantially to its integrity (Cohen 2001; Vincent and Wegst 2004). Chitin is synthesized from uridine diphosphate-*N*-Acetylglucosamine (UDP-GlcNAc) in a polymerization reaction by the transmembrane enzyme chitin synthase isoform 1 (CHS-1). CHS-1 is localized on the apical side in the cuticular epithelium.

Since chitin and the process of chitin synthesis does not occur in vertebrates, it can and has been exploited for the design of pest controlling agents. Inhibitors of chitin synthesis may not only be of use for the control of unwanted arthropods and fungi, they may also pose a risk for beneficial arthropods such as insects and crustaceans. Disruption of chitin synthesis or the endocrine mechanisms controlling molting generally lead to a disruption of ecdysis (Merzendorfer et al. 2012; Song et al. 2017a; Song et al. 2017b). If the amount of chitin in the cuticle decreases, the affected organism may not be able to molt properly and will most probably die of starvation or suffocation (Camp et al. 2014; Song et al. 2017a). Alternatively, if molting is completed despite an immature cuticle, the organism may be deformed and die as a consequence of a weak cuticle.

Therefore, the present AOP should build the basis of a mechanistic approach for the systematic evaluation and the risk assessment of chemicals interfering with chitin synthesis by directly inhibiting CHS-1.

## Summary of the AOP

### Events

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

Sequence	Type	Event ID	Title	Short name
1	MIE	1522	Increase, Chitin synthase 1 inhibition ( <a href="https://aopwiki.org/events/1522">https://aopwiki.org/events/1522</a> )	Increase, CHS-1 inhibition
2	KE	1523	Decrease, Cuticular chitin content ( <a href="https://aopwiki.org/events/1523">https://aopwiki.org/events/1523</a> )	Decrease, Cuticular chitin content
3	KE	1524	Increase, Premature molting ( <a href="https://aopwiki.org/events/1524">https://aopwiki.org/events/1524</a> )	Increase, Premature molting
4	AO	350	Increase, Mortality ( <a href="https://aopwiki.org/events/350">https://aopwiki.org/events/350</a> )	Increase, Mortality

### Key Event Relationships

Upstream Event	Relationship Type	Downstream Event	Evidence	Quantitative Understanding
Increase, Chitin synthase 1 inhibition ( <a href="https://aopwiki.org/relationships/1742">https://aopwiki.org/relationships/1742</a> )	adjacent	Decrease, Cuticular chitin content	Moderate	Low
Decrease, Cuticular chitin content ( <a href="https://aopwiki.org/relationships/1743">https://aopwiki.org/relationships/1743</a> )	adjacent	Increase, Premature molting	Moderate	Low
Increase, Premature molting ( <a href="https://aopwiki.org/relationships/1744">https://aopwiki.org/relationships/1744</a> )	adjacent	Increase, Mortality	Moderate	Low

### Stressors

Name	Evidence
Polyoxin B	High
Polyoxin D	High
Nikkomycins	High
Captan	Moderate
Captafol	Moderate
Folpet	Moderate

## Overall Assessment of the AOP

### Domain of Applicability

#### Life Stage Applicability

Life Stage	Evidence
larvae	High
Juvenile	High
Adult	Moderate

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Pieris brassicae	Pieris brassicae	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7116">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7116</a> )
Anopheles gambiae	Anopheles gambiae	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7165">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7165</a> )
Lucilia cuprina	Lucilia cuprina	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375</a> )
Tribolium castaneum	Tribolium castaneum	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7070">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7070</a> )
Bombyx mori	Bombyx mori	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7091">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7091</a> )
Anopheles quadrimaculatus	Anopheles quadrimaculatus	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7166">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7166</a> )
Trichoplusia ni	Trichoplusia ni	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7111">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7111</a> )
Artemia salina	Artemia salina	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=85549">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=85549</a> )
Daphnia magna	Daphnia magna	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525</a> )
Hyalophora cecropia	Hyalophora cecropia	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7123">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7123</a> )
Ostrinia nubilalis	Ostrinia nubilalis	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=29057">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=29057</a> )

Term	Scientific Term	Evidence	Links
Bradysia hygida	Bradysia hygida	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35572">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35572</a> )
Mamestra brassicae	Mamestra brassicae	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=55057">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=55057</a> )
Chilo suppressalis	Chilo suppressalis	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=168631">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=168631</a> )
Locusta migratoria	Locusta migratoria	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7004">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7004</a> )
Nilaparvata lugens	Nilaparvata lugens	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=108931">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=108931</a> )
Aphis glycines	Aphis glycines	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=307491">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=307491</a> )
Lepeophtheirus salmonis	Lepeophtheirus salmonis	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=72036">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=72036</a> )
Panonychus citri	Panonychus citri	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=50023">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=50023</a> )
Grapholita molesta	Grapholita molesta	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=192188">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=192188</a> )
Ectropis obliqua	Ectropis obliqua	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=248899">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=248899</a> )
Tigriopus japonicus	Tigriopus japonicus	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=158387">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=158387</a> )

#### Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Effect data along the AOP exist from Dipteran, Lepidopteran and Coleopteran insect species as well as from Branchiopods and Anostracans of the crustacea . Sequence alignment of CHS1 protein sequences using the Sequence Alignment to Predict Across Species Susceptibility (SeqAPASS, <https://seqapass.epa.gov/seqapass> (<https://seqapass.epa.gov/seqapass/info.xhtml>)) tool, yielded susceptibility predictions for various insect species, arachnids and crustacean taxa such as branchiopods, hexanauplia, malacostraca and merostomata. However, most of the protein sequences were not identified as CHS-1. The alignment of amino acid residues believed to be critical for ligand binding were therefore carried out with sequences identified as CHS1. Evidence was rated as high for species with a susceptibility prediction and/or effect data. Evidence was rated as moderate when only alignment data were available. Although most of the sequences are not annotated as CHS-1, all arthropods rely on the synthesis of cuticular chitin therefore it is extremely likely that the AOP is applicable to all arthropods.

**Life stage:** The AOP is applicable for organisms undergoing continuous molt cycles. As insects do not molt in their adulthood, the AOP is only applicable for larval and pupal stages of insects. Crustaceans and arachnids grow and molt throughout their lifetime (Passano 1961; Uhl et al. 2015), which makes the AOP applicable to all life stages, where juvenile life stages might be more susceptible to chemical perturbations due to higher growth rate and therefore more frequent molting .

**Sex:** The AOP is applicable to all sexes.

**Chemical:** Substances known to trigger the MIE and leading to the AO are of the family of pyrimidine nucleosides (e.g. polyoxin D, polyoxin B and nikkomycin Z) (Osada 2019). There also exists evidence for phthalimides (captan, captafol and folpet) to inhibit CHS-1 activity and to decrease the cuticular chitin content *in vitro* (Cohen and Casida 1982; Gelman and Borkovec 1986). However, as these substances are known to covalently bind to thiol groups in proteins (Lukens and Sisler 1958), it is not clear if the inhibition is due to specific CHS-1 inhibition or due to unspecific protein binding.

## Essentiality of the Key Events

The essentiality of all key events was considered as high. Essentiality evaluations were mainly based on specifically designed studies demonstrating the expected effect pattern predicted by the AOP to occur after knockdown of CHS-1.

**Inhibition, Cuticular chitin synthase (High):** Knockdown of the cuticular chitin synthase leads to the expected pattern of effects described in this AOP. It decreases the cuticular chitin content and leads to premature molting associated mortality in insects (Arakane et al. 2005; X. Zhang et al. 2010; Li et al. 2017; Zhai et al. 2017). If the cuticular chitin content was not directly measured as endpoint, knockdown of the CHS-1 led directly to the occurrence of premature molting associated increase of mortality (Chen et al. 2008; X. Zhang et al. 2010; Wang et al. 2012; Yang et al. 2013; Shang et al. 2016; Mohammed et al. 2017; Wang et al. 2019; Ye et al. 2019; Ullah et al. 2020).

**Decrease, Cuticular chitin content (High):** Abolishment of the cuticular chitin synthesis through knockdown of CHS-1 leads to premature molting associated mortality (Arakane et al. 2005; X. Zhang et al. 2010; Li et al. 2017; Zhai et al. 2017). By knocking down the UDP-GlcNAc pyrophosphorylase (UAP), which catalyzes the last sugar conversion before the polymerization to chitin, it was shown that reduced chitin synthesis leads to the same outcome as the knockdown of CHS-1. Namely premature molting and increased mortality (Arakane et al. 2011; Liu et al. 2013). Knockdown of trehalase genes, which constitutes the start of the chitin synthetic pathway and convert trehalose to glucose, leads to a similar pattern of effects, namely premature molting associated mortality (Chen et al. 2010; Shi et al. 2016).

**Increase, Premature molting (High):** Several studies show that premature molting is a direct consequence of decreased chitin synthesis and leads to increased mortality. The KE is consistently listed as cause for mortality when CHS-1 is knocked down throughout a number of studies (Arakane et al. 2005; Chen et al. 2008; J. Zhang et al. 2010; X. Zhang et al. 2010; Wang et al. 2012; Yang et al. 2013; Shang et al. 2016; Li et al. 2017; Mohammed et al. 2017; Zhai et al. 2017; Wang et al. 2019; Ye et al. 2019; Ullah et al. 2020).

**Increase, Mortality (High):** Increased mortality was observed in all of the abovementioned studies.

## Weight of Evidence Summary

**Biological Plausibility:** The biosynthesis of chitin is well characterized and is conserved among arthropods. Although the exact mode of action of chitin synthases remains elusive, it is widely accepted and well established that the chitin synthase is the key enzyme in the pathway, polymerizing chitin using UDP-*N*-Acetylglucosamine as substrate (Merzendorfer and Zimoch 2003).

Arthropod cuticles mostly consist of chitin embedded into a matrix of cuticular proteins. It is therefore widely accepted that chitin contributes crucially to the quality and function of the cuticle (Reynolds 1987; Muthukrishnan et al. 2012). The molting process requires the new cuticle to be strong enough to withstand the stresses of ecdysis.

During ecdysis, arthropods pause food intake and growth. If ecdysis is initiated before the new cuticle is strong enough, the organism likely dies of starvation or growth arrest (Song, Villeneuve, et al. 2017). It was also reported that certain arthropods pause respiration during ecdysis, which may lead to suffocation (Camp et al. 2014).

Based on the well-established biological knowledge on the processes this AOP bases on, the biological plausibility for all KER was rated as high.

**Empirical Evidence:** Empirical evidence assessment was conducted on the basis of *in vitro* and *in vivo* experiments performed with stressors affecting key events throughout the AOP. Studies showed that the key events are affected by model stressors such as Polyoxin D and Nikkomycin Z, which are able to competitively inhibit CHS1 (Endo et al. 1970). Several studies provide evidence that polyoxin B, polyoxin D and nikkomycin Z trigger the MIE (Cohen 1982; Turnbull and Howells 1982; Kuwano and Cohen 1984; Cohen and Casida 1990; Zhang and Yan Zhu 2013). Also the cuticular chitin content was shown to be decreased by polyoxin D and nikkomycin Z (Gijswijt et al. 1979; Calcott and Fatig 1984; Gelman and Borkovec 1986; Zhuo et al. 2014). The AO is supported by *in vivo* studies with polyoxin D and nikkomycin Z (Tellam et al. 2000; Tellam and Eisemann 2000; Zhu et al. 2007; Zhang and Yan Zhu 2013; New Zealand Environmental Protection Authority 2015).

A major data gap constitutes the absence of data covering the KE "Increase, premature molting". This KE is mentioned in some studies but never assessed as an individual endpoint (Gijswijt et al. 1979; Tellam et al. 2000).

Another major data gap is the lacking quantitative data connecting KE by KERs. As endpoints were only measured as individual endpoints and not in sequence, it makes it nearly impossible to evaluate the dose and temporal concordance for the KEs and KERs.

Based on the major data gaps and therefore the lacking information on dose and temporal concordance of the KER empirical evidence was evaluated to be low for the whole AOP.

**Overall confidence in the AOP:** Both, essentiality of KEs and the biological plausibility of the whole AOP were considered to be high. However, due to lack of quantitative data, empirical evidence was judged to be low. Therefore the overall confidence in the AOP was evaluated as moderate.

## Quantitative Consideration

Quantitative data are limited for all KER and therefore the whole AOP. Therefore, predictions on the occurrence of downstream KE and the AO on the basis of the occurrence of upstream KEs is not readily feasible. Quantitative understanding of the AOP was therefore considered to be low.

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

Arthropods are responsible for many functions in terrestrial as well as aquatic ecosystems and are therefore jointly responsible for ecosystem health (Seastedt and Crossley 1984; Losey and Vaughan 2006; LeBlanc 2007). Therefore, it is important to develop AOPs which enhance the mechanistic knowledge on chemicals, such as chitin synthesis inhibitors, which may pose a risk to non-target arthropods. Those AOPs will contribute to the systematic use of mechanistic data to preserve beneficial arthropod populations and ecosystem health.

The present AOP will help to guide future experimental studies by identifying data gaps and missing links. This will lead to the identification and development suitable bioassays in order to populate the AOP with (quantitative) experimental data which may allow for predictions of regulatory relevant endpoints on the basis of the occurrence of the MIE.

The present AOP may also guide screening strategies in order to broaden its chemical applicability domain. The identified substances may then be prioritized and undergo a thorough hazard assessment.

As there already exist approaches to assess mixture toxicity using the AOP framework (Altenburger et al. 2012; Beyer et al. 2014), the present

AOP could be employed for the effect assessment of mixtures of chemicals that share the same KEs (e.g. AOP #361, [aopwiki.org/aops/361](https://aopwiki.org/aops/361) (<https://aopwiki.org/aops/361>), AOP #358, [aopwiki.org/aops/358](https://aopwiki.org/aops/358) (<https://aopwiki.org/aops/358>), and AOP #359, [aopwiki.org/aops/359](https://aopwiki.org/aops/359) (<https://aopwiki.org/aops/359>)).

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## Appendix 1

### List of MIEs in this AOP

Event: 1522: Increase, Chitin synthase 1 inhibition (<https://aopwiki.org/events/1522>)

Short Name: Increase, CHS-1 inhibition

#### Key Event Component

Process	Object	Action
chitin synthase activity		decreased

#### AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:342 - S-adenosylmethionine depletion leading to population decline (1) ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	MolecularInitiatingEvent
Aop:360 - Chitin synthase 1 inhibition leading to mortality ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	MolecularInitiatingEvent

#### Stressors

Name
Polyoxin B
Polyoxin D
Nikkomycins
Captan

#### Biological Context

Level of Biological Organization
Molecular

#### Cell term

Cell term
cuticle secreting cell

#### Organ term

Organ term
epithelium

### Evidence for Perturbation by Stressor

#### Overview for Molecular Initiating Event

Stressors known to competitively inhibit CHS1 are polyoxin B, polyoxin D and Nikkomycin Z (Cohen and Casida 1982; Cohen and Casida 1990; Zhang and Yan Zhu 2013). There may also be stressors that inhibit CHS-1 in a non-competitive manner which may become apparent in further

characterization efforts of this MIE. There is also a study that reports inhibition of CHS-1 by the phthalimide fungicide captan (Cohen and Casida 1982). However, it remains elusive if the observed inhibition is due to specific interaction with the enzyme or due to unspecific protein binding which is the predominant mode of action of phthalimides (Lukens and Sisler 1958).

## Domain of Applicability

### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Anopheles gambiae	Anopheles gambiae	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7165">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7165</a> )
Tribolium castaneum	Tribolium castaneum	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7070">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7070</a> )
Trichoplusia ni	Trichoplusia ni	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7111">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7111</a> )
Hyalophora cecropia	Hyalophora cecropia	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7123">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7123</a> )
Bradysia hygida	Bradysia hygida	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35572">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35572</a> )
Mamestra brassicae	Mamestra brassicae	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=55057">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=55057</a> )
Chilo suppressalis	Chilo suppressalis	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=168631">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=168631</a> )
Locusta migratoria	Locusta migratoria	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7004">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7004</a> )
Nilaparvata lugens	Nilaparvata lugens	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=108931">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=108931</a> )
Aphis glycines	Aphis glycines	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=307491">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=307491</a> )
Lepeophtheirus salmonis	Lepeophtheirus salmonis	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=72036">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=72036</a> )
Panonychus citri	Panonychus citri	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=50023">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=50023</a> )
Grapholita molesta	Grapholita molesta	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=192188">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=192188</a> )
Ectropis obliqua	Ectropis obliqua	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=248899">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=248899</a> )
Tigriopus japonicus	Tigriopus japonicus	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=158387">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=158387</a> )

### Life Stage Applicability

Life Stage	Evidence
larvae	High
Juvenile	High
Adult	Moderate

## Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Effect data for the occurrence of CHS1 inhibition exist from Dipteran, Lepidopteran and Coleopteran insect species. Sequence alignment of CHS1 protein sequences using the Sequence Alignment to Predict Across Species Susceptibility (SeqAPASS, <https://seqapass.epa.gov/seqapass> (<https://seqapass.epa.gov/seqapass/info.xhtml>)) tool, yielded susceptibility predictions for various insect species, arachnids and crustacean taxa such as branchiopods, hexanauplia, malacostraca and merostomata. However, most of the protein sequences were not identified as CHS1. The alignment of amino acid residues believed to be critical for ligand binding were therefore carried out with sequences identified as CHS1. Evidence was rated as high for species with a susceptibility prediction and/or effect data. Evidence was rated as moderate when only alignment data were available. Although most of the sequences are not annotated as CHS1, all arthropods rely on the synthesis of cuticular chitin therefore it is extremely likely that the AOP is applicable to the whole phylum of arthropods.

**Life stage:** This MIE is applicable for organisms undergoing continuous molt cycles. Namely larval stages of insects and all life stages of crustaceans and arachnids.

**Sex:** The MIE is applicable to all sexes.

**Chemical:** Substances known to trigger inhibit CHS-1 are of the family of pyrimidine nucleosides (e.g. polyoxin D, polyoxin B and nikkomycin Z) (Cohen and Casida 1982; Kuwano and Cohen 1984; Cohen and Casida 1990; Zhang and Yan Zhu 2013; Osada 2019). There also exists evidence for the phthalimide captan to inhibit CHS-1 activity *in vitro* (Cohen and Casida 1982). However, as phthalimides are known to covalently bind to thiol groups in proteins (Lukens and Sisler 1958), it is not clear if the inhibition is due to specific CHS-1 inhibition or due to unspecific protein binding.

## Key Event Description

Chitin synthases are essential enzymes for all organisms synthesizing chitin, for example arthropods and fungi (Latgé 2007; Merzendorfer 2011). Chitin synthases polymerize chitin and subsequently translocate chitin through the cell membrane (Merzendorfer 2006; Merzendorfer 2011). In arthropods, two isoforms of the chitin synthase are known, CHS1, which is responsible for the synthesis of cuticular chitin, and chitin synthase isoform 2, which synthesizes chitin in the midgut (Arakane et al. 2005). In this MIE, inhibition of CHS-1 is characterized. The biological state being measured is the activity of the enzyme. CHS-1 has an essential role in the cuticle biology, as it constitutes the last and most critical step in the chitin biosynthetic pathway by catalyzing the polymerization of UDP-GlcNAc to chitin (Merzendorfer and Zimoch 2003; Merzendorfer 2006).

## How it is Measured or Detected

Since the purification or even recombinant production of CHS1 has not been achieved yet, the most common way is to use crude enzyme preparations for CHS1 activity assays. It is noteworthy that in crude enzyme preparations of whole organisms both CHS isoforms, CHS1 and CHS2, are present. However, the expression of CHS1 was shown to be much higher than CHS2 in *Anopheles gambiae* (Zhang et al. 2012), therefore the effect of CHS2 may be regarded as negligible. Alternatively, the digestive tract of the respective organism could be removed before producing the enzyme preparation. Different ways exist to detect the activity of the enzyme. One can incubate the enzyme preparation with radioactively labelled chitin precursors (e.g. 14C-UDP-GlcNAc) and measure radioactivity in the formed chitin chains by scintillation counting (Cohen 1982; Cohen and Casida 1990). Another approach for the detection of CHS1 activity involves the binding of formed chitin chains to wheat germ agglutinin (WGA) which possesses specific chitin binding properties (Lucero et al. 2002; Zhang and Yan Zhu 2013). The assay builds on the principle of a sandwich-ELISA, where chitin binds to a layer of WGA. A second layer of WGA which is conjugated to horseradish peroxidase (HRP) is then added and subsequently incubated with a HRP substrate. The cleavage of the HRP substrate leads to color formation and the amount of chitin synthesized can be determined colorimetrically.

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## AOP360

Lukens RJ, Sisler HD. 1958. 2-Thiazolidinethione-4-carboxylic acid from the reaction of captan with cysteine. *Science* (80- ). 127(3299):650. doi:10.1126/science.127.3299.650.

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Merzendorfer H, Zimoch L. 2003. Chitin metabolism in insects: structure, function and regulation of chitin synthases and chitinases. *J Exp Biol*. 206(24):4393 LP – 4412. doi:10.1242/jeb.00709. <http://jeb.biologists.org/content/206/24/4393.abstract>.

Osada H. 2019. Discovery and applications of nucleoside antibiotics beyond polyoxin. *J Antibiot (Tokyo)*. 72(12):855–864. doi:10.1038/s41429-019-0237-1. <http://dx.doi.org/10.1038/s41429-019-0237-1>.

Zhang X, Yan Zhu K. 2013. Biochemical characterization of chitin synthase activity and inhibition in the African malaria mosquito, *Anopheles gambiae*. *Insect Sci*. 20(2):158–166. doi:10.1111/j.1744-7917.2012.01568.x.

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## List of Key Events in the AOP

Event: 1523: Decrease, Cuticular chitin content (<https://aopwiki.org/events/1523>)

Short Name: Decrease, Cuticular chitin content

### Key Event Component

Process	Object	Action
cuticle development	cuticle	decreased

### AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:343 - S-adenosylmethionine depletion leading to population decline (2) ( <a href="https://aopwiki.org/aops/343">https://aopwiki.org/aops/343</a> )	KeyEvent
Aop:342 - S-adenosylmethionine depletion leading to population decline (1) ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	KeyEvent
Aop:360 - Chitin synthase 1 inhibition leading to mortality ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	KeyEvent
Aop:361 - Sulfonylureareceptor binding leading to mortality ( <a href="https://aopwiki.org/aops/361">https://aopwiki.org/aops/361</a> )	KeyEvent

### Stressors

Name
Polyoxin D
Nikkomycins
Captan
Captafol
Folpet

### Biological Context

Level of Biological Organization
Tissue

### Organ term

Organ term
cuticle

## Domain of Applicability

## Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Pieris brassicae	Pieris brassicae	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7116">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7116</a> )
Lucilia cuprina	Lucilia cuprina	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375</a> )
Bombyx mori	Bombyx mori	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7091">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7091</a> )
Artemia salina	Artemia salina	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=85549">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=85549</a> )
Ostrinia nubilalis	Ostrinia nubilalis	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=29057">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=29057</a> )

## Life Stage Applicability

Life Stage	Evidence
larvae	High
Juvenile	High
Adult	Moderate

## Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Effect data for the occurrence of this KE exist from *Pieris brassicae*, *Lucilia cuprina*, *Bombyx mori*, *Artemia salina* and *Ostrinia nubilalis*, defining its taxonomic applicability. Most likely, this KE is applicable to the whole phylum of arthropods, as they all rely on chitin as part of their exoskeleton.

**Life stage:** This KE is applicable for organisms synthesizing chitin in order to grow and develop, namely larval stages of insects and all life stages of crustaceans and arachnids.

**Sex:** This KE is applicable to all sexes.

**Chemical:** Substances known decrease the cuticular chitin content are of the family of pyrimidine nucleosides (e.g. polyoxin D and nikkomycin Z) (Gijswijt et al. 1979; Turnbull and Howells 1982; Calcott and Fatig 1984; Zhuo et al. 2014; Osada 2019). There also exists evidence for phthalimides (captan, captafol and folpet) to decrease the cuticular chitin content *in vitro* (Gelman and Borkovec 1986). However, as these substances are known to covalently bind to thiol groups in proteins (Lukens and Sisler 1958), it is not clear if the inhibition is due to specific CHS-1 inhibition or due to unspecific protein binding.

## Key Event Description

This key event describes the decrease in cuticular chitin content. Chitin is a major part of the arthropod cuticle and therefore also responsible for its integrity (Reynolds 1987; Muthukrishnan et al. 2012). The cuticle is the exoskeleton of arthropods and has manifold functions, it protects organisms from predators, loss of water, acts as a physical barrier against microbial pathogens and provides support for muscular function (Vincent and Wegst 2004). Hence, cuticular chitin is also indispensable for the development of arthropods, as an immaculate cuticle is required for proper molting and therefore also for the growth of an organism.

During molting, the newly secreted cuticle is subject to mechanical stress associated and therefore needs to possess enough structural and functional integrity. The ecdysis motor program, which constitutes the behavioral part of the cuticle shedding requires the newly secreted cuticle to possess a certain strength to support for muscular force in order to shed the old cuticle (Ewer 2005). Cuticular integrity is also important after

ecdysis, as insects and crustaceans expand their new cuticle by increasing internal pressure by swallowing air and water, respectively. This happens in order to expand and provide stability to the new cuticle until it is hardened (tanned) (Clarke 1957; Lee 1961; Dall et al. 1978; deFur et al. 1985).

## How it is Measured or Detected

Several ways to determine cuticular chitin are described in the literature. Some of them are based on the determination of amino sugars after digestion or hydrolysis of chitin. For example, after the digestion of chitin by a bacterial chitinase, the GlcNAc amount can be determined colorimetrically by a modified Morgan-Elson assay (Reissig et al. 1955; Arakane et al. 2005). Alternatively, one can also quantify glucosamine colorimetrically after deacetylation and hydrolysis of chitin (Lehmann and White 1975; Zhang and Zhu 2006).

There also exists an approach based on the detection of fluorescence after staining with calcofluor white. In this assay, no treatment of the samples is necessary, the detection is carried out in homogenates of the respective organisms as calcofluor white directly binds to chitin (Henriques et al. 2020).

Chitin can also be quantified using radioactively labelled precursors (e.g.  $^{14}\text{C}$ -UDP-GlcNAc) which are incorporated into *in vitro* cultured integument pieces or into the cuticle of whole organisms (Gijswijt et al. 1979; Turnbull and Howells 1982; Calcott and Fatig 1984; Gelman and Borkovec 1986).

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## AOP360

Event: 1524: Increase, Premature molting (<https://aopwiki.org/events/1524>)

Short Name: Increase, Premature molting

Key Event Component

Process	Object	Action
ecdysis, chitin-based cuticle		decreased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:343 - S-adenosylmethionine depletion leading to population decline (2) ( <a href="https://aopwiki.org/aops/343">https://aopwiki.org/aops/343</a> )	KeyEvent
Aop:342 - S-adenosylmethionine depletion leading to population decline (1) ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	KeyEvent
Aop:358 - Chitinase inhibition leading to mortality ( <a href="https://aopwiki.org/aops/358">https://aopwiki.org/aops/358</a> )	KeyEvent
Aop:359 - Chitobiase inhibition leading to mortality ( <a href="https://aopwiki.org/aops/359">https://aopwiki.org/aops/359</a> )	KeyEvent
Aop:360 - Chitin synthase 1 inhibition leading to mortality ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	KeyEvent
Aop:361 - Sulfonylureareceptor binding leading to mortality ( <a href="https://aopwiki.org/aops/361">https://aopwiki.org/aops/361</a> )	KeyEvent

Stressors

Name
Polyoxin D
Nikkomycins

Biological Context

Level of Biological Organization
Individual

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Pieris brassicae	Pieris brassicae	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7116">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7116</a> )
Lucilia cuprina	Lucilia cuprina	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375</a> )

Life Stage Applicability

Life Stage	Evidence
larvae	High
Juvenile	High
Adult	Moderate

Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Effect data for the occurrence of this KE exist from *Pieris brassicae* and *Lucilia cuprina*, defining its taxonomic applicability. However, all arthropods undergo molting, so it is highly likely that this KE is applicable to the whole phylum of arthropods.

**Life stage:** This KE is applicable for organisms that undergo molting in order to grow and develop, namely larval stages of insects and all life stages of crustaceans and arachnids.

**Sex:** This KE is applicable to all sexes.

**Chemical:** Substances known to induce premature molting are of the family of pyrimidine nucleosides (e.g. polyoxin D and nikkomycin Z) (Gijswijt et al. 1979; Tellam et al. 2000; Arakawa et al. 2008).

## Key Event Description

This key event is measured on the level of the individual. In order to grow and develop, arthropods need to shed their exoskeleton periodically (Heming 2018). If they are not able to molt properly, the organism will eventually die. Premature molting summarizes a variety of effects related to molting disruption. It describes the unsuccessful molting where the organism is not able to shed the old cuticle, but also other effects related to molting in an immature stage where the new cuticle is not mature enough for the molt, such as rupture of the new cuticle and associated desiccation, deformities, higher susceptibility to pathogens or impaired locomotion.

## How it is Measured or Detected

Premature molting can be determined by observation. For example, during an OECD 202 *Daphnia* sp. Acute immobilization test (OECD 2004), the cumulative number of molts can be assessed as an additional endpoint. One could even prolong the test to 96h to get a clearer result of this endpoint. Additionally, one could apply histopathological methods to monitor the maturity of the newly synthesized cuticle (e.g. thickness of procuticle).

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## List of Adverse Outcomes in this AOP

Event: 350: Increase, Mortality (<https://aopwiki.org/events/350>)

Short Name: Increase, Mortality

### Key Event Component

Process	Object	Action
mortality		increased

## AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:4 - Ecdysone receptor agonism leading to incomplete ecdysis associated mortality ( <a href="https://aopwiki.org/aops/4">https://aopwiki.org/aops/4</a> )	KeyEvent
Aop:286 - Mitochondrial complex III inhibition leading to growth inhibition (1) ( <a href="https://aopwiki.org/aops/286">https://aopwiki.org/aops/286</a> )	AdverseOutcome

## AOP360

AOP ID and Name	Event Type
Aop:287 - Mitochondrial complex III inhibition leading to growth inhibition (2) ( <a href="https://aopwiki.org/aops/287">https://aopwiki.org/aops/287</a> )	AdverseOutcome
Aop:331 - Formation of DNA photoproducts leading to growth inhibition (1) ( <a href="https://aopwiki.org/aops/331">https://aopwiki.org/aops/331</a> )	AdverseOutcome
Aop:327 - Excessive reactive oxygen species production leading to mortality (1) ( <a href="https://aopwiki.org/aops/327">https://aopwiki.org/aops/327</a> )	AdverseOutcome
Aop:328 - Excessive reactive oxygen species production leading to mortality (2) ( <a href="https://aopwiki.org/aops/328">https://aopwiki.org/aops/328</a> )	AdverseOutcome
Aop:329 - Excessive reactive oxygen species production leading to mortality (3) ( <a href="https://aopwiki.org/aops/329">https://aopwiki.org/aops/329</a> )	AdverseOutcome
Aop:330 - Excessive reactive oxygen species production leading to mortality (4) ( <a href="https://aopwiki.org/aops/330">https://aopwiki.org/aops/330</a> )	AdverseOutcome
Aop:343 - S-adenosylmethionine depletion leading to population decline (2) ( <a href="https://aopwiki.org/aops/343">https://aopwiki.org/aops/343</a> )	AdverseOutcome
Aop:342 - S-adenosylmethionine depletion leading to population decline (1) ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	AdverseOutcome
Aop:358 - Chitinase inhibition leading to mortality ( <a href="https://aopwiki.org/aops/358">https://aopwiki.org/aops/358</a> )	AdverseOutcome
Aop:359 - Chitobiase inhibition leading to mortality ( <a href="https://aopwiki.org/aops/359">https://aopwiki.org/aops/359</a> )	AdverseOutcome
Aop:360 - Chitin synthase 1 inhibition leading to mortality ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	AdverseOutcome
Aop:361 - Sulfonyleareceptor binding leading to mortality ( <a href="https://aopwiki.org/aops/361">https://aopwiki.org/aops/361</a> )	AdverseOutcome

### Stressors

Name
Polyoxin D
Nikkomycins

### Biological Context

Level of Biological Organization
Individual

### Domain of Applicability

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
Lucilia cuprina	Lucilia cuprina	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=7375</a> )
Daphnia magna	Daphnia magna	High	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525</a> )

#### Life Stage Applicability

Life Stage	Evidence
All life stages	High

#### Sex Applicability

Sex	Evidence
Unspecific	High

**Taxonomic:** This AO is applicable to all living organisms.

**Life stage:** This AO is applicable to all life stages.

**Sex:** This AO is applicable to all sexes.

**Chemical:** Substances known to increase mortality in arthropods are of the family of pyrimidine nucleosides (e.g. polyoxin D and nikkomycin Z) (Gijswijt et al. 1979; Tellam et al. 2000; Arakawa et al. 2008).

## Key Event Description

This key event is observed at the biological level of the individual and describes the increase of mortality of individuals upon exposure to a stressor.

## How it is Measured or Detected

The AO can be detected by observation, for example by immobilization of the respective organisms. There exist guidelines for the characterization of this AO in arthropods. For example, the OECD 202 *Daphnia* sp. Acute immobilization test (OECD 2004) which can also be modified depending on the effect one expects.

## Regulatory Significance of the AO

The Adverse Outcome is highly significant from a regulatory point of view. It is employed as regulatory endpoint in most studies assessing the toxicity of stressors.

## References

- Arakawa T, Yukuhiro F, Noda H. 2008. Insecticidal effect of a fungicide containing polyoxin B on the larvae of *Bombyx mori* (Lepidoptera: Bombycidae), *Mamestra brassicae*, *Mythimna separata*, and *Spodoptera litura* (Lepidoptera: Noctuidae). *Appl Entomol Zool.* 43(2):173–181. doi:10.1303/aez.2008.173.
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# Appendix 2

## List of Key Event Relationships in the AOP

### List of Adjacent Key Event Relationships

Relationship: 1742: Increase, CHS-1 inhibition leads to Decrease, Cuticular chitin content (<https://aopwiki.org/relationships/1742>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
<b>S-adenosylmethionine depletion leading to population decline (1)</b> ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	adjacent		
<b>Chitin synthase 1 inhibition leading to mortality</b> ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	adjacent	Moderate	Low

Evidence Supporting Applicability of this Relationship

**Taxonomic Applicability**

Term	Scientific Term	Evidence	Links
crustaceans	Daphnia magna	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525</a> )
insects	insects	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=0">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=0</a> )

**Life Stage Applicability**

Life Stage	Evidence
larvae	High
Juvenile	High
Adult	Moderate

**Sex Applicability**

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Likely, this KER is applicable to the whole phylum of arthropods as they all depend on the synthesis of chitin.

**Life stage:** This KER is applicable for organisms synthesizing chitin in order to grow and develop, namely larval stages of insects and all life stages of crustaceans and arachnids.

**Sex:** This KER is applicable to all sexes.

**Chemical:** Substances inducing both, the inhibition of CHS-1 and the decrease in cuticular chitin content are of the family of pyrimidine nucleosides (e.g. polyoxin D, polyoxin B and nikkomycin Z) (Gijswijt et al. 1979; Cohen and Casida 1982; Turnbull and Howells 1982; Calcott and Fatig 1984; Kuwano and Cohen 1984; Cohen and Casida 1990; Zhang and Yan Zhu 2013; Zhuo et al. 2014; Osada 2019). The phthalimide captan was also shown to induce CHS-1 inhibition and a decrease in cuticular chitin content (Cohen and Casida 1982; Gelman and Borkovec 1986). However, studies assessing both endpoints in sequence are lacking.

**Key Event Relationship Description**

Chitin in the arthropod cuticle is synthesized by the chitin synthase isoform 1 (CHS-1) which spans the plasma membrane on the apical plasma membrane of epithelial cells (Locke and Huie 1979; Binnington 1985; Merzendorfer and Zimoch 2003; Merzendorfer 2006). Since CHS-1 is the enzyme to polymerize chitin from UDP-*N*-Acetylglucosamine (UDP-GlcNAc) (Merzendorfer 2006), it is solely responsible for the content of chitin in the exoskeleton. Consequently, the inhibition of CHS-1 leads to a decrease in chitin content in the arthropod cuticle.

**Evidence Supporting this KER****Biological Plausibility**

The process of chitin synthesis in arthropods is well characterized. Although the exact mechanism of the polymerization reaction remains elusive, CHS-1 is known to be the key enzyme in the biosynthesis of chitin and therefore, responsible for the cuticular chitin content (Merzendorfer and Zimoch 2003; Merzendorfer 2006). Therefore, the biological plausibility of this KER can be regarded as high.

**Empirical Evidence**

Empirical evidence for the occurrence of both KEs, the inhibition of CHS-1 and the decrease in cuticular chitin content exist. For example, the occurrence of chitin synthase inhibition was characterized using cell free crude enzyme preparations *in vitro* from coleopteran, lepidopteran and dipteran insect species upon treatment with polyoxin B, polyoxin D and nikkomycin Z (Cohen and Casida 1982; Kuwano and Cohen 1984; Cohen and Casida 1990; Zhang and Yan Zhu 2013). The cuticular chitin content was characterized *in vivo* in *Artemia salina* or using cultured integumental tissue from lepidopteran and dipteran species after exposure to polyoxin D and nikkomycin Z as well as the phthalimides captan, captafol, and folpet (Gijswijt et al. 1979; Turnbull and Howells 1982; Calcott and Fatig 1984; Gelman and Borkovec 1986; Zhuo et al. 2014). However, studies assessing both endpoints and therefore linking both KEs are lacking.

**Uncertainties and Inconsistencies**

The major uncertainty in this KER is the absence of studies which assess both, the inhibition of the chitin synthase and the decrease in cuticular chitin content.

**Quantitative Understanding of the Linkage****Response-response relationship**

Due to the lack of studies linking the inhibition of CHS-1 to the decrease in cuticular chitin content, it is not possible to describe the nature of the response-response relationship.

**Time-scale**

Due to the lack of studies assessing the inhibition of CHS-1 and the decrease in cuticular chitin content, it is not possible to make a statement on the timescale of the relationship. However, the expression of CHS-1 peaks at the time of ecdysis (Ampasala et al. 2011; Wang et al. 2012),

indicating the highest rate of chitin synthesis at this timepoint. Hence it can be assumed that a decrease in chitin content in the newly synthesized cuticle should become apparent shortly after.

#### Known modulating factors

CHS is dependent on bivalent ions as cofactor such as  $Mg^{2+}$  or  $Mn^{2+}$  (Merzendorfer 2006). Both low and high levels of  $Mg^{2+}$  inhibited CHS activity *in vitro* (Zhang and Yan Zhu 2013).

#### Known Feedforward/Feedback loops influencing this KER

Upon knockdown of CHS-1 in the salmon louse *Lepeophtheirus salmonis*, upregulation of the UDP-GlcNAc pyrophosphorylase (UAP), which catalyzes the conversion of GlcNAc to UDP-GlcNAc, was observed (Braden et al. 2020). The knockdown of UAP also led to upregulation of CHS-1 demonstrating a clear dependence of the two enzymes. Most likely, the upregulation of UAP is a compensatory mechanism with the goal to restore homeostasis in absence of CHS-1. The exact regulation of the feedback, however, remains to be investigated.

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Relationship: 1743: Decrease, Cuticular chitin content leads to Increase, Premature molting (<https://aopwiki.org/relationships/1743>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
S-adenosylmethionine depletion leading to population decline (2) ( <a href="https://aopwiki.org/aops/343">https://aopwiki.org/aops/343</a> )	adjacent		
S-adenosylmethionine depletion leading to population decline (1) ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	adjacent		
Chitin synthase 1 inhibition leading to mortality ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	adjacent	Moderate	Low
Sulfonylureareceptor binding leading to mortality ( <a href="https://aopwiki.org/aops/361">https://aopwiki.org/aops/361</a> )	adjacent	Moderate	Moderate

#### Evidence Supporting Applicability of this Relationship

##### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
crustaceans	Daphnia magna	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525</a> )
insects	insects	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=0">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=0</a> )

##### Life Stage Applicability

Life Stage	Evidence
larvae	High
Juvenile	High
Adult	Moderate

##### Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** In all likelihood, this KER is applicable to the whole phylum of arthropods as they all depend on the synthesis of chitin and molting in order to develop.

**Life stage:** This KER is applicable for organisms synthesizing chitin and molting in order to grow and develop, namely larval stages of insects and all life stages of crustaceans and arachnids.

**Sex:** This KER is applicable to all sexes.

**Chemical:** Occurrence of a decrease in cuticular chitin content as well as premature molting was observed after treatment with the pyrimidine nucleosides polyoxin D, polyoxin B and nikkomycin Z (Gijswijt et al. 1979; Turnbull and Howells 1982; Calcott and Fatig 1984; Gelman and Borkovec 1986; Tellam et al. 2000; Arakawa et al. 2008; Zhuo et al. 2014). However, studies causally linking both endpoints are lacking.

#### Key Event Relationship Description

As the arthropod cuticle is a central part in the molting process, its proper composition is indispensable for a proper molt. The ecdysis motor program, the behavioral part of ecdysis, constitutes a distinct motor pattern to split and shed the old cuticle (Ayali 2009). As the cuticle supports muscular function (Vincent and Wegst 2004), it needs to possess a certain integrity in order to successfully molt. The integrity of the cuticle is also important after ecdysis as arthropods, such as insects and crustaceans, expand the new cuticle by swallowing air or water in order to build up pressure to split the old and expand the new exoskeleton and provide stability to the soft new cuticle (Clarke 1957; Lee 1961; Dall et al. 1978; deFur et al. 1985). The arthropod cuticle mostly consists of chitin embedded in and crosslinked with a matrix of proteins (Muthukrishnan et al. 2012). If the chitin content is too low, the cuticle may not possess enough integrity to support muscular function or withstand the beforementioned stresses of ecdysis, which leads to the organism being stuck in the old cuticle or the rupture of the new cuticle.

#### Evidence Supporting this KER

##### Biological Plausibility

The ecdysis motor program, the behavioral part of ecdysis, constitutes a distinct motor pattern to split and shed the old cuticle (Ayali 2009). As

the cuticle supports muscular function (Vincent and Wegst 2004), it needs to possess a certain integrity in order to successfully molt. The integrity of the cuticle is also important after ecdysis as arthropods, such as insects and crustaceans, expand the new cuticle by swallowing air or water in order to build up pressure to expand the new exoskeleton and provide stability to the soft new cuticle (Clarke 1957; Lee 1961; Dall et al. 1978; deFur et al. 1985). The arthropod cuticle mostly consists of chitin embedded in and crosslinked with a matrix of proteins (Muthukrishnan et al. 2012). Given the well biological understanding of the processes, the biological plausibility can be regarded as high.

### Empirical Evidence

The cuticular chitin content was characterized *in vivo* in *Artemia salina* or using cultured integumental tissue from lepidopteran and dipteran insect species after exposure to polyoxin D and nikkomycin Z as well as the phthalimides captan, captafol, and folpet (Gijswijt et al. 1979; Turnbull and Howells 1982; Calcott and Fatig 1984; Gelman and Borkovec 1986; Zhuo et al. 2014). The event of premature molting was not assessed as endpoint in studies involving specific stressors rather than mentioned after exposure to polyoxin D, polyoxin B and nikkomycin Z (Gijswijt et al. 1979; Tellam et al. 2000; Arakawa et al. 2008). Evidence from studies which assess and link both endpoints is lacking.

### Uncertainties and Inconsistencies

The absence of studies (quantitatively) assessing premature molting constitutes a major data gap. A further data gap is the absence of studies which assess both, the decrease in cuticular chitin content and the increase in premature molting.

## Quantitative Understanding of the Linkage

### Response-response relationship

Due to the lack of studies linking the decrease in cuticular chitin content with the increase in premature molting, it is not possible to describe the nature of the response-response relationship.

### Time-scale

Due to the nature of the process, premature molting onsets at the time of ecdysis after the decrease in cuticular chitin content.

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Relationship: 1744: Increase, Premature molting leads to Increase, Mortality (<https://aopwiki.org/relationships/1744>)

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
S-adenosylmethionine depletion leading to population decline (2) ( <a href="https://aopwiki.org/aops/343">https://aopwiki.org/aops/343</a> )	adjacent		
S-adenosylmethionine depletion leading to population decline (1) ( <a href="https://aopwiki.org/aops/342">https://aopwiki.org/aops/342</a> )	adjacent		
Chitinase inhibition leading to mortality ( <a href="https://aopwiki.org/aops/358">https://aopwiki.org/aops/358</a> )	adjacent	Moderate	Low
Chitobiase inhibition leading to mortality ( <a href="https://aopwiki.org/aops/359">https://aopwiki.org/aops/359</a> )	adjacent	Moderate	Low
Chitin synthase 1 inhibition leading to mortality ( <a href="https://aopwiki.org/aops/360">https://aopwiki.org/aops/360</a> )	adjacent	Moderate	Low
Sulfonylureareceptor binding leading to mortality ( <a href="https://aopwiki.org/aops/361">https://aopwiki.org/aops/361</a> )	adjacent	High	High

#### Evidence Supporting Applicability of this Relationship

#### Taxonomic Applicability

Term	Scientific Term	Evidence	Links
crustaceans	Daphnia magna	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=35525</a> )
insects	insects	Moderate	NCBI ( <a href="http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=0">http://www.ncbi.nlm.nih.gov/Taxonomy/Browser/wwwtax.cgi?mode=Info&amp;id=0</a> )

#### Life Stage Applicability

Life Stage	Evidence
larvae	High
Juvenile	Moderate
Adult	Moderate

#### Sex Applicability

Sex	Evidence
Unspecific	Moderate

**Taxonomic:** Likely, this KER is applicable to the whole phylum of arthropods as they all depend on molting in order to develop.

**Life stage:** This KER is applicable for organisms molting in order to grow and develop, namely larval stages of insects and all life stages of crustaceans and arachnids.

**Sex:** This KER is applicable to all sexes.

**Chemical:** Occurrence of premature molting and an increase in mortality observed after treatment with the pyrimidine nucleosides ( e.g. polyoxin D, polyoxin B and nikkomycin Z) (Gijswijt et al. 1979; Tellam et al. 2000; Tellam and Eisemann 2000; Arakawa et al. 2008; New Zealand Environmental Protection Authority 2015). However, studies causally linking both endpoints are lacking.

#### Key Event Relationship Description

During molting, arthropods pause food uptake and in certain cases also respiration (Camp et al. 2014; Song et al. 2017a). If molting is disrupted and the organism is not able to shed the old exoskeleton, the organism may eventually die of starvation, suffocation or the rupture of the exoskeleton.

#### Evidence Supporting this KER

##### Biological Plausibility

In order to grow and develop, arthropods need to molt periodically (Heming 2018). Since molting is a determining point in arthropod development, the disruption of molting leads to increased mortality (Arakawa et al. 2008; Merzendorfer et al. 2012; Song et al. 2017a; Song et al. 2017b). During ecdysis, arthropods pause food intake and respiration (Camp et al. 2014; Song et al. 2017a). Therefore, if the molt cannot be completed, the

organism may die of starvation or suffocation. Additionally, if the cuticle is immature, it may not withstand the stresses associated with ecdysis (Clarke 1957; Lee 1961; Dall et al. 1978; deFur et al. 1985), and the organism may die of desiccation or increased susceptibility to pathogens. Given the well understood biological processes, the biological plausibility of this KER was rated as high.

### Empirical Evidence

The event of premature molting is not well characterized. It gets mentioned as cause of death in studies with *Pieris brassicae*, *Spodoptera litura*, *Bombyx mori* and *Lucilia cuprina* after treatment with polyoxin D, polyoxin B, polyoxin AL (a mixture of polyoxins) and nikkomycin Z (Gijswijt et al. 1979; Tellam et al. 2000; Arakawa et al. 2008). The increase in mortality was reported in studies with *Lucilia cuprina*, *Spodoptera litura* and *Bombyx mori* (Tellam et al. 2000; Tellam and Eisemann 2000; Arakawa et al. 2008). However, evidence of studies which assess and link both endpoints is lacking.

### Uncertainties and Inconsistencies

The absence of studies (quantitatively) assessing premature molting constitutes a major data gap. A further data gap is the absence of studies which assess both, increase in premature molting and the increase in mortality are lacking.

### Quantitative Understanding of the Linkage

#### Response-response relationship

Due to the lack of studies linking the increase in premature molting with the increase in mortality, it is not possible to describe the nature of the response-response relationship.

#### Time-scale

Death occurs after premature molting. However, an exact time frame in which death occurs cannot be defined yet.

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