Caspofungin primes the immune response of the larvae of *Galleria mellonella* and induces a non-specific antimicrobial response

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INTRODUCTION

Interest in using insects as alternative models to mammals for the *in vivo* screening of novel antimicrobial drugs (Hamamoto *et al.*, 2004, 2009) or for assessing the virulence of microbial pathogens (Brennan *et al.*, 2002; Lionakis & Kontoyiannis, 2005) has been growing for a number of years, since the immune response of insects shares a high level of homology with the innate immune response of mammals (Kavanagh & Reeves, 2004). Insect models of microbial infections have been employed to investigate the antimicrobial properties of drugs (Lionakis & Kontoyiannis, 2005; Johny *et al.*, 2007) and offer many advantages over the use of mammals (Kavanagh & Reeves, 2004). Larvae of the Greater Wax Moth, *Galleria mellonella*, have been used to evaluate the antifungal activity of amphotericin B, flucytosine and fluconazole following infection with *Cryptococcus neoformans* (Mylonakis *et al.*, 2005), while silkworms have also been used to investigate the activity of commonly used antimicrobials including the antifungal fluconazole (Hamamoto *et al.*, 2004).

Larvae of *G. mellonella* are inexpensive to purchase, results can be obtained within 48 h and a large number of insects can be inoculated in a short period of time (Cotter *et al.*, 2000). *G. mellonella* larvae have been used to assess the pathogenicity of mutants of *Pseudomonas aeruginosa* and a correlation has been established between their virulence in *G. mellonella* and in mice (Dunphy *et al.*, 1986; Jander *et al.*, 2000). Similarly a correlation between the virulence of *Candida albicans* mutants in *G. mellonella* and mice has been demonstrated (Brennan *et al.*, 2002), and the larval model has been used to allow the determination of the virulence of relatively ‘weak’ fungal pathogens (Bergin *et al.*, 2003). In addition, *G. mellonella* larvae have been established as a good model for studying the virulence of *Cryptococcus neoformans* (Mylonakis *et al.*, 2005).

The insect immune system bears a number of structural and functional similarities to the innate immune response of mammals (Zhao & Kanost, 1996; Rock *et al.*, 1998; Wittwer *et al.*, 1999). The cuticle of the insect serves a function analogous to the skin in mammals and provides a barrier to infection. The haemolymph of insects is contained within the body cavity (haemocoel) and serves a function comparable to blood, where it transports nutrients, waste products and signal molecules (Matha & Acke, 1984). Haemolymph contains circulating immune cells (haemocytes) that are capable of immobilizing and killing invading microbes (Lavine & Strand, 2002). The humoral element of the insect immune response consists of the processes of melanization, haemolymph clotting,
antimicrobial peptide (AMP) synthesis and wound healing (Kavanagh & Reeves, 2004). AMPs are released from haemocytes, other cells and organs into the haemolymph, where they attack components of the bacterial and fungal cell membrane and wall (Ratcliffe, 1985).

The echinocandins are a relatively new group of antifungal agents and caspofungin was the first of this group to be licensed for use (Kartsonis et al., 2003). Echinocandins show potent activity against the yeast *C. albicans* and are unique in their mode of action by targeting the biosynthesis of the fungal cell wall. In particular, echinocandins inhibit the synthesis of 1,3-β-glucan, the major polymer of the fungal cell wall (Eggimann et al., 2003). Since caspofungin targets the synthesis of the cell wall, a structure not found in mammalian cells, minimal toxicities are observed in humans, and excellent *in vivo* activity has been observed in patients (Petraille et al., 2002).

This study examined the *in vivo* activity of caspofungin in larvae of the insect *G. mellonella*. The objective of this work was to determine whether the survival of larvae administered caspofungin was due to the antifungal activity of the drug alone or to the induction of a protective immune response by the drug in the treated larvae.

**METHODS**

Assessment of the effect of caspofungin on the viability of *G. mellonella* inoculated with *C. albicans* or *Staphylococcus aureus*. Sixth instar larvae of *G. mellonella* (the greater wax moth, which belongs to order Lepidoptera, family Pyralidae) were obtained from The Mealworm Company (Sheffield, England) and stored in wood shavings in the dark at 15 °C. Larvae chosen for experiments weighed between 0.2 and 0.4 g. Ten healthy larvae were placed in sterile 9 cm Petri dishes containing a sheet of Whatman filter paper.

*C. albicans* strain MEN (a gift from Professor D. Kerridge, University of Cambridge, Cambridge, England) was grown to early stationary phase (1–2 × 10⁶ ml⁻¹) in YEPD liquid [2 %, w/v, glucose; (Sigma-Aldrich), 2 %, w/v, bacteriological peptone (Oxoid) and 1 %, w/v, yeast extract (Scharlau Chemie)] in an orbital shaker (200 r.p.m.) at 30 °C. Cells were harvested and washed in PBS (Sigma-Aldrich), and resuspended in PBS at cell densities of either 5 × 10⁶ or 1 × 10⁷ cells per 20 μl. Larvae were inoculated through the last left pro-leg into the haemocoel with a volume of 20 μl using a Micropipette syringe (Terumo Europe) and placed at 30 °C in the dark. All experiments included a control that consisted of larvae injected with sterile PBS (20 μl) and/or untouched larvae.

For the assessment of the *in vivo* antifungal activity of caspofungin, larvae of *G. mellonella* were inoculated with *C. albicans* as described, and 1 h post-inoculation were further injected with a 20 μl volume of caspofungin at concentrations of 0.19, 0.095 or 0.0475 μg ml⁻¹ (Merck) or PBS, and placed at 30 °C for 24, 48 and 72 h. The concentrations of caspofungin used here relate to the MIC₉₀, 1/2 MIC₉₀ and 1/4 MIC₉₀ values for *C. albicans*, respectively (Kelly et al., 2009).

Alternatively, larvae were injected with PBS or caspofungin (as above), placed at 30 °C for 24 h and subsequently inoculated with a 20 μl volume of either *C. albicans* (5 × 10⁶ cells) or *S. aureus* (clinical isolate grown in nutrient broth (Oxoid) at 37 °C and 200 r.p.m. to early stationary phase). A culture of *S. aureus* with an OD₆₅₀ value of 1 was diluted 1 in 4 in PBS for the inoculation. Infected larvae were placed at 30 °C and survival was monitored over 72 h.

**Determination of the haemocyte density of *G. mellonella***. *G. mellonella* larvae were injected with PBS or caspofungin as above, placed at 30 °C, and the haemocyte density was determined after 4 and 24 h. Haemocyte density was ascertained by collecting the haemolymph in a pre-chilled 1 ml tube containing a few grains of 1-phenyl-3-(2-thiazolyl)-2-thiourea (Sigma-Aldrich) to prevent melanization. Haemolymph was diluted 1 in 10 in cold PBS containing 0.37 % (v/v) 2-mercaptoethanol (Sigma-Aldrich) to reduce clotting and melanization. Haemocytes were counted on a haemocytometer and the density (ml haemolymph)⁻¹ was calculated.

**RNA extraction and PCR analysis from *G. mellonella* RNA**. Extracted RNA was DNase treated (DNase1; Sigma-Aldrich) prior to cDNA synthesis and PCR analysis from *G. mellonella*. The objective of this work was to determine whether the survival of larvae administered caspofungin was due to the antifungal activity of the drug alone or to the induction of a protective immune response by the drug in the treated larvae.

**Effect of caspofungin on the haemolymph protein profile assessed by two-dimensional (2D) gel electrophoretic separation and liquid chromatography–mass spectrometry (LC–MS).** Haemolymph was collected from larvae that had been injected 24 h previously with either PBS or caspofungin (0.19 μg ml⁻¹), and the protein (300 μg) was separated by 2D gel electrophoresis as described by Bergin et al. (2006). PBS-injected larvae were used as a control. Gel results were visualized using colloidal Coomassie staining. Gel images (in triplicate) were analysed by Progenesis SameSpots software (Nonlinear Dynamics) in order to assess the fold change between the control and caspofungin-injected larvae. Protein spots that displayed altered intensities between control and drug-treatment samples were excised, washed and trypsin digested as described by Shevchenko et al. (2006). Samples were analysed using a 6340 Ion Trap LC–MS spectrometer (Agilent Technologies) with BSA as external standards. The mass lists generated were BLAST searched using the Mascot MS/MS ion search program available at http://www.matrixscience.com.
Statistical analysis. All experiments were performed on three independent occasions. The results presented are given as the mean ± SE. A 2-tailed, 2-sample equal variance (homoscedastic) Student’s t-test was performed and samples with a P value <0.05 were deemed significant.

RESULTS

Analysis of the effect of caspofungin on the survival of G. mellonella infected with C. albicans prior to administration of the drug

To establish the effectiveness of caspofungin in an insect model, larvae of G. mellonella were inoculated with C. albicans (5×10⁵ cells per insect). After 1 h, larvae were injected with caspofungin (0.19, 0.095 or 0.0475 μg ml⁻¹; 20 μl) or PBS (20 μl) and incubated for up to 72 h at 30 °C. Larvae that were injected with the given concentrations of caspofungin showed no ill-effects and there was no decrease in survival over 72 h (data not presented). Fig. 1 illustrates the effect of caspofungin on the survival of G. mellonella after inoculation with C. albicans. A statistically significant increase in survival at all time points was detected for 0.19 μg caspofungin ml⁻¹ treatment compared to the control. The survival rate increased from 66.6±8.8% in the control to 93.3±3.3% after 24 h with this concentration of caspofungin. After 72 h, survival in the control larvae was 3.3±3.3% compared to 56.6±12.0% in larvae that had received caspofungin. Smaller increases in survival were observed using 0.095 and 0.0475 μg caspofungin ml⁻¹.

Analysis of the effect of caspofungin on the survival of G. mellonella infected with C. albicans or S. aureus after administration of the drug

Larvae of G. mellonella were injected with PBS or caspofungin, placed at 30 °C for 24 h and inoculated with 20 μl of either C. albicans (5×10⁵ cells) or S. aureus (a culture with an OD₆₀₀ value of 1 was diluted 1 in 4 in PBS). Fig. 2(a) illustrates the effect of pre-injecting larvae with caspofungin 24 h before inoculating with C. albicans. A statistically significant increase in survival was observed after 48 h with all concentrations of caspofungin compared to the control. After 48 h, survival increased from 43.3±3.3% in the control to 80±5.7% in 0.019 μg caspofungin ml⁻¹ injected larvae. A significant increase in survival was also observed after 72 h when 0.19 and 0.0475 μg caspofungin ml⁻¹ was administered.

Although caspofungin is a well established antifungal agent, we endeavoured to examine whether the immunomodulatory effect observed above was active against a...
bacterial infection. Fig. 2(b) illustrates the effect of pre-injecting larvae with caspofungin 24 h before infecting with *S. aureus*. It is evident that pre-injecting larvae with caspofungin resulted in a significant increase in survival of larvae compared to the control. For example, after 48 h larval survival was 13.3±6.6% in the control and 50±15.3% when larvae were administered 0.095 μg caspofungin ml⁻¹. Indeed, after 72 h, survival of larvae increased from 3.3±3.3% in the control to 26.6±13.3% in those larvae injected with the same concentration of caspofungin. These data illustrate that pre-injecting larvae with caspofungin provides protection to subsequent fungal (*C. albicans*) or bacterial (*S. aureus*) infection, indicating that survival is not due to the antifungal activity of caspofungin alone.

**Analysis of the effect of caspofungin on haemocyte densities in *G. mellonella***

Administration of a foreign agent to an insect has the potential to evoke an antimicrobial immune response independent of whether the original agent has any inherent antimicrobial properties (Bergin et al., 2006; Mowlds et al., 2010). We investigated whether caspofungin altered the haemocyte density since this is an indication of larval susceptibility to infection (Bergin et al., 2003). Larvae were injected with caspofungin (0.19, 0.095 and 0.0475 μg ml⁻¹) or PBS, and after 4 and 24 h, haemocytes were extracted and counted using a haemocytometer. The result (Fig. 3) indicates that after 24 h incubation, caspofungin-treated larvae demonstrated an increase in haemocyte density. The haemocyte density was 1.7±0.1×10⁶ haemocytes (ml haemolymph)⁻¹ in the control, 2.8±0.3×10⁶ haemocytes (ml haemolymph)⁻¹ in larvae that had received a dose of 0.19 μg caspofungin ml⁻¹, 3.1±0.4×10⁶ haemocytes (ml haemolymph)⁻¹ in larvae that received a dose of 0.095 μg caspofungin ml⁻¹ and 2.8±0.5×10⁶ haemocytes (ml haemolymph)⁻¹ in larvae that received 0.0475 μg caspofungin ml⁻¹. These results suggest that administration of caspofungin to larvae induced an elevation in haemocyte density, which could contribute to the overall antimicrobial activity within the haemolymph.

**Analysis of the effect of caspofungin on the expression of antimicrobial genes in *G. mellonella***

It has been demonstrated previously that survival of larvae of *G. mellonella* following inoculation with *C. albicans* is mediated by an increase in the expression of AMP and immune protein-encoding genes (Bergin et al., 2006). The expression of the genes that encode transferrin (iron-binding protein; Yoshiga et al., 1997), galiomicin (defensin; Lee et al., 2004), IMPI (inducible metallo-proteinase inhibitor; Clermont et al., 2004) and gallerimycin (cysteine-rich antifungal peptide; Schuhmann et al., 2003) in *G. mellonella* in response to caspofungin administration was investigated. Expression of the IMPI-encoding gene increased to 206.1±26.1% relative to the control when 0.095 μg caspofungin ml⁻¹ was used (Fig. 4). In the case of the transferrin-encoding gene, the greatest increase in expression was noted at a concentration of 0.19 μg caspofungin ml⁻¹, which gave a relative value of 208.6±6.7%. Smaller increases were observed at the other concentrations of drug used (133.3±19.9 and 128.7±4.2% at 0.095 and 0.0475 μg ml⁻¹, respectively). Expression of the galiomicin-encoding gene showed small increases over the different concentrations resulting in increases to 122.1±3.6, 130.4±10.4 and 119.0±16.0% at 0.19, 0.095 and 0.0475 μg caspofungin ml⁻¹, respectively. The gallerimycin-encoding gene demonstrated the smallest alteration in expression following exposure to the drug.

**Assessment of the effect of caspofungin on the expression of larval proteins**

Larvae were injected with 0.019 μg caspofungin ml⁻¹ and after 24 h, haemolymph protein was extracted and resolved by 2D electrophoresis in order to determine changes in the protein profile. Spots of interest were excised from 2D gels (Fig. 5) and trypsin-digested prior to identification by LC–MS (Table 1). A number of spots showing homology to proteins with immune function or involved in regulating metabolism were found to be altered in expression. The 32 kDa ferritin subunit I and II (spots 3 and 4) were shown to have increased by 2 and 1.6-fold, respectively, following caspofungin administration. Ferritin is important in iron binding, and storage and maintaining cellular iron homeostasis, along with playing a role in the immune response (Levy et al., 2004). Recent research has demonstrated increased expression of this protein in larvae in response to mercury (Choi et al., 2006). Spot 6 showed homology to prophenoloxidase,
which is a protein involved in melanin synthesis, a key defence against pathogens (Kavanagh & Reeves, 2004). Prophenoloxidase is found in the haemocyte as the inactive form of phenoloxidase, which catalyses the formation of melanin. Administration of caspofungin to G. mellonella resulted in a 1.9-fold increase in expression. Spot 8 showed homology to juvenile hormone binding protein (JHBP), which is an important regulator of growth, development and reproduction in insects. JHBP carries juvenile hormone (JH) to the target tissues and protects it from digestion by non-specific esterases (Sanburg et al., 1975; Kramer & Childs, 1977). Here it was shown that this protein was increased by 1.2-fold upon caspofungin treatment of larvae. Spot 7 showed homology to arginine kinase, which is a kinase involved in the transfer of a phosphate from ATP, and the protein was observed to have increased by 2.2-fold when larvae were injected with caspofungin. These results demonstrate that upon administration of caspofungin there is an increase in the expression of some proteins with antimicrobial functions or with metabolic activity.

**DISCUSSION**

Conventional assays to examine the virulence of various microbial pathogens have traditionally relied upon the use of vertebrate species. In recent years it has been demonstrated that insects may be employed to evaluate the virulence of fungi (Cotter et al., 2000; Reeves et al., 2004; Lionakis & Kontoyiannis, 2005; Mylonakis et al., 2005), bacteria (Mansfield et al., 2003) and parasites (Boulanger et al., 2001), and may be employed for the in vivo screening of antimicrobial drugs (Hamamoto et al., 2004, 2009; Johny et al., 2007). The immune response of insects is similar to the innate immune response of mammals (Kavanagh & Reeves, 2004), and contains structural and passive barriers, as well as cellular and humoral responses mediated by haemocytes and the fat body within the haemolymph. As a consequence of these similarities there is a strong correlation between the virulence of various pathogens when tested in insects and in mice (Brennan et al., 2002; Jander et al., 2000).

Caspofungin demonstrates potent in vivo antifungal activity (Petraitiene et al., 2002) and an excellent safety profile with patients suffering few adverse effects (Maertens et al., 2004; Walsh et al., 2004). In this work it was demonstrated that injection of larvae with caspofungin following inoculation with C. albicans resulted in statistically significant increases in survival. Similarly, it was demonstrated that injection of caspofungin before infecting with a fungal or bacterial pathogen significantly increases the survival rate. Interestingly, administration of caspofungin can provide protection against both a fungal (C. albicans) and a bacterial (S. aureus) infection indicating that, in addition to the inherent antifungal activity of the drug, caspofungin administration also induces a non-specific antimicrobial response in larvae.

Haemocytes are similar to the phagocytes of mammals (Bergin et al., 2005) and the majority circulate freely in the haemolymph, but a significant number can be found associated with internal organs such as the fat body, trachea or digestive system (Ratcliffe, 1985). There are six types of haemocytes, and some are involved in phagocytosis and encapsulization, which are important in the insect cellular defence against microbes (Tojo et al., 2000). The administration of caspofungin to G. mellonella larvae caused an increase in haemocyte density after 4 h and this increase was also evident after 24 h, which may be due to the release of haemocytes from the associated organs and/or the proliferation of haemocytes. The ability of caspofungin-treated larvae to survive a fungal or bacterial infection could be due, in part, to the elevation in the haemocyte density evident in such larvae.

G. mellonella can synthesize a number of AMPs that are released into the haemolymph where they can attack invading microbes (Kavanagh & Reeves, 2004). It was observed that the expression of the gene encoding transferrin was upregulated approximately twofold when larvae were injected with 0.19 μg caspofungin ml⁻¹. Interestingly, the
**Fig. 5.** 2D gels of *G. mellonella* haemolymph protein showing spots chosen for identification by LC–MS. (a) Haemolymph protein separated from PBS-injected larvae. (b) Haemolymph protein separated from (0.19 μg ml⁻¹) caspofungin-injected larvae. Spots 1–8 were excised for identification by LC–MS. The gel images are representative images of experiments performed in triplicate.

**Table 1.** *G. mellonella* protein spots identified by LC–MS plus fold changes in expression in response to caspofungin

Spots were removed, trypsin-digested and analysed by LC–MS as described in Methods. Images were analysed with Progenesis SameSpots software to assess the fold change in expression.

<table>
<thead>
<tr>
<th>Protein</th>
<th>Spot no.</th>
<th>Fold change upon injection of 0.19 μg caspofungin ml⁻¹ (compared to control)</th>
<th>Mascot score</th>
<th>Coverage (%)</th>
<th>UniProtKB accession no.</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apolipophorin III</td>
<td>1</td>
<td>–</td>
<td>459</td>
<td>44</td>
<td>P80703</td>
<td>Antimicrobial; antibiotic; induced by bacterial infection; immune response; transport of lipids</td>
</tr>
<tr>
<td>27 kDa haemolymph protein</td>
<td>2</td>
<td>+1.2</td>
<td>552</td>
<td>49</td>
<td>P83632</td>
<td>Secreted; signal; extracellular region</td>
</tr>
<tr>
<td>32 kDa ferritin subunit I</td>
<td>3</td>
<td>+2</td>
<td>329</td>
<td>20</td>
<td>Q8WSA5</td>
<td>Ferric iron binding and transport; oxidoreductase activity</td>
</tr>
<tr>
<td>32 kDa ferritin subunit II</td>
<td>4</td>
<td>+1.6</td>
<td>314</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transferrin precursor</td>
<td>5</td>
<td>−1.2</td>
<td>609</td>
<td>21</td>
<td>Q6UQ29</td>
<td>Cellular iron ion homeostasis and transport; extracellular region; ferric iron binding</td>
</tr>
<tr>
<td>Prophenoloxidase subunit II</td>
<td>6</td>
<td>+1.9</td>
<td>393</td>
<td>10</td>
<td>Q6UEH6</td>
<td>Transport; oxygen transporter activity; oxidoreductase activity</td>
</tr>
<tr>
<td>Arginine kinase</td>
<td>7</td>
<td>+2.2</td>
<td>201</td>
<td>19</td>
<td>B3TG12</td>
<td>Transferase, kinase activity</td>
</tr>
<tr>
<td>JHBP</td>
<td>8</td>
<td>+1.2</td>
<td>182</td>
<td>20</td>
<td>Q8ITP4</td>
<td>JH regulates embryogenesis and stimulates reproductive maturation in the adult; JHBP protects JH molecules from hydrolysis by non-specific esterases</td>
</tr>
</tbody>
</table>
protein transferrin precursor (spot 5 in Fig. 5) was observed to have a fold change of $-1.2$ when larvae were injected with caspofungin. A possible reason for this difference may be due to the time at which the larvae were sampled after administration of the drug (gene expression after 4 h, protein analysis after 24 h). The levels of transferrin in G. mellonella may initially rise upon caspofungin injection, but may decrease after several hours. Expression of IMPI was also increased approximately twofold following caspofungin treatment (0.095 mg ml$^{-1}$). Smaller increases were observed for galiomycin and gallerimycin following administration of the agent. These results suggest that while caspofungin may not induce the expression of a wide range of AMPs it may activate a selected subset of proteins involved in the immune response (i.e. transferrin and IMPI). This phenomenon has been observed previously where physical stress induced the expression of a selected number of AMPs in G. mellonella (Mowlds et al., 2008). Analysis of the proteome of larvae that had received caspofungin 24 h previously revealed the increased expression of a number of peptides that show homology to proteins that exhibit immune properties (e.g. prophenoloxidase, ferritin), and those involved with growth and development (arginine kinase, JHBP).

An increase in AMP or immune protein gene expression and haemocyte density in G. mellonella following caspofungin treatment may indicate a novel means of protection against infection. It appears that not only can caspofungin kill fungal cells in vitro, but also it may enhance the insect’s natural defences against infection. The injection of non-self material into the haemocoel of G. mellonella can prime the immune response against a subsequent microbial challenge although the original material may have no inherent antimicrobial properties (Bergin et al., 2006; Mowlds et al., 2010). Administration of mercury to larvae also resulted in an increase in the expression of ferritin, which has a role in the insect’s immune response (Choi et al., 2006). The ability of caspofungin to stimulate the larval immune response is an added benefit in that it constitutes a second line of attack against the invading pathogen.

While the utility of employing insects to assess the virulence of microbial pathogens or examine the in vivo properties of antimicrobial agents is now well established, researchers should be aware that, in addition to the inherent antimicrobial activity of the test agent, administration of the agent to larvae can trigger an increase in the insect’s immune response. Controls to allow discrimination between the antimicrobial properties of a novel agent and the alteration in the immune response of insects induced by the agent should be included in all experiments to ensure that the efficacy of the antimicrobial agent, rather than its immune priming abilities, is measured.

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REFERENCES


