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Secondary metabolites produced by the citrus phytopathogen *Phyllosticta citricarpa*

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Abstract

The isolation and structure elucidation of one new fungal metabolite, phenguignardic acid butyl ester (**1a**), and four previously reported metabolites (**1b**, **2a**, **3-4**) from the citrus phytopathogen *Phyllosticta citricarpa* LGMF06 are described. The new dioxolanone phenguignardic acid butyl ester (**1a**) had low phytotoxic activity in citrus leaves and fruits (at dose of 100 µg), and its importance as virulence factor in citrus black spot disease needs to be further addressed. Beside the phytotoxic analysis, we also evaluated the antibacterial (against methicillin sensitive and resistant *Staphylococcus aureus*) and cytotoxic (A549 non-small cell lung cancer, PC3 prostate cancer and HEL 299 normal epithelial lung) activities of the isolated compounds, which revealed that compounds **1a**, **1b** and **2a** were responsible for the antibacterial activity of this strain.

Introduction

Phyllosticta citricarpa is an important pathogen associated with citrus black spot (CBS) disease, causing severe economic losses to citrus producers in South Africa, Brazil and the United States [1, 2]. Besides CBS, *Phyllosticta* species are responsible for diseases in several crops including grape, horse chestnut, papaya, pomelo fruit and banana [3]. To control diseases caused by *Phyllosticta* species, it is important to understand the mechanisms involved in this pathosystem. Experiments with pathogen culture filtrates have shown that tissue response in vitro may correlate with disease reaction of the host species and the isolated compounds produced by the phytopathogen may allow to understand the virulence and pathogenicity mechanisms, as well as to select important traits to disease control [4].

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Conflict of interest The authors declare that they have no conflict of interest.

The investigation of dioxolanone as a virulence factor in four species of *Phyllosticta* were performed by Buckel et al. [5]. The authors demonstrated that phenguignardic acid (**1c**) and guignardic acid are involved in the development of grape black rot, a serious disease in grapes. Guignardic acid was described as the first member of a new class of natural compounds containing a dioxolanone moiety in 2001, since then, dioxolanone derivatives have been isolated from *Phyllosticta* species and other genera, such as *Aspergillus*, [6–8] as potential virulence factors. Based on these data we isolated and characterized the secondary metabolites produced by *P. citricarpa* LGMF06, a fungus strain isolated from lesions of CBS in Brazil, in order to identify the major secondary metabolites produced by this phytopathogen.

After a large-scale fermentation of the fungus strain LGMF06 in malt extract medium (Fig. S1), the extraction of the filtrate resulted in 752 mg of brown oil crude extract. Purification of the obtained crude extract (752 mg) using various chromatographic techniques afforded one new compound, phenguignardic acid butyl ester (**1a**), along with four previously reported compounds [phenguignardic acid methyl ester (**1b**), peniisocoumarin G (**2a**), protocatechuic acid (**3**) and tyrosol (**4**)], (Fig. 1 and supplementary file, Fig. S1). The chemical structure of the new metabolite (**1a**) was determined by cumulative 1D and 2D NMR spectroscopy, high resolution mass spectrometry (HRMS), chemical synthesis and by comparison with related structures [5–9].

The physicochemical properties of compounds **1a**, **1b** and **3-4** are summarized in the experimental section (see Supplementary Information). Compound **1b** (15.0 mg) was isolated as brown oil using standard chromatographic techniques (Supplementary Information, Fig. S1), and its spectroscopic and spectrometric data were consistent with phenguignardic acid methyl ester, a dioxolanone originally isolated and characterized from the endophytic fungus *Aspergillus flavipes* AIL8 [8]. The physicochemical properties of compound **1a** (6.3 mg) were similar to those of **1b**. The molecular formula of **1a** was deduced as C₂₂H₂₂O₅ on the basis of (+)-HRESI-MS [*m/z* 384.1809 [M + NH₄]⁺ (calcd for C₂₂H₂₆N₁O₅, 384.1805)] and NMR, with a molecular mass of 42 amu higher than that of **1b**, which is corresponding to C₃H₆. The proton NMR data of **1a** in CD₃OD (Table 1) were almost identical to those of **1b**, except for the missing of a singlet methoxy at δ_{H} 3.84 (in **1b**) and the presence of a new signals at δ_{H} 4.27 (2H, CH₂-18), δ_{H} 1.63 (2 H, CH₂-19) and δ_{H} 1.33 (2H, CH₂-20), along with a triplet methyl signal at δ_{H} 0.87 (3 H, CH₃-21). Likewise, the ¹³C NMR and HSQC spectra of **1a** (Table 1) differed from that of **1b**: a methoxy group of **1b** (δ_{C} 53.9, CH₃-18) was replaced by four up-field shifted signals at δ_{C} 68.0 (CH₂-18), δ_{C} 31.6 (CH₂-19), δ_{C} 20.1 (CH₂-20) and δ_{C} 14.0 (CH₃-21), consistent with the replacement of the methoxy group of **1b** (16-OCH₃) with an butoxy group (–OCH₂CH₂CH₂CH₃) in **1a** (Fig. 1, Supplementary Information, Fig. S2, and Table 1). Cumulative analyses of the ¹H, ¹H-COSY/HMBC/TOCSY/NOESY spectra (Supplementary Information, Fig. S2) also confirmed the presence of the butyl group in **1a**, and a key ³J_{C-H} HMBC correlation from the methylene group at δ_{H} 4.27 (CH₂-18) to C-16 (δ_{C} 166.8); Fig. S2 confirmed the attachment of the butoxy group at 16-position. All of the remaining HMBC correlations (Fig. S2) and NMR data (Table 1) are in full agreement with structure **1a**. The absolute configuration of **1a** stereocenter was established by comparison of the

NMR shifts, optical rotation to those of **1b** (which have been isolated/characterized from the same strain crude extract), and by its total synthesis (Table 1, Experimental Section and Supplementary Information, Fig. S4). Compounds **1a** and **1b** were chemically synthesized from phenguignardic acid (**1c**) following the procedure previously described by Stoye et al. [7]. Treatment of **1c** with methyl iodide and *n*-butyl bromide in acetone using K₂CO₃ as the base yielded the phenguignardic acid methyl ester (**1b**, 65%) and phenguignardic acid butyl ester (**1a**, 55%), respectively (Fig. S4). The ¹H NMR data of **1a** and **1b** were in full agreement to those of our isolated natural products (Figs S8, S9 and S26, S29) and the reported data of **1b** [7, 8]. In summary, cumulative analyses of 1D (¹H, ¹³C) and 2D (HSQC, ¹H/¹H-COSY, TOCSY, HMBC and NOESY) NMR and chemical synthesis established the structure of **1a** (Fig. 1) as a new dioxolanone analogue and was named as phenguignardic butyl ester. It is also important to note that, the NMR assignments of **1b** was incorrectly reported in literature [the NMR data at the two aromatic rings were switched (positions C-6 to C-15)] and this has been corrected herein for the first time [8].

Compound **2a** was isolated as pale yellow solid using various chromatographic techniques (Fig. S1). The physicochemical properties and UV/VIS spectrum of **2a** (λ_{max} 230, 265, 350 nm) suggested an isocoumarin chromophore for **2a**, the molecular formula of **2a** was deduced as C₁₂H₁₂O₆ on the basis of (-)-HRESI-MS [*m/z* 251.0553 [M – H]⁻ (calcd for C₁₂H₁₁O₆, 251.0561), 503.1187 [2M – H]⁻ (calcd for C₂₄H₂₃O₁₂, 503.1195)]. Based on the analyses of 1D and 2D NMR spectra (Fig. S2 and Table S1), the planar structure of **2a** appears to be same as penicoumarin G (5-hydroxy-orthosporin), an isocoumarin recently reported from the endophytic fungus *Penicillium commune* QQF-3 [10]. Finally, based on the NMR and MS data analyses, compounds **3** and **4** were identified as protocatechuic acid and tyrosol, respectively (Fig. 1), which are common metabolites previously reported from plants and fungi [11, 12].

Compound **1b** was isolated previously from *Aspergillus* sp. in 2014, and until now, there was not much information reported regarding the biological activity of this compound, neither antibacterial nor cytotoxicity data were available. Based on this information, and the isolation of a new dioxolanone analogue (**1a**), we decided to evaluate the phytotoxic activities of these dioxolanones (**1a**, **1b**) and penicoumarin G (**2a**) in the host plant tissues. To avail larger quantities for the biological analysis compounds **1a** and **1b** were chemically synthesized from phenguignardic acid (**1c**) (see experimental section), and **1c** was synthesized following the procedure previously described by Stoye et al. [7]. The plant assays were conducted using leaf disks of *Citrus sinensis*, *Citrus reticulata* and *Citrus limon* and the treatment with compound **1a**, at a dose of 100 μ g, resulted in lesion development after 12 h of inoculation in *C. sinensis* (Fig. 2a, b), *C. reticulata*, and after 24 h in *C. limon* (Fig. S52). However, even after 48 h compound **1b** did not cause any lesion, even at the higher dose (100 μ g), in any of the plants species evaluated. We also assayed the cytotoxicity of phenguignardic acid butyl ester (**1a**) in *C. sinensis* fruits, and a small necrotic zone, similar to CBS lesion, was observed in the area where compound **1a** was deposited (Fig. 2d). The epidemiological and infection processes of CBS were explored in various studies [2, 13]. It was suggested that the production of pycnidia in fruits is related to the disease symptoms, however the impact of phytotoxins in the disease development, to date, has not

been addressed. Therefore, it is possible that phenguignardic acid butyl ester (**1a**), a new dioxolanone, is involved in the development of CBS by *P. citricarpa*, in view of its toxicity in citrus leaves and fruits. Phenguignardic acid butyl ester (**1a**) is closely related to compound phenguignardic acid (**1c**), with a butoxy group attached at 16-position (instead of an OH group, Fig. 1), and phenguignardic acid (**1c**) was described as an important virulence factor in the grape black rot disease development, caused by *Guignardia bidwellii* (*P. ampellicida*) [5]. Interestingly, the mechanism of action of this class of compounds remains unknown, and some authors suggested that these compounds could be used as an herbicide, because of their non-host specific toxicity [14]. In addition, orthosporin and closely related compounds, such as diaporthin, can be associated with necrosis in some plants [15], however, at 100 µg, 5-hydroxy-orthosporin (**2a**) did not show any toxicity in citrus leaves or fruits, suggesting that this compound is not related with CBS development.

Compounds **1a**, **1b**, **2a**, **3** and **4** were also evaluated for their antibacterial and cytotoxic activities, i.e. against *Staphylococcus aureus* and methicillin resistant *S. aureus* and against three human cancer cell lines (A549, non-small cell lung cancer; PC3, prostate cancer; and HEL 299, normal epithelial lung). None of the compounds demonstrated cytotoxicity to human cancer cells at concentrations below 80 µM (Fig. S3). However, phenguignardic acid butyl ester (**1a**) displayed low activity against both methicillin sensitive and resistant *S. aureus*, an MIC value of 111 µg ml⁻¹ (Table S2). Thus, the methoxy group attached at 16-position in **1b** reduced its antibacterial activity (MIC of 333 µg ml⁻¹), in comparison with the butoxy group in the same position in **1a** (Table S2), which suggest that modifications at 16-position of these molecules influence the antibacterial activity of this class of molecules. Peniisocoumarin G (**2a**) also displayed antibacterial activity against *S. aureus* (MIC 333 µg ml⁻¹ - Table S2); however, the closely related compound orthosporin showed even lower activity in the disc diffusion analysis performed by Medeiros et al. [16]. Isocoumarins are common plant metabolites, and were reported having a broad range of biological activities, including antibacterial, anti-fungal and cytotoxic. For example, the isocoumarin NM-3 was in phase I of clinical tests due its antineoplastic effect [17]. Consistent with previous reports [11, 12] protocatechuic acid (**3**) and tyrosol (**4**) did not show any biological activity in our assays.

Supplementary Material

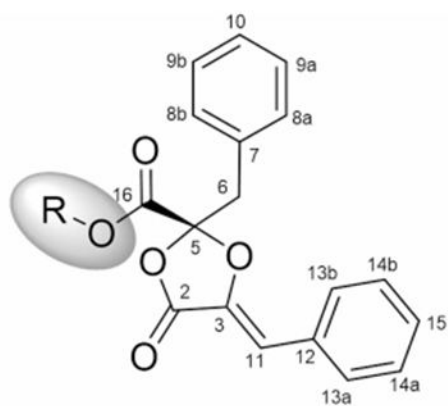
Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

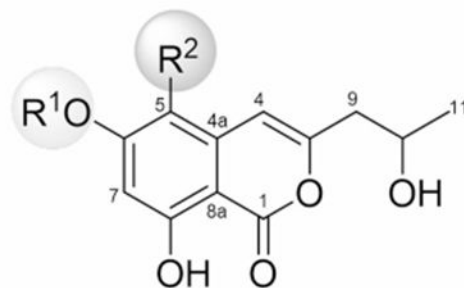
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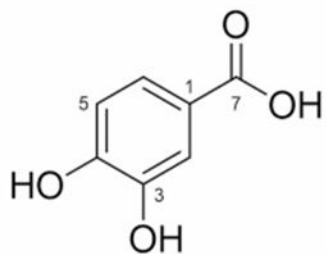
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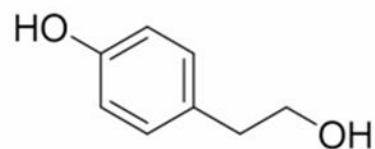
- 1a:** R=CH₂CH₂CH₂CH₃; Phenguignardic acid butyl ester
1b: R=CH₃; Phenguignardic acid methyl ester
1c: R=H; Phenguignardic acid



- 2a:** R¹=H, R²=OH; Peniisocoumarin G
2b: R¹=R²=H; Orthosporin
2c: R¹=CH₃, R²=H; Diaporthin



3: Protocatechuic acid



4: Tyrosol

Fig. 1.
Chemical structures of compounds **1a-4**

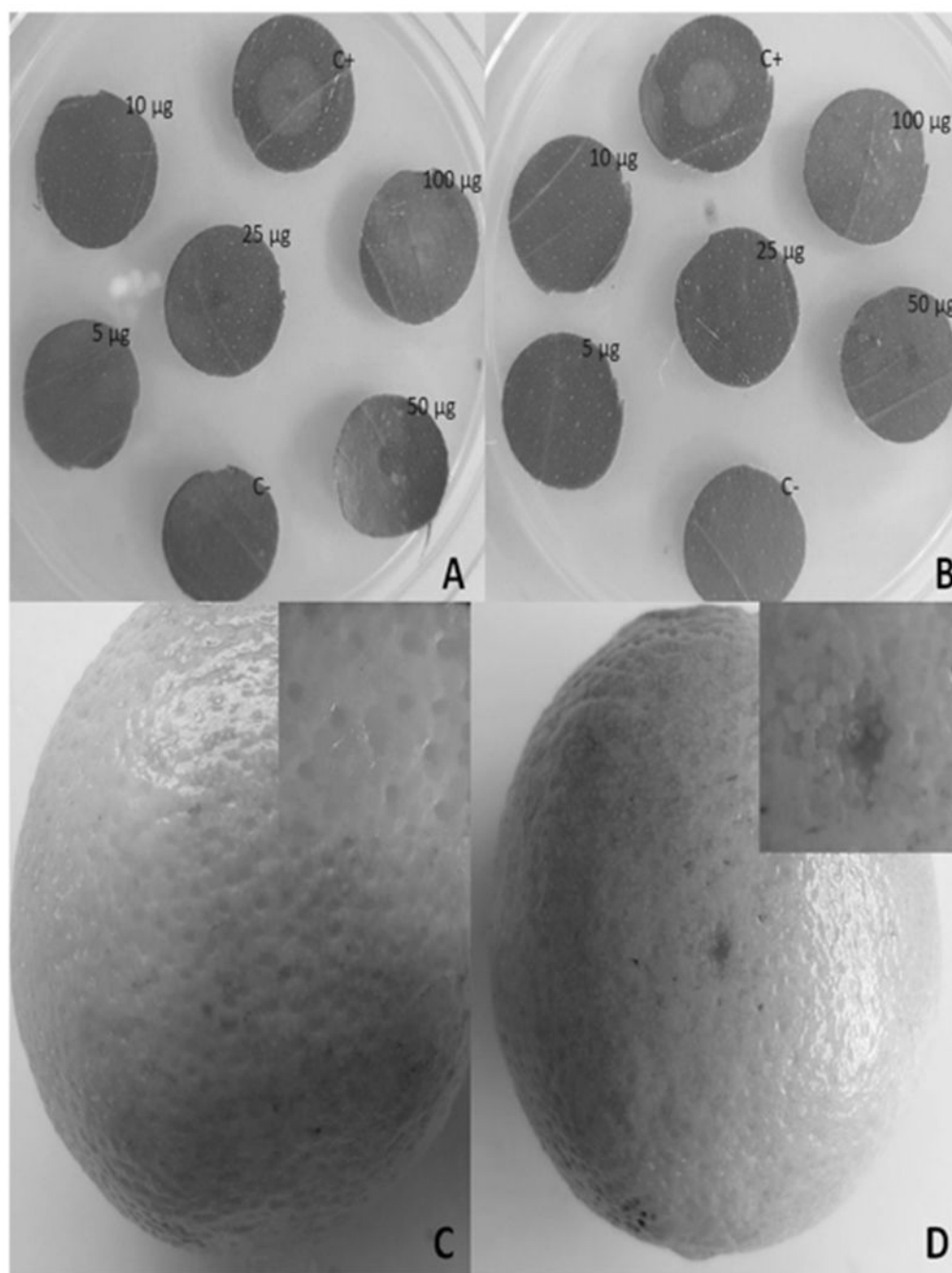


Fig. 2. Phytotoxicity assay in *Citrus sinensis* leaf disks and fruits. **a, b** cytotoxicity of phenguignardic acid butyl ester (**1a**) and phenguignardic acid methyl ester (**1b**) in leaves, respectively; **c** control with methanol; **d** cytotoxicity of phenguignardic acid butyl ester (**1a**) in fruits. C+ positive control, 10% of lactic acid, c methanol

Table 1

^{13}C (100 MHz) and ^1H (400 MHz) NMR spectroscopic data for compounds **1a** and **1b** (δ in ppm)

| Position | Compound 1a (CD ₃ OD) | | Compound 1a (CDCl ₃) | | Compound 1b (CDCl ₃) | | Compound 1b (CDCl ₃) [8] ^d | |
|----------|----------------------------------|--|----------------------------------|--|----------------------------------|--|---|--|
| | δ_{C} , type | δ_{H} (mult, <i>J</i> in [Hz]) | δ_{C} , type | δ_{H} (mult, <i>J</i> in [Hz]) | δ_{C} , type | δ_{H} (mult, <i>J</i> in [Hz]) | δ_{C} , type | δ_{H} (mult, <i>J</i> in [Hz]) |
| 2 | 163.8, C | | 162.7, C | | 162.6, C | | 162.3, C | |
| 3 | 136.9, C | | 135.6, C | | 135.4, C | | 135.2, C | |
| 5 | 106.9, C | | 105.5, C | | 105.4, C | | 105.2, C | |
| 6 | 41.3, CH ₂ | 3.61 (d, 14.8) | 40.8, CH ₂ | 3.55 (d, 14.7) | 41.0, CH ₂ | 3.56 (d, 14.7) | 109.6, CH | 6.33 (s) |
| | | 3.55 (d, 14.7) | | 3.50 (d, 14.6) | | 3.50 (d, 14.8) | | |
| 7 | 132.6, C | | 130.9, C | | 130.7, C | | 132.2, C | |
| 8a/8b | 132.4, CH | 7.30 (m) | 131.2, CH | 7.29-7.20 (m, overlapped) | 131.2, CH | 7.26 (m) | 129.8, CH | 7.67 (d, 7.5) |
| 9a/9b | 129.5, CH | 7.24 (m) | 128.7, CH | 7.29-7.20 (m, overlapped) | 128.7, CH | 7.24 (m) | 128.7, CH | 7.44 (d, 7.5) |
| 10 | 128.9, CH | 7.24 (m) | 128.1, CH | 7.29-7.20 (m, overlapped) | 128.1, CH | 7.24 (m) | 129.0, CH | 7.38 (t, 7.5) |
| 11 | 110.1, CH | 6.30 (s) | 109.7, CH | 6.30 (s) | 109.9, CH | 6.29 (s) | 40.8, CH ₂ | 3.61 (dd, 15.0) |
| 12 | 133.7, C | | 132.4, C | | 132.3, C | | 130.6, C | |
| 13a/13b | 131.0, CH | 7.67 (d, 8.0) | 130.0, CH | 7.61 (dd, 7.0, 1.2) | 130.1, CH | 7.62 (d, 7.2) | 131.0, CH | 7.32 (m) |
| 14a/14b | 129.9, CH | 7.40 (t, 7.4) | 128.9, CH | 7.42-7.32 (m, overlapped) | 129.0, CH | 7.39 (t, 7.2) | 128.4, CH | 7.28 (m) |
| 15 | 130.3, CH | 7.37 (t, 7.2) | 129.2, CH | 7.42-7.32 (m, overlapped) | 129.3, CH | 7.35 (m) | 127.8, CH | 7.28 (m) |
| 16 | 166.8, C | | 165.6, C | | 166.0, C | | 165.8, C | |
| 18 | 68.0, CH ₂ | 4.27 (tt, 6.4, 2.8) | 67.2, CH ₂ | 4.22 (t, 6.6) | 53.9, CH ₃ | 3.84 (s) | 53.6, CH ₃ | 3.87 (s) |
| 19 | 31.6, CH ₂ | 1.63 (dt, 14.3, 6.6) | 30.5, CH ₂ | 1.61 (m) | | | | |
| 20 | 20.1, CH ₂ | 1.33 (m) | 19.1, CH ₂ | 1.29 (m) | | | | |
| 21 | 14.0, CH ₃ | 0.87 (t, 7.4) | 13.7, CH ₃ | 0.85 (t, 7.4) | | | | |

See Supplementary Information for NMR spectra. Assignments supported by 2D HSQC and HMBC experiments.

^dThe NMR assignments of **1b** have been wrongly reported in literature [they have switched the NMR data at the two aromatic rings (positions C-6 to C-15)] and this been corrected herein.