Complete transcriptome assembly and annotation of a critically important amphipod species in freshwater ecotoxicological risk assessment: *Gammarus fossarum*

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**ABSTRACT**

Because of their crucial role in ecotoxicological risk assessment, amphipods (Crustacea) are commonly employed as model species in a wide range of studies. However, despite their ecological importance, their genome has not yet been completely annotated and molecular mechanisms underlying key pathways, such as the serotonin pathway, in development of ecotoxicological biomarkers of exposure to neuroactive pharmaceuticals are still poorly understood. Furthermore, genetic similarities and discrepancies with other model arthropods (e.g., *Drosophila melanogaster*) have not been completely clarified. In this report, we present a new transcriptome assembly of *Gammarus fossarum*, an important amphipod species, widespread in Central Europe. RNA-Seq with Illumina HiSeq technology was used to analyse samples extracted from total internal tissues. We used the Trinity and Trinotate software suites for transcriptome assembly and annotation, respectively. The quality of this assembly and the affiliated targeted homology searches greatly enrich the molecular knowledge on this species. Because of the lack of publicly available molecular information on the serotonin pathway, we also highlighted sequence homologies and divergences of the genes encoding the serotonin pathway components of the well-annotated arthropod *D. melanogaster* and Crustacea with the corresponding genes of our assembly. An inferior number of hits was found when running a BLAST analysis of both *D. melanogaster* and Crustacea mRNA sequences encoding serotonin receptors available in GenBank against the total assembly, compared to other serotonin pathway components. A lack of information on important components for serotonin biosynthesis and vesicle endocytosis (i.e., tryptophan hydroxylase and vesicular monoamine transporter) in Crustacea was also brought to light. Our results will provide an extensive transcriptional resource for this important species in ecotoxicological risk assessment and highlight the need for a more detailed categorization of neuronal pathways components in invertebrates.

1. Introduction

Identifying new sentinel species and acquiring molecular data for biomarker analyses are fundamental objectives in today’s ecotoxicological research. Given the number and diversity of chemicals released into natural environments, the need for a deeper understanding of the molecular mechanisms taking place in native species in response to exposure to these substances is increasing more and more. Fortunately, the degree of specificity and above all the number of biomolecules that can be simultaneously analysed in a given species have exponentially increased over the last decade due to the use of multi-omics platforms, such as next generation sequencing (NGS) technologies (Simmons et al., 2015). In research on aquatic species for instance, -omics platforms have allowed the development of new biomarkers of exposure to a considerably higher number of chemicals, allowing an even more precise description of the molecular effects in response to the exposure to a range of ecologically dangerous substances (Hauser-Davis et al., 2012; Jayapal, 2012; Barrera and Ariza, 2017; Poynton et al., 2018). With particular regard to freshwater species, numerous studies have been carried out to evaluate the molecular effects of a large spectrum of substances unremoved by wastewater treatment plants (WWTPs). These include endocrine disruptor...
compounds (Bahamonde et al., 2014; Schneider et al., 2015; Gouveia et al., 2018), pharmaceuticals (Sanchez et al., 2011; Pascoe et al., 2003; Brandão et al., 2013), metals (Atli and Canli, 2007; Gismondi et al., 2017; Lebrun et al., 2017) and polychlorinated biphenyls (Rylander et al., 1998; Leroy et al., 2010) on various species of fish and invertebrates. Other important studies focusing on acquiring genomic sequences or applying multiple omics platforms to elucidate unclear biological mechanisms in species of ecotoxicological interest are also available (Trapp et al., 2016; Macher et al., 2017; Poynton et al., 2018).

Because of their ecological relevance, invertebrates and in particular amphipods, are commonly used as test organisms in ecotoxicological assessments. Among amphipods, the genus *Gammarus* represents the greatest number of epigean freshwater species distributed throughout the Northern Hemisphere (Trapp et al., 2014a, 2014b). They are commonly used as model species in aquatic ecotoxicology for several reasons (Kunz et al., 2010). First, they are widespread and found throughout a large habitat range, where they often occur at high densities. Second, they occupy a large trophic repertoire as: herbivores, predators, and detritivores playing a major role in leaf-litter breakdown processes (Dangles and Guéridel, 2001). They also constitute a food reserve for macroinvertebrates and fish. Gammarids can be easily maintained in the laboratory or used in field bioassays (Kunz et al., 2010), in which it is possible to assess the impact of pollutants by measuring molecular markers related to diverse modes of action, such as neurotoxicity (Xuereb et al., 2009), as well as by using life-history-trait reproducive features (Geffard et al., 2010). In particular, *Gammarus fossarum* has been shown as notably useful in ecotoxicology studies due to an intrinsic sensitivity to anthropogenic pollutants (Trapp et al., 2016; Wigh et al., 2017) and a spatial distribution across Central Europe (Stráskraba, 1962; Meijering, 1971), making them ideal for freshwater risk assessment in the European geographical area. As a basic premise, a detailed elucidation of the molecular pathways is key to understanding the effects of pollutants on exposed organisms. In the literature, there are several studies that specifically applied sequencing platforms to *G. fossarum*. For example, Weiss et al. (2014) used sequencing of the genes encoding rRNA 16s and cytochrome c oxidase 1 (CO1) for a taxonomic purpose. Trapp et al. (2014a, 2014b) used a proteogenomics strategy to generate a molecular report specifically on the reproductive tissues of female individuals of *G. fossarum* and Macher et al. (2017) sequenced the complete mitochondrial genome of this amphipod species. However, the lack of publicly available molecular information on amphipod physiological pathways compared to other model species is still clear. This is particularly true when considering neurological pathways, especially the molecular processes at the synapse and a clear elucidation of the genetic differences of the main components (i.e., enzymes for serotonin biosynthesis, synaptic re-uptake and receptors) compared to other well-annotated arthropods such as *D. melanogaster*, will have a highly positive impact on the development of new ecotoxicological biomarkers. This aspect becomes even more important when considering the historical contribution of crustaceans in the synaptic physiology research. For instance, the presence of many parallels found in central synaptic physiology between crustaceans and vertebrates (Wu and Cooper, 2012) and the amount of knowledge about the basic principles underlying the generation, maintenance, and modulation of rhythmically active behaviours (e.g., walking, chewing and breathing) in humans, gained through studies on crustaceans (Selverston and Moulins, 1987; Harris-Warrick et al., 1992; Marder et al., 1995; Selverston et al., 1998; Nusbaum et al., 2001; Skiebe, 2001; Cooke, 2002; Fénelon et al., 2003; Selverston, 2005; Selverston and Ayers, 2006; Marder and Bucher, 2007; Stein; 2009; Christie et al., 2010; Blitz and Nusbaum, 2011; Christie, 2011; Dickinson et al., 2016). While much work has focused on examining the behavioural effects of neuroactive drugs active on the serotonergic synapse in invertebrates, commonly released in aquatic environments throughout wastewaters, (De Lange et al., 2006; Guler and Ford, 2010; Bossus et al., 2014), many physiological and molecular details remain largely unknown. Although there are studies that have applied high-throughput omics technologies on various species of amphipods (Short et al., 2014a, 2014b; Gouveia et al., 2017), the genomes of many organisms belonging to this species have not yet been completely annotated. To our knowledge the only study applying a next-generation sequencing approach, in order to give an overall report on the *G. fossarum* transcriptome was performed by Cogne et al., (2019). The authors sequenced the transcriptome of 7 different taxonomic groups of *G. fossarum* and combined the sequencing data with a high-throughput proteomics analysis, in order to provide a broad molecular dataset on this amphipod. Our report will significantly add to the gene discovery work on this critically important species in ecotoxicological risk assessment as well as providing an overview on the publicly available sequence resources on the serotonin pathway in the sub-species A of *G. fossarum*. In this study, we employed a de novo transcriptome assembly approach to identify functionally relevant transcripts and explored the serotonin pathway.

2. Materials and methods

2.1. Sampling

The sampling was performed in mid-September 2017 at the Eulach river. The sampling site is located in Elgg, Switzerland at the following geographic coordinates: 47°30′04.23″N – 8°51′09.40″E. *G. fossarum* individuals were collected from beneath stones and leaves at the bottom of the stream, using a standard kick-net method. A net with 1 mm mesh size was used. The amphipods were removed from the net using forceps and sorted, separating the species of interest from leaves and other invertebrates. The animals were placed into 10 L buckets containing stream water and quickly transported to the laboratory where they were placed in controlled conditions. The amphipods were placed in glass tanks filled with continuously aerated stream water (20 cm depth). Incubation conditions were 16 ± 2 °C with a 12/12 light-dark cycle (Blarer and Burkhardt-Holm, 2016). Gammarids were fed ad libitum with alder leaves (*Alnus glutinosa*) collected at the sampling site. After a 24 h period, RNA was extracted.

2.2. Total RNA extraction

Total RNA was extracted from *G. fossarum* total internal tissues using RNeasy* Mini Kit (Qiagen, Hombrechtikon, Switzerland), following manufacturer’s instructions. A total of 100 amphipod dissections were conducted, but in order to increase the RNA yield 5 independent amphipods were pooled per replicate, resulting in a total of 20 distinct pools. Each pool was considered an independent biological replicate for downstream analyses. Sampling was conducted independently for both
males and females (10 male pools and 10 female pools). Fresh amphipods were anaesthetised for 10–15 min in a 5% (v/v) clove oil solution prepared in water and washed in DEPC water (Sigma-Aldrich, Schnelldorf, Germany) prior to dissection, to remove any residual debris. Dissections were performed under a stereo-binocular (×3-4 magnification; SZ2 – ILST, Olympus), using stainless steel forceps. Heads were removed from the body, allowing an easier removal of the internal tissues. Internal tissues were washed in DEPC water and placed in 1.5 mL tubes previously cooled. Tubes were quickly snap-frozen in liquid nitrogen and placed at −80 °C until RNA extractions. For each tube, one pre-treated stainless-steel bead (Qiagen, Hilden, Germany) and 350 µL of lysis buffer plus 10 µL β-mercaptoethanol (Sigma-Aldrich, Buchs, Switzerland) were added and the samples were immediately placed into the adaptors of a Tissue Lyser II machine (Qiagen, Hilden, Germany). Stainless-steel beads were previously subject to two treatments of 15% (v/v) H2O2 and 70% (v/v) ethanol washings followed by 20 min of UV irradiation, to remove any potential chemical/biological contamination. Three 20 sec mechanical stirring cycles at 30 Hz speed were performed, in order to disrupt the tissues and homogenize the cell suspension. The lysed tissue samples were centrifuged at full speed at room temperature for 3 min to separate the cell debris from the supernatant and the supernatants were transferred to fresh tubes. Total RNA was then extracted from H. fossarum tissue samples. RNA concentrations and purity were assessed measuring the absorbance at 230, 260 and 280 nm using Nanodrop ND-1000 (Witec, Littau, Switzerland). Finally, RNA integrity was checked using an Agilent 2100 Bioanalyzer (Agilent Technologies, Wahausel, Germany) assay. All RNA samples displayed low background signal with sharp peaks corresponding to intact ribosomal RNA.

2.2.1. RNA sequencing

An Illumina TruSeq Stranded mRNA library kit was used to generate cDNA libraries for each of the 20 RNA samples, which were run on an Illumina HiSeq 2500 sequencer by GATC Biotech (Konstanz, Germany) to generate paired-end 150 bp reads.

2.2.2. Quality control

Quality control of the raw reads was performed using FastQC v0.11.7 (Andrews, 2015). Species-specific sequence purity was assessed by using a multiple genome alignment approach, by mapping reads against a database of different model species taken from the Ensembl database (Aken et al., 2017), a draft transcriptome for Gammarus chevreuxi (Truebano et al., 2016), and all RefSeq entries for Gammarus fossarum using MGA v1.4 (Hadfield and Eldridge, 2014). Read trimming was performed using Trim Galore v0.4.4 (Krueger, 2012) using the following parameters “--illumina -q 20 –stringency 5 –e 0.1 –length 20 –trim-n” to remove Illumina adapter sequence contamination, and to trim reads for ambiguous or low-quality base calls.

2.2.3. Assembly and annotation

Reads were combined across the data set and used to generate a putative transcriptome assembly using Trinity v2.5.1 (Grabherr et al., 2011) with parameters “--seqType fq --max_memory 100G --CPU 24 --min_contig_length 200 --min_kmer_cov 1 --SS_lib_type RF–verbos –fullclean up”. Raw sequencing data were deposited in the NCBI Sequence Read Archive (SRA) and the complete transcriptome was deposited in the Transcriptome Shotgun Assembly (TSA) database. These data have been collected under BioProject accession code PRJNA556212. Unique transcript sequences were clustered into potential alternatively spliced isoform groups and paralogous “genes”. TransDecoder v5.0.2 (Haas et al., 2013) was run using default parameters to identify open reading frames (ORF) of 100 amino acids or more within transcripts, and putative protein amino acid sequences were produced. Transcripts were annotated against the Universal Protein Knowledge Base (UniProtKB) SwissProt database (The UniProt Consortium, 2017) using BLAST (Altschul, 1990), either at the protein level by taking the TransDecoder derived peptide sequence (using “blastp”) or from the translated nucleotide sequence directly if no ORF was identified (using blastx). Additional annotation was performed against the Protein family (Pfam) database (Finn et al., 2013) using HMMPR (Finn et al., 2011), Clusters of Orthologous Groups of proteins (eggNOG) database (Huerta-Cepas et al., 2015), the Kyoto Encyclopedia of Genes and Genomes (KEGG) database (Kanehisa, 2000), and Gene Ontology (GO) database (Ashburner et al., 2000). Results were collated into a single output table using Trinotate v3.02 (http://trinotate.github.io/). Transcriptome completeness was assessed by comparing the assembly against a database of metazoan universal single copy orthologs using BUSCO v2.0 (Simão et al., 2015).

2.2.4. G. fossarum sub-species assignment

A sequence alignment of the transcript sequences against the complete G. fossarum mitochondrial genome (Macher et al., 2017) was conducted using Blast2GO 5 Basic software (Conesa et al., 2005), in order to identify transcripts corresponding to mitochondrial genes that may allow for taxonomic assignment (i.e., rRNA 16S and CO1) (Müller, 2000; Weiss et al., 2014). The following parameters were used for the analysis:

- E-value: 1.0E−3
- Number of blast hits: 20
- Word size: 11
- HSP length cutoff: 33

BLAST was then used to align putative mitochondrial transcripts against the NCBI non-redundant database (Altschul et al., 1990) for “amphipods – taxid:6821”, to assign both G. fossarum sub-species and CO1 type.

2.3. Serotonin pathway survey

Serotonin-specific nucleotide sequences were identified from GenBank (Benson et al., 2017) and were filtered to identify serotonin-specific mRNAs for enzymes, transporters and receptors, belonging to either D. melanogaster or Crustacea. In cases where multiple transcript variants were identified, all were considered, including in silico predicted transcripts. cDNA and single exon sequences were excluded. Genes encoding serotonin non-specific components (i.e., non-specific ion channels, G proteins, cytochrome p450 enzymes, receptors specific for other neurotransmitters) were not included and their corresponding boxes in Fig. 3 were left blank. A BLAST search for each nucleotide sequence was conducted against our transcriptome using BLAST2GO (Conesa et al., 2005) with parameters as described above to identify G. fossarum-specific serotonin genes. Fig. 1 shows a schematic overview of the workflow used, including both laboratory and bioinformatics procedures.

3. Results

3.1. G. fossarum de novo transcriptome assembly

Sequencing generated a total of 325,393,762 paired end reads across the 20 samples. Base calling quality was excellent across the entire data set, with the vast majority of reads showing average quality scores greater than 30. Mapping of reads against a range of different target genomes identified similar mapping rates for each of the 20 samples, with around 50% of reads mapping to either G. fossarum, G. pulex or E. marinus, whilst the remaining reads importantly did not map to any other model organism indicating no sign of cross-contamination. Trimming of reads to remove Illumina adapters, ambiguous base calls and poor-quality bases resulted in the loss of only 0.1% of reads. In total, 324,958,898 quality-trimmed reads were used for de novo transcriptome assembly. The final assembly consisted of 680,840
Table 1
Summary statistics of *G. fossarum* transcriptome assembly. The table shows the main parameters describing the overall structure and quality of the assembly.

| Trinity outputs | 407,060 |
|-----------------|---------|
| Total Trinity transcripts | 680,840 |
| Percent GC | 44.68% |
| Longest contig | 31,653 bp |
| Shortest contig | 100 bp |
| Greater than 10 Kb | 352 |
| Greater than 5 Kb | 5,389 |
| Greater than 2 Kb | 94,819 |
| Transcript contig N10 | 4,671 bp |
| Transcript contig N20 | 3,075 bp |
| Transcript contig N30 | 2,184 bp |
| Transcript contig N40 | 1,531 bp |
| Transcript contig N50 | 1,026 bp |
| Median contig length | 324 bp |
| Average contig | 628.1 bp |
| Total assembled bases | 427,679,404 |

This suggests that the vast majority of non-annotated non-coding transcripts are likely a result of fragmented RNA. Annotation for all transcripts identified in this assembly can be seen in Table S1 (Supplementary Information).

3.2. *G. fossarum* sub-species assignment

Previous studies have reported strong genetic differences among populations of *G. fossarum* (Siegismund, 1988; Siegismund and Müller, 1991, Müller, 2000). Although this amphipod has been a subject of controversial debate in taxonomy for decades (e.g., Roux, 1971; Goedmakers, 1972; Jazdzewski, 1977; Goedmakers, 1980; Scheepemaker and van Dalfsen, 1989; Pinkster and Scheepmaker, 1994; Müller, 1998; Westram et al., 2011), to date at least 3 main sub-species have been identified based on nucleotide differences within the mitochondrial gene encoding rRNA 16S (Müller, 2000). An additional taxonomic system in *G. fossarum* based on the differences in the gene encoding *cytochrome oxidase I* (COI) was proposed by Weiss et al., (2014). In this study, a BLAST analysis of the transcriptome assembly was conducted against the complete *G. fossarum* mitochondrial genome (Macher et al., 2017). Putative mitochondrial transcript sequences from our assembly were aligned against the amphibid NCBI nucleotide database using BLAST in order to identify transcripts corresponding to rRNA 16S and COI. Among the 20 putative mitochondrial transcripts, one (TRINITY_DN95725_c7_g2_i2) showed a hit against “*Gammarus fossarum*” type A mitochondrial partial 16S rRNA gene, haplotype A14 suggesting that these data are specific to sub-species assignment (*G. fossarum* A) (Müller, 2000) (Table 2). Additionally, another transcript (TRINITY_DN93353_c3_g3_i1) showed a hit against “*Gammarus fossarum*” isolate Glos_47 cytochrome oxidase subunit 1 (COI) gene, partial cds; mitochondrial” and “*Gammarus fossarum*” isolate Glos_45 cytochrome oxidase subunit 1 (COI) gene, partial cds; mitochondrial” (Table 2). One other transcript (TRINITY_DN93353_c3_g1_i3) also showed hits against COI, but from the amphibid taxa *Chiltoniidae*.

3.3. Serotonin pathway survey

To further test the depth and accuracy of this dataset, we aimed to identify serotonin-related transcripts by comparing against known serotonin-related genes from the NCBI database GenBank (Benson et al., 96.4% of the universal single-copy orthologs were present in a complete form, with 335 (34.3%) showing a single copy and 607 (62.1%) showing 2 or more copies. 19 (1.9%) were found in a fragmented form whilst only 17 (1.7%) were missing. This suggests that this assembly represents a very complete transcriptome for *G. fossarum*. Annotation against the UniProt/Swissprot database identified candidate hits for only 80,476 (11.8%) of the transcripts. However, 53.5% of transcripts with an identified open-reading frame (ORF) showed a hit, whilst only 5.6% of transcripts with no ORF showed a hit. ORF transcripts (78.7%) were shorter in length than 500 bp (Fig. 2).
Given the well-known effects of exposure to antidepressants (a pharmaceutical class specifically acting on the serotonin pathway) on aquatic organisms (Guler and Ford, 2010; Styrishave et al., 2011; Bossus et al., 2014; Chen et al., 2018), a detailed exploration of these specific transcripts was of interest from an ecotoxicological perspective. D. melanogaster is often used as a reference to investigate the metabolic pathways in other arthropods, such as amphipods (Bossus et al., 2013; Trapp et al., 2014a, 2014b; Poynton et al., 2018). However, mRNA
Table 2

G. fossarum sub-type assignment BLAST parameters. A BLAST analysis of the complete G. fossarum mitochondrial genome was conducted against the total assembly, in order to identify the transcripts corresponding to rRNA 16S and CO1 genes. The table shows the BLAST parameters of the best hits obtained when re-BLASTing the transcripts coding rRNA 16S and CO1 genes in the NCBI database.

| Transcript ID | Max score | Total score | Query cover | E-value | % identity | Accession |
|---------------|-----------|-------------|-------------|---------|------------|-----------|
| TRINITY_DN95725_c7_g2_i2 | 725 | 725 | 17% | 0.0 | 100% | A29669.0.1 |
| TRINITY_DN93353_c3_g3_i1 | 1110 | 1110 | 73% | 0.0 | 100% | M98860.9.1 |

* Top 2 hits for TRINITY_DN95725_c7_g2_i2 were "G. fossarum mitochondrial, complete genome" and "Gammarus fossarum isolate GG04 mitochondrial DNA gene, partial sequence, mitochondrial". The table shows the third hit, which was useful for the sub-species assignment (A), according to Müller (2000) classification.

3.3.1. 5-HT biosynthesis components

Serotonin is synthesized from the amino acid tryptophan in two enzymatic steps: hydroxylation of tryptophan by the neuronal form of tryptophan hydroxylase (TPH), which generates 5-hydroxytryptophan (5-HTP), and conversion to 5-hydroxytryptamine (5-HT) by the enzyme DOPA-decarboxylase (DDC) (Daubert and Condron, 2010). No mRNA sequences encoding TPH were available in GenBank for Crustacea, but 3 out of 4 sequences encoding this enzyme in D. melanogaster showed a putative hit in the G. fossarum transcriptome. No hit was found for the enzyme DDC, represented in GenBank by 3 and 2 mRNA sequences for D. melanogaster and Crustacea, respectively.

3.3.2. 5-HT transport proteins

After synthesis, the vesicular monoamine transporter (VMAT) transports 5-HT into vesicles for storage. Upon vesicle fusion with the plasma membrane, 5-HT is released where it interacts with autoreceptors located on the releasing cell or heteroreceptors, serotonin receptors located on other cell types. The serotonin transporter (SERT) transports 5-HT back into the releasing cell where it is likely to be re-packaged for release by VMAT or degraded by monoamine oxidase A (MAO-A) located on the outer mitochondrial membrane (Daubert and Condron, 2010). Similarly to TPH, no mRNA sequences encoding the vesicle monoamine transporter VMAT were found in Crustacea. However, each of the 4 sequences encoding this carrier protein found for D. melanogaster gave a hit with at least one transcript. mRNA sequences encoding the re-uptake protein SERT were found for both D. melanogaster and Crustacea and all showed hits with at least one transcript (Fig. 3).

3.3.3. 5-HT receptors

To date, at least fourteen different serotonin receptor subtypes have been identified and are grouped into seven families in human (5-HT1–5-HT7) (Daubert and Condron, 2010). Although some of these receptors are present in different isoforms in D. melanogaster and Crustacea (Wu and Cooper, 2012), they mediate the whole range of serotonin’s effects and are distributed throughout the body (Daubert and Condron, 2010). All of the serotonin receptors are G-protein-coupled receptors, except for the 5-HT3 ligand-gated ion channel (Nichols and Nichols, 2008). Compared to other components of the serotonergic synapse, fewer hits were found against D. melanogaster and Crustacea mRNA sequences encoding 5-HT receptors. In fact, of all of the presynaptic receptors, 5-HT1A was the only one that gave at least one hit in Crustacea. In contrast, 5-HT1B, 5-HT2, 5-HT2A, 5-HT3, and 5-HT7 gave no hits for Crustacea nor for D. melanogaster (Fig. 3). No mRNA sequences were found in GenBank for 5-HT1D, 5-HT1E, and 5-HT4 for D. melanogaster nor Crustacea. Interestingly, 5-HT5, 5-HT6 gave at least one hit when using human sequences (Fig. 3).

3.3.4. 5-HT inactivation enzyme

An additional serotonin inactivation mechanism is mediated by the enzyme monoamine oxidase A (MAO-A). This enzyme is located on the outer mitochondrial membrane and is responsible for degradation of 5-HT at the presynaptic terminal (Daubert and Condron, 2010). Surprisingly, no mRNA sequences were found in GenBank for D. melanogaster and none of the 4 sequences found for Crustacea gave hits.
4. Discussion

Much has changed in recent years, and researchers are now more aware of the importance of obtaining detailed molecular information in species of ecotoxicological interest (Simmons et al., 2015). The search for new molecular biomarkers for the evaluation of the status of natural habitats, as well as the study of specific pathways affected as a result of anthropogenic activities, has increased exponentially (Pascoe et al., 2003; Atli and Canli, 2007; Leroy et al., 2010; Sanchez et al., 2011; Brandão et al., 2013; Bahamonde et al., 2014; Schneider et al., 2015; Gisondi et al., 2017; Lebrun et al., 2017; Gouveia et al., 2018).

In parallel, the use of “-omics” platforms has greatly increased the depth of molecular analyses, allowing the acquisition of data from hundreds of thousands of molecules simultaneously. This provides a valuable resource for ecotoxicological research (Simmons et al., 2015). Particular attention has been given to a sub-group of Crustacea, amphipods, due to their sensitivity to aquatic pollutants (Trapp et al., 2015; Wigh et al., 2017) and their central role in the freshwater food web (Dangles and Guérold, 2001). Furthermore, the potential of amphipods to bioaccumulate toxic substances is likely among the main reasons for their crucial role in ecotoxicological research. Munz et al. (2018) found higher concentrations of frequently detected risk-driving substances (i.e., various classes of pharmaceuticals, corrosion inhibitors, biocides, pesticides and personal care products) in Gammarus fossarum and Gammarus pulex sampled downstream of several Swiss WWTPs compared to upstream sites. In a recent study by Miller et al. (2019), the authors performed a sampling of G. pulex amphipods from several shores of the United Kingdom and assessed the potential presence of various dangerous chemicals within them. Surprisingly, illicit drugs such as cocaine and ketamine, as well as banned pesticides and pharmaceuticals, were found. However, the lack of molecular information on these species still represents a limiting factor and a more detailed genomic annotation is fundamental to highlighting homologies and discrepancies compared with other model organisms. Although some progress has already been made, for instance, the parallels to vertebrate central synaptic physiology of phenomenon described at Crustacea neuromuscular junctions (Wu and Cooper, 2012), there is still a lot of work to be done.

4.1. G. fossarum sub-species assignment

A correct sub-type assignment of the amphipod G. fossarum is essential. In fact, the genetic differences between the sub-types are considered strong enough to prevent crossbreeding in a natural setting (Müller, 1998; Wiese, 2013). Although Pinkster and Scheepmaker (1994) were able to obtain G. fossarum F1 juveniles from ex-situ crossbreeding experiments, Müller, the author who differentiated G. fossarum into 3 distinct cryptic species (A, B, C) (Müller, 1998, 2000), found out that sub-types A and B are to be considered reproductively isolate in a natural setting (Müller, 1998). An additional taxonomic system in G. fossarum, based on the differences in the faster evolving gene encoding cytochrome oxidase 1 (CO1) was proposed by Weiss et al. (2014). In this study, we have attributed the G. fossarum sub-type A, haplotype A14 to our species using a BLAST analysis of our assembly against the complete G. fossarum mitochondrial genome (Macher et al., 2017). Although the BLAST analysis did not allow an unambiguous assignment of the CO1 type, it revealed CO1-45 and CO1-47 as most probable CO1 types of the amphipod subject of study.

4.2. Serotonin pathway survey

Considering that the historical contribution of Crustacea in synaptic physiology is unsurpassed (Atwood, 1976; Wiese, 2013) and much is still unclear concerning the synaptic molecular mechanisms within this taxon (Wu and Cooper, 2012), we also carried out a manual annotation of the genes encoding the serotonin-related molecular components present in the final assembly. We focused on this particular neurotransmitter because of the lack of general molecular information in invertebrates in contrast with the wide range of documented behavioural and transcriptional effects of antidepressants released in aquatic environments (Nentwig, 2007; Guler and Ford, 2010; Bossus et al., 2014; Ford and Fong, 2016; Estévez-Calvar et al., 2017). The acquisition of further molecular details underlying the serotonin pathway in amphipods will also be useful in the field of invertebrate neurobiology. In fact, it has been shown that, similarly to neuroactive drugs, some parasite species (e.g., trematodes) are able to manipulate their invertebrate host’s behaviour through modification of monoamine pathways, such as the serotonin pathway (Guler et al., 2015). We therefore aimed to use BLAST to identify putative candidate genes from our assembly that match serotonin-specific mRNA sequences available in GenBank for D. melanogaster, a widely used arthropod for genomic annotation (Bossus et al., 2013; Trapp et al., 2014a, 2014b; Poynton et al., 2018), and Crustacea.

Interestingly, the 5-HT transporter SERT was the only component of this pathway to show matches from both D. melanogaster and Crustacea within our assembly. Although further investigations will be needed to confirm this, we speculate that the re-uptake carriers at synaptic level might have a higher rate of evolutionary conservation compared to other components of the serotonergic synapse. In comparison, no mRNA sequences encoding the degradation enzyme MAO-A were found in GenBank for D. melanogaster, and none of the sequences found for Crustacea gave hits against our assembly.

Surprisingly, no mRNA sequences encoding the first enzyme of the serotonin biosynthetic chain (TPH) were found in GenBank for Crustacea, but all splicing variants of this enzyme in D. melanogaster sequences gave at least one hit against our assembly, highlighting the homology of this enzyme in D. melanogaster and amphipods. However, none of the splicing variants found for the second serotonin biosynthesis enzyme in D. melanogaster, DOPA-decarboxylase, gave hits. Although two predicted nucleotide sequences encoding DDC enzyme were found for Crustacea, neither gave hits in the G. fossarum assembly. At present, we are unable to clarify whether this enzyme may have additional isoforms in Crustacea not present in GenBank, or whether sequence differences within this taxon are stronger than expected.

When looking at the serotonin receptors sequences, 5-HT1A was the only receptor that gave at least one hit against Crustacea, but not D. melanogaster sequences. 5-HT1B, 5-HT2, 5-HT3, 5-HT5A gave no hits against either the D. melanogaster or the Crustacea sequences. No mRNA sequences were found in GenBank for 5-HT1A or 5-HT7 for either D. melanogaster and Crustacea. 5-HT7 gave no hits against D. melanogaster and Crustacea sequences.

It has previously been shown that the classification of serotonin receptors in humans is not totally applicable to invertebrates (Wu and Cooper, 2012). For instance, 5-HT1 and 4-HT are shown to have different splicing variants (Hoyer, Hannon and Martin, 2002) and 5-HT2C can have different RNA-edited isoforms (Burns et al., 1997; Niswender et al., 1998). This analysis highlights the fact that further studies on a more precise classification of receptors for serotonin in invertebrates is strongly needed, considering the well documented effects that pharmaceutical waste targeting the serotonin pathway can have on aquatic species (Guler and Ford, 2010; Styishave et al., 2011; Bossus et al., 2014; Chen et al., 2018). 5-HT1A was the only receptor that gave at least one hit when using Crustacea mRNA sequences found in GenBank. Despite no sequences being found for 5-HT3, we did identify hits in our assembly for human 5-HT4 and 5-HT6 mRNA sequences. Therefore, the lower hit-rate observed for serotonin receptors compared to other molecular components of the pathway might be due to a scarcity of genetic information in Crustacea rather than a strong evolutionary divergence of the 5-HT receptor sequences of this taxon.

Taken together, these findings reveal that molecular comparisons between the serotonin pathway of different organisms, or even within Crustacea taxon, may not be possible for all components. However, the
amount of genetic information available still represents a limiting factor. Given the importance of the serotonin pathway in ecotoxicological research, further studies on the classification of 5-HT receptors in invertebrates as well as their pharmaceutical targets will be fundamental.

5. Conclusions

The amphibip species G. fossarum represents an important organism in ecotoxicological risk assessment, and yet there remains a significant lack of genomic information. To further add to our current understanding, we used RNA sequencing and de novo assembly to generate a complete transcriptome of G. fossarum - type A. Our dataset will provide an additional resource of genomic information in this poorly annotated species and will represent a reference source for further and more focused molecular analysis on this and other amphibip species. Given the importance of the serotonin pathway in behavioural and neurological studies on invertebrates (Wu and Cooper, 2012; Guler et al., 2015) an exploration of the publicly available mRNAs sequences involved in this pathway in D. melanogaster and Crustacea was also conducted. An inferior number of hits was found when running sequence alignment of our assembly against both D. melanogaster and Crustacea mRNA sequences encoding serotonin receptors available in GenBank, compared to other serotonin pathway components. This may indicate a lack of publicly available sequence information on important components of the serotonin pathway in crustaceans, for instance tryptophan hydroxylase and vesicular monoamine transporter, suggesting the need for an additional resource of genomic information in this poorly annotated species and important model species for both ecotoxicological and neurological studies.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105319.

References

Aken, Browne L., Achathun, Premanand, Akanni, Wasiu, Ridwan Amode, M., Bernsdorff, Friedenke, Bhai, Jey throughput search tool. J. Mol. Biol. 215 (3), 403–410.

Andrews, S., 2015. A quality control tool for high throughput sequence data. 2010. URL: http://www.bioinformatics.babraham.ac.uk/projects/fastqc.

Ashburner, M., Ball, C.A., Blake, J.A., Botstein, D., Butler, H., Cherry, J.M., Davis, A.P., Dolinski, K., Dwight, S., Eppig, J.T., Harris, M.A., 2000. Gene ontology: tool for the unification of biology. Nat. Genet. 25 (1), 25.

Atti, G., Canli, M., 2007. Enzymatic responses to metal exposures in a freshwater fish Oreochromis niloticus. Comp. Biochem. Physiol. Part C. Toxicol. Pharmacol. 145 (2), 289–295.

Atwood, H.L., 1976. Organization and synaptic physiology of crustacean neuramal systems. Progr. Neurobiol. 7, 291–391.

Bahamonde, P.A., Tetreault, G.R., McMaster, M.E., Servos, M.R., Martyrnick, C.J., Munkittrick, K.R., 2014. Molecular signatures in rainbow darter (Etheostoma caeruleum) inhabiting an urbanized river reach receiving wastewater effluents. Aquat Toxicol. 148, 211–220.

Barrera, T.G., Ariza, J.L.G., 2017. New Trends in Aquatic Pollution Monitoring: From Conventional Biomarkers to Environmental Proteomics. In Environmental Problems in Aquatic Biology. CRC Press, pp. 166–187.

Benson, Dennis A., Cavanaugh, Mark, Clark, Karen, Korsch-Mizrachi, Ilene, Lipman, David J., Ostell, James, Sayers, Eric W., 2017. GenBank. Nucl. Acids Res. 45 (D1), D42–D63.

Blarer, P., Burkhardt-Holm, P., 2016. Microplastics affect assimilation efficiency in the freshwater amphipod Gammarus fossarum. Environ. Sci. Pollut. Res. 23 (23), 25522–25532.

Blitz, D.M., Noubiap, M.P., 2011. Neural circuit flexibility in a small sensorimotor system. Curr. Opin. Neurobiol. 21 (4), 544–552.

Bossut, M.C., Guler, Y.Z., Short, S.J., Morrison, A.R., Ford, A.T., 2014. Behavioural and transcriptional changes in the amphibip Echinogammarus marinus exosed to two antidepressants, fluoxetine and sertraline. Aquatic Toxicol. 151, 45–56.

Brandon, F.P., Rodrigues, S., Castro, B.B., Goncalves, A., Antunes, S.C., Nunes, B., 2013. Short-term effects of neuroactive pharmaceutical drugs on a fish species: biochemical and behavioural effects. Aquatic Toxicol. 144, 218–229.

Burns, C.M., Kh, H., Ruter, S.M., Huttson, L.K., Canten, H., Sanders-Bush, E., Emonon, R.B., 1997. Regulation of serotonin - 2C receptor G-protein coupling by RNA editing. Nature 387, 303–308.

Chen, H., Zeng, X., Lu, H., Liu, Y., Yang, Z., Zhao, J., Schlenk, D., Wong, X., Liao, Q., 2018. Effects of acute and chronic exposures of fluoxetine on the Chinese mude, topmouth gudgeon Pseudorasbora parva. Aquatic Toxicol. Environ. Safety 160, 104–113.

Christie, A.E., 2011. Crustacean neuroendocrine systems and their signalling agents. Cell Tissue Res. 345, 41–67.

Christie, A.E., Stemmler, E.A., Dickinson, P.S., 2010. Crustacean neuropeptides. Cell Mol. Neurobiol. 41, 149–163.

Cogné, Y., Degli-Esposti, D., Pibó, O., Gouvreau, L., Piché, O., Bizien, D., Ech, C., Ford, A., Geffard, M., Aarnegam, A., Chau, M., 2019. De novo transcriptomes of 14 gammarid individuals for proteomegenetic analysis of seven taxonomic groups. Scientific Data 6 (1), 1–7.

Conea, A., Gót, S., García-Gómez, J.M., Terol, J., Talón, M., Robles, M., 2005. Blast2GO: a universal tool for annotation, visualization and analysis in functional genomics research. Bioinformatics 21 (18), 3674–3676.

Cooper, I.W., 2002. Reliable, responsive pacemaking and pattern generation with minimal synaptic input: the crustacean cardiac ganglion. Biol. Bull. 202 (2), 108–130.

Dangles, O., Fénelon, V., 2003. Maturation of rhythmic neural network: role of central modulatory inputs. J. Physiol.-Paris 97 (1), 59–72.

De Lange, H.J., Noordoven, W., Murk, A.J., Lürling, M.F.L.L.W., Peeters, E.T.H.M., 2006. Concluding statement: the crustacean system. Progr. Neurobiol. 7, 291–313.

Dolinski, K., Dwight, S.S., Eppig, J.T., Harris, M.A., 2000. Gene ontology: tool for the generation of biology. Nat. Genet. 25 (1), 25.

Ebling, J., 2008. Effects of antidepressants on GABAergic transmission in the mouse neostriatum. J. Neurosci. 28, 14511–14519.

Feng, V., Le Feuvre, V., Bent, M., Meyrand, F., 2003. Maturation of rhythmic neural network: role of central modulatory inputs. J. Physiol.-Paris 97 (1), 59–68.

Finn, R.D., Bateman, A., Clements, J., Coggill, P., Eberhardt, R.Y., Eddy, S.R., Heger, A., Heger, A., Hedges, S.R., 2018. Divergent evolution of the mammalian clock: evidence from the mammalian circadian clock. Mol. Biol. Evol. 35 (8), 2075–2090.

Ford, A., Geffard, M., Aarnegam, A., Chau, M., 2019. De novo transcriptomes of 14 gammarid individuals for proteomegenetic analysis of seven taxonomic groups. Scientific Data 6 (1), 1–7.

Garric, J., Charmantier, G., Charmantier-Daures, M., 2010. Ovarian cycle and embryonic development in Gammarus fossarum: application for reproductive toxicity assessment. Environ. Toxicol. Chem. 29 (10), 2249–2258.

Garrigues, D., Caputo, D.R., et al. Environment International 137 (2020) 105319
Procambarus clarkii and Orconectes rusticus. Comp. Biochem. Physiol. Part A Mol. Integrat. Physiol. 139, 495–502.

Trapp, J., Armengaud, J., Pible, O., Gaillard, J.C., Abbaci, K., Habtoul, Y., Chaumot, A., Geffard, O., 2014a. Proteomic investigation of male Gammarus fossarum, a freshwater crustacean, in response to endocrine disruptors. J. Proteome Res. 14 (1), 292–303.

Trapp, J., Geffard, O., Imbert, G., Gaillard, J.C., Davin, A.H., Chaumot, A., Armengaud, J., 2014b. Proteogenomics of Gammarus fossarum to document the reproductive system of amphipods. Mol. Cell. Proteom. 13 (12), 3612–3625.

Trapp, J., Almunia, C., Gaillard, J.C., Pible, O., Chaumot, A., Geffard, O., Armengaud, J., 2016. Proteogenomic insights into the core-proteome of female reproductive tissues from crustacean amphipods. J. Proteom. 135, 51–61.

Truebano, M., Tills, O., Spicer, J.J., 2016. Embryonic transcriptome of the brackishwater amphipod Gammarus chevreuxi. Mar. Genom. 28, 5–6.

Weiss, M., Macher, J.N., Seefeldt, M.A., Leese, F., 2014. Molecular evidence for further overlooked species within the Gammarus fossarum complex (Crustacea: Amphipoda). Hydrobiologia 721 (1), 165–184.

Westram, A.M., Jokela, J., Baumgartner, C., Keller, I., 2011. Spatial distribution of cryptic species diversity in European freshwater amphipods (Gammarus fossarum) as revealed by pyrosequencing. PLoS one 6 (8), e23879.

Wiese, K. (Ed.), 2013. The Crustacean Nervous System. Springer Science & Business Media.

Wijh, A., Geffard, O., Abbaci, K., Francois, A., Noury, P., Bergé, A., Vulliet, E., Domenjoud, B., Gonzalez-Ospina, A., Bony, S., Devaux, A., 2017. Gammarus fossarum as a sensitive tool to reveal residual toxicity of treated wastewater effluents. Sci. Total Environ. 564, 1012–1021.

Wu, W.H., Cooper, R.L., 2012. Serotonin and synaptic transmission at invertebrate neuromuscular junctions. Exp. Neurobiol. 21 (3), 101–112.

Xuereb, B., Chaumot, A., Mons, R., Garric, J., Geffard, O., 2009. Acetylcholinesterase activity in Gammarus fossarum (Crustacea Amphipoda): intrinsic variability, reference levels, and a reliable tool for field surveys. Aquatic Toxicol. 93 (4), 225–233.

Yeoman, M.S., Pieneman, A.W., Ferguson, G.P., Ter Maat, A., Benjamin, P.R., 1994. Modulatory role for the serotonergic cerebral giant cells in the feeding system of the snail, Lymnaea. J. Neurophysiol. 72, 1357–1371.