

Synergy and Mechanism of Leflunomide Plus Fluconazole Against Resistant *Candida albicans*: An in vitro Study

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Objective: The global rise in the resistance of *Candida albicans* to conventional antifungals makes *Candida albicans* infections harder to treat. The main objective of this study was to investigate the antifungal effects and underlying mechanisms of leflunomide in combination with triazoles against resistant *Candida albicans*.

Methods: In this study, the microdilution method was used to determine the antifungal effects of leflunomide in combination with three triazoles on planktonic cells in vitro. The morphological transition from yeast to hyphae was observed under a microscope. The effects on ROS, metacaspase, efflux pumps, and intracellular calcium concentration were investigated, respectively.

Results: Our findings suggested that leflunomide + triazoles showed a synergistic effect against resistant *Candida albicans* in vitro. Further study concluded that the synergistic mechanisms were resulted from multiple factors, including the inhibited efflux of triazoles, the inhibition of yeast-to-hyphae transition, ROS increasing, metacaspase activation, and $[Ca^{2+}]_i$ disturbance.

Discussion: Leflunomide appears to be a potential enhancer of current antifungal agents for treating candidiasis caused by resistant *Candida albicans*. This study can also serve as an example to inspire the exploration of new approaches to treating resistant *Candida albicans*.

Keywords: *Candida albicans*, triazoles, leflunomide, synergy, synergistic mechanism

Background

Increasing drug resistance in microorganisms is very common worldwide. Previous studies have mainly focused on multidrug-resistant bacteria. However, the global rise in antifungal resistance must also be emphasized. Indeed, mortality rates caused by invasive fungal infections are 40–60% or higher, particularly in settings with antifungal resistance.^{1–3} Even worse, the severe acute respiratory syndrome coronavirus (SARS-CoV-2) pandemic globally raises the risk of fungal infections because the SARS-CoV-2 infection alters patients' immune and metabolic responses, which together creates an inflammatory environment that is highly conducive to fungal infections.^{4–6} In response to the rising threat of fungal infections, as well as the existing and emerging resistance and treatability issues, WHO developed the first fungal priority pathogens list.⁷ Among the list, *Candida albicans* (*C. albicans*) is assigned to the critical group, mainly given its antifungal resistance, mortality, evidence-based treatment, access to diagnostics, annual incidence and complications.

Notably, infections in the bloodstream are difficult to treat and sometimes deadly because of the drug resistance of *C. albicans*. Most available conventional antifungal drugs are either ineffective against triazole-resistant *C. albicans* or exhibit efficacy only when used at very high doses. To solve the problem of resistant *C. albicans*, studies on adjuvants to existing antifungal agents have received wide attention. Combination therapy with antifungals and non-antifungals may have strong beneficial effects against resistant *C. albicans* and has been a research focus in recent years. Numerous studies have found that several non-antifungal agents, such as antibacterials, calcium channel blockers, and immunomodulators, could enhance the sensitivity of resistant *C. albicans* to antifungal drugs.^{8–11}

Since leflunomide (LEF), an immunomodulator, was approved by the US Food and Drug Administration in 1988 for rheumatoid arthritis, it has been increasingly used in clinical applications.¹² Until now, LEF has been reported to exert multiple effects, including anti-inflammatory, antiproliferative, anti-chemotherapeutic resistance, and anti-angiogenic effects.¹³ Nevertheless, many questions remain to be answered about the potential clinical applications of LEF. Several immunomodulators have been studied with a view to repurpose them as antifungal chemotherapies. Immunomodulators, such as tacrolimus, cyclosporine A, and budesonide, have been proven to exert synergistic effects with triazoles against resistant *C. albicans* in vitro.^{10,14,15} Inspired by these findings, the present study aimed to evaluate whether LEF and triazoles can exert synergistic effects against resistant *C. albicans* in vitro, and the underlying synergistic mechanisms for these drug combinations.

Materials and Methods

Strains

Four *C. albicans* strains, and eight non-*albicans* *Candida* species (NAC) strains, including four *Candida krusei* (*C. krusei*) strains and four *Candida glabrata* (*C. glabrata*) strains, were used in this study. All these *Candida* strains were clinical isolates from previously established stocks and were kindly provided by Professor Shujuan Sun (Shandong Provincial Qianfoshan Hospital, Jinan, China). These strains were by Matrix-Assisted Laser Desorption Ionization Time-of-flight Mass Spectrometry (EXS3000, Zhongyuan Huiji Biotechnology Co., LTD), and their relevant information was shown in [Table S1](#).

Antifungal Agents

All active pharmaceutical ingredients, including LEF, fluconazole (FLC), itraconazole (ITR), and voriconazole (VRC) were purchased from Dalian Meilun Biotech Co., Ltd., Dalian, China. Solutions of LEF, ITR and VRC were prepared with ethyl alcohol. FLC solution was dissolved in sterile water. Stock solutions were stored away from light at -20°C .

Determination of Minimum Inhibitory Concentrations (MICs) of Planktonic Cells in vitro

The in vitro antifungal effects of LEF and triazoles against *Candida* spp. were determined using the broth microdilution method according to the M27-A3 guidelines of the Clinical and Laboratory Standards Institute (CLSI).¹⁶ MIC in this study was defined as the lowest drug concentration of the drug capable of inhibiting cell growth by 80% in comparison with the control by visual observation.^{16,17}

All drug solutions were diluted twofold to achieve final concentrations ranging from 16–1024 $\mu\text{g/mL}$ for LEF, 0.0625–128 $\mu\text{g/mL}$ for ITR, and 0.0313–64 $\mu\text{g/mL}$ for VRC. Next, 100 μL cell suspension of *Candida* spp. was added to 96-well microplates. Wells containing 100 μL of fungal suspension and 100 μL of RPMI 1640 served as the control. Susceptibility tests were performed in 96-well plates at 35°C for 24 h (for FLC) or 48 h (for ITR and VRC), according to the CLSI M27-A3.¹⁶ All experiments were repeated thrice.

The fractional inhibitory concentration index (FICI) model was used to evaluate the synergistic effects of these drug combinations in vitro. Calculation of FICIs was carried out as shown below:

$$\text{FICI} = \text{FIC}_{\text{LEF}} + \text{FIC}_{\text{triazole}} = (\text{MIC of LEF in combination} / \text{MIC of LEF alone}) + (\text{MIC of triazoles in combination} / \text{MIC of triazoles alone})$$

FICI values were interpreted by the rule described by Odds.¹⁸ $\text{FICI} \leq 0.5$ indicates synergy, $\text{FICI} > 4$ indicates antagonism, and $0.5 \leq \text{FICI} < 4$ indicates no interaction.

Test of the Inhibitory Effect on Yeast-to-Hypha Transition

Spider medium was used to induce the morphological transition from yeast to hypha in 96-well plates.^{19,20} Test plates were supplemented with a cell suspension (2×10^5 CFU/mL) of resistant *C. albicans* CA10 and drugs. Plates without drugs served as the control. *C. albicans* was allowed to grow for 4 h at 35 °C. Before imaging, the medium was gently removed and discarded to retain the adherent cells, and the wells in the plate were washed three times with sterilized PBS to remove the nonadherent cells. The hyphal growth in the control and drug-treated plates was visualized under a bright-field Olympus fluorescence microscope (Leica DMI8, Germany) using a 40× objective lens. The experiment was repeated three times.

Test of Rhodamine 6G (Rh6G) Efflux

Rh6G efflux was assessed to specifically detect the interference of LEF on the intracellular concentration of triazoles in resistant *C. albicans* CA10 cells, according to a previously described protocol with minor modifications.²¹ Briefly, *C. albicans* cells were incubated overnight at 35 °C in a liquid YPD medium. The cells were harvested and resuspended in sterilized PBS (without glucose) at 1×10^7 cells/mL and then starved for 1 h. After centrifugation and washing three times, the cells were stained with Rh6G at a final concentration of 10 μM for 50 min in the dark. Rh6G absorption was stopped by an ice-water bath (15 min). The equilibrated cells with Rh6G were washed to remove the extracellular Rh6G and then co-incubated with 64 μg/mL LEF. Equilibrated cells without LEF treatment were used as the control. The mean fluorescent intensity (MFI) of cells was recorded with a BD FACS Aria II flow cytometer (Becton Dickinson, United States) at an excitation wavelength of 488 nm and an emission wavelength of 530 nm. The interval point was 50 min. Each assay was performed in triplicate.

Test of ROS Production

Intracellular ROS production in resistant *C. albicans* CA10 was determined by a BD FACS Aria II flow cytometer (Becton Dickinson, United States) using 2, 7-dichlorodihydrofluorescein diacetate (DCFH-DA), according to our previous publication with minor modifications.²¹ DCFH-DA is a nonpolar, nonfluorescent compound that readily diffuses across membranes. It is hydrolyzed within the cell by esterases to the polar, nonfluorescent, membrane-impermeable derivative 2, 7-dichlorodihydrofluorescein (DCFH), which is rapidly oxidized by ROS to the highly fluorescent 2, 7-dichlorofluorescein (DCF).²² CA10 cell suspensions (5×10^5 CFU/mL) were treated with different drugs for 4 h, and cells treated without drugs served as the control group. Then, the cells were harvested and stained with 10 μM DCFH-DA (MedChem Express, NJ, USA) in the dark for 30 min at room temperature. The MFI of each group was detected by flow cytometry.

Test of Metacaspase Activity

CaspACETM FITC-VAD-FMK (Promega, Madison, Wisconsin, USA) is a fluorescent dye that binds specifically to the active site of metacaspases, which fluorescence intensity was measured to identify the metacaspase activation in resistant *C. albicans* CA10, as described previously with a few modifications.¹⁹ A suspension (5×10^6 CFU/mL) of CA10 cells was treated with drugs and incubated overnight (35 °C, 200 rpm). Cells treated without drugs served as the control. Subsequently, the cells were washed twice with sterilized PBS and collected. The collected cells were treated with a mixed liquid of 50 mmol/L K₂HPO₄, 5 mmol/L EDTA, and 50 mmol/L DTT for 30 min (35 °C, 100 rpm) to dissolve the cell wall. After washing twice with sterilized PBS and collection, the cells were incubated with 1.5% snailase for 45 min (35 °C, 100 rpm) to obtain CA10 cells without the cell wall. Finally, the cells were stained with 5 μM CaspACE FITC-VAD-FMK at 35 °C for 1 h in darkness. Then, 30 μL of cell suspension was placed on a glass slide and photographed using a 40× objective lens under an Olympus fluorescence microscope (Leica DMI8, Germany). The experiment was repeated three times.

Test of Intracellular Calcium Concentration ($[Ca^{2+}]_i$)

Fura-3AM is an indicator of $[Ca^{2+}]_i$. The effects of LEF in combination with FLC on $[Ca^{2+}]_i$ were tested using the fluorescent probe Fluo-3AM.²³ Briefly, resistant *C. albicans* CA10 cells were collected and washed twice with a HBSS buffer. Cells were resuspended in 1 mL of HBSS buffer treated with 0.1% pluronic F-127, and stained with Fluo-3AM (5 μ M) for 40 min without light. Unabsorbed Fluo-3AM was removed by washing the cells. After the cells were treated with or without drugs, the MFIs of Fluo-3AM were immediately recorded using the flow cytometry as above described. $[Ca^{2+}]_i$ calculation was performed using protocols as we previously described.²¹ All experiments were repeated thrice.

Statistical Analysis

Every experiment was independently carried out at least three times, and data are shown as the mean $\pm$ SD. The results were analyzed by the GraphPad Prism 8 software. Asterisks indicate statistically significant data (* $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$).

Results

Planktonic Cell Assay

The antifungal effects of LEF in combination with three triazoles (FLC, ITR and VRC) against twelve *Candida* spp. strains were evaluated as shown in Tables 1–3. The data in Tables 1–3 show that LEF alone has little obvious antifungal effects on twelve *Candida* spp. strains, with MIC > 1024 μ g/mL. However, when LEF (0.0313–0.5 μ g/mL) was combined with each of the triazoles, the MICs of the triazoles against the two resistant *C. albicans* strains were significantly reduced: the MIC of FLC from > 512 μ g/mL to 0.25–0.5 μ g/mL, the MIC of ITR from > 64 μ g/mL to 0.0625 μ g/mL, and the MIC of VRC from > 64 μ g/mL to 0.0313–0.0625 μ g/mL, indicating a strong synergistic effect. No synergistic effect was found for triazole-susceptible *C. albicans* and NAC strains.

Treatment with FLC+LEF Inhibited Yeast-to-Hypha Transition

The inhibition of yeast-to-hypha transition in resistant *C. albicans* was shown using Spider medium. Microscopic images of the hyphae showed the effects against the hyphal growth of resistant *C. albicans*. The control and drug alone groups showed massive hyphal growth; however, the presence of FLC+LEF significantly inhibited hyphal growth by reducing

Table 1 Drug Interactions of LEF and FLC Against *Candida* spp. in vitro

Drugs	Strains ^a	MIC (μ g/mL) ^b				FICI Model ^c	
		MIC _{FLC}	C _{FLC}	MIC _{LEF}	C _{LEF}	FICI ^c	IN ^d
LEF+FLC	CA4 (S)	0.5	0.5	> 1024	> 1024	2.00	NI
	CA8 (S)	0.5	0.5	> 1024	> 1024	2.00	NI
	CA10 (R)	> 512	0.5	1024	64	0.06	SYN
	CA16 (R)	> 512	0.25	1024	32	0.03	SYN
	CG1 (S)	4	4	> 1024	> 1024	2.00	NI
	CG2 (R)	128	64	> 1024	1024	1.50	NI
	CG3 (R)	64	16	> 1024	1024	1.25	NI
	CG8 (S)	8	8	> 1024	> 1024	2.00	NI
	CK2 (S)	> 4	> 4	> 1024	> 1024	2.00	NI
	CK3 (S)	> 4	> 4	> 1024	> 1024	2.00	NI
	CK9 (R)	64	64	> 1024	> 1024	2.00	NI
	CK10 (R)	64	64	> 1024	> 1024	2.00	NI

Notes: ^aCA, *C. albicans*; CG, *Candida glabrata*; CK, *Candida krusei*; "S" indicates that the strain is susceptible to azoles; "R" indicates that the strain is resistant to azoles. ^bMIC: minimum inhibitory concentration; MIC_{FLC} and MIC_{LEF}: the MICs of drugs used alone; C_{FLC} and C_{LEF}: the MICs of drugs used in combination. ^cFICI ≤ 0.5 : synergism; FICI > 4.0 : antagonism; $0.5 < \text{FICI} \leq 4.0$: no interaction. ^dIN, interpretation; SYN, synergism; NI, no interaction.

Table 2 Drug Interactions of LEF and ITR Against *Candida* spp. in vitro

Drugs	Strains ^a	MIC (μg/mL) ^b				FICI Model ^c	
		MIC _{ITR}	C _{ITR}	MIC _{LEF}	C _{LEF}	FICI	IN ^d
LEF+ITR	CA4 (S)	0.0625	0.0625	>1024	>1024	2.00	NI
	CA8 (S)	0.25	0.25	>1024	>1024	2.00	NI
	CA10 (R)	>512	0.0625	>1024	32	0.03	SYN
	CA16 (R)	>512	0.0625	>1024	32	0.03	SYN
	CG1 (S)	1	1	>1024	>1024	2.00	NI
	CG2 (R)	128	32	>1024	>1024	1.25	NI
	CG3 (R)	128	128	>1024	>1024	2.00	NI
	CG8 (S)	1	1	>1024	>1024	2.00	NI
	CK2 (S)	>1	>1	>1024	>1024	2.00	NI
	CK3 (S)	1	1	>1024	>1024	2.00	NI
	CK9 (R)	128	128	>1024	256	1.25	NI
	CK10 (R)	128	128	>1024	>1024	2.00	NI

Notes: ^aCA, *C. albicans*; CG, *Candida glabrata*; CK, *Candida krusei*; "S" indicates that the strain is susceptible to azoles; "R" indicates that the strain is resistant to azoles. ^bMIC: minimum inhibitory concentration; MIC_{ITR} and MIC_{LEF}: the MICs of drugs used alone; C_{ITR} and C_{LEF}: the MICs of drugs used in combination. ^cFICI ≤ 0.5: synergism; FICI > 4.0: antagonism; 0.5 < FICI ≤ 4.0: no interaction. ^dIN, interpretation; SYN, synergism; NI, no interaction.

Table 3 Drug Interactions of LEF and VRC Against *Candida* spp. in vitro

Drugs	Strains ^a	MIC (μg/mL) ^b				FICI Model ^c	
		MIC _{VRC}	C _{VRC}	MIC _{LEF}	C _{LEF}	FICI	IN ^d
LEF+VRC	CA4 (S)	0.0313	0.0313	>1024	>1024	2.00	NI
	CA8 (S)	0.0625	0.0625	>1024	>1024	2.00	NI
	CA10 (R)	512	0.0313	>1024	64	0.06	SYN
	CA16 (R)	512	0.0625	>1024	32	0.03	SYN
	CG1 (S)	<0.5	0.5	>1024	>1024	2.00	NI
	CG2 (R)	4	4	>1024	>1024	2.00	NI
	CG3 (R)	2	2	>1024	>1024	2.00	NI
	CG8 (S)	1	1	>1024	>1024	2.00	NI
	CK2 (S)	1	1	>1024	>1024	2.00	NI
	CK3 (S)	0.5	0.5	>1024	>1024	2.00	NI
	CK9 (R)	2	1	>1024	256	0.75	NI
	CK10 (R)	4	2	>1024	256	0.75	NI

Notes: ^aCA, *C. albicans*; CG, *Candida glabrata*; CK, *Candida krusei*; "S" indicates that the strain is susceptible to azoles; "R" indicates that the strain is resistant to azoles. ^bMIC: minimum inhibitory concentration; MIC_{VRC} and MIC_{LEF}: the MICs of drugs used alone; C_{VRC} and C_{LEF}: the MICs of drugs used in combination. ^cFICI ≤ 0.5: synergism; FICI > 4.0: antagonism; 0.5 < FICI ≤ 4.0: no interaction. ^dIN, interpretation; SYN, synergism; NI, no interaction.

the length and number of hyphae (Figure 1). The results from these experiments indicated that FLC+LEF inhibits the yeast-to-hypha transition of resistant *C. albicans*.

Rh6G Efflux Assay

Both Rh6G and triazoles are substrates for efflux pumps. Here, Rh6G was used as the fluorescent alternative of triazoles to evaluate the efflux of triazoles. Previous works by our group indicated that inhibiting the efflux of triazoles plays a role in reversing antifungal resistance.^{15,24} The cells in the presence of LEF showed significantly lower MFI values than those obtained from the control group, suggesting that the efflux of triazoles is inhibited in the LEF-treated cells (Figure 2).

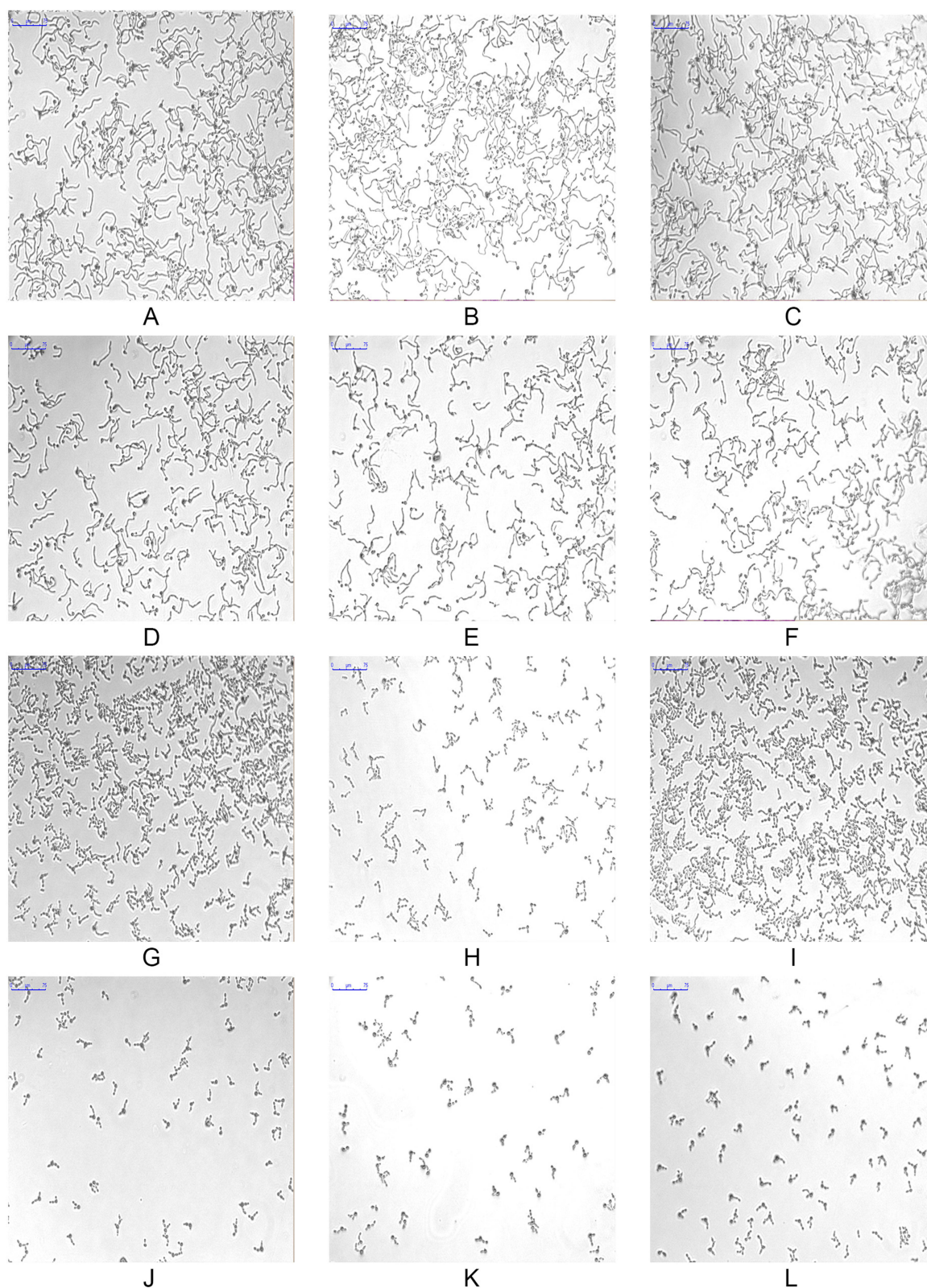


Figure 1 Observation of morphological transition from yeast to hyphae. CA10 cells in diluted in hyphae-inducing media (RPMI 1640 medium) were treated with FLC (1 µg/mL) (D–F), LEF (64 µg/mL) (G–I), or a combination of FLC (1 µg/mL) with LEF (64 µg/mL) (J–L), respectively. CA10 cells without drug treatment were used as the control (A–C). The cellular morphology of CA10 cells was photographed after incubation at 35 °C for 4 h. The photographs were collected from three independent experiments.

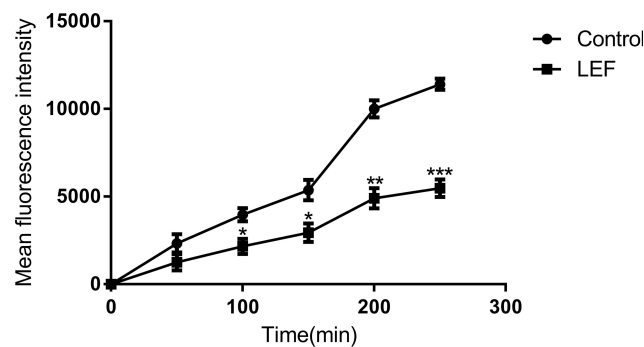


Figure 2 Influence of LEF on Rh6G efflux. The efflux of Rh6G in the absence and presence of LEF (64 $\mu\text{g/mL}$) were determined by a flow cytometer. The Y-axis represents the fluorescence intensity of intracellular Rh6G in CA10 cells. Values are the mean ($n = 3$) $\pm$ SD (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Treatment with FLC+LEF Increases ROS Level

ROS plays an important role as an initiator of early apoptosis in yeasts and other filamentous fungi. To determine whether the antifungal mechanism of FLC+LEF is conferred by apoptosis, we examined the ROS levels. DCFH-DA is the preferred dye to detect changes in ROS. The increased DCFH-DA fluorescence represents an increase in ROS. The intracellular ROS in the drug combination group was elevated as there were significant increases in DCFH-DA fluorescence (Figure 3) compared with that in the control and drug alone groups. These findings preliminarily indicated that FLC+LEF partially exerts synergistic antifungal effects on resistant *C. albicans* by triggering cell apoptosis.

Treatment with FLC+LEF Induces Metacaspase Activation

Metacaspases, which are caspase-like cysteine proteases in yeast, are significantly associated with the generation of ROS and mitochondrial dysfunction. Metacaspases play a central role in the early stages of apoptosis and can be detected by FITC-VAD-FMK staining. Cells with activated intracellular metacaspases show green fluorescence. In our study, obvious green fluorescence was observed in the FLC+LEF group, but was nearly undetectable in the other three groups was nearly undetectable (Figure 4). These results demonstrated that FLC+LEF could induce metacaspase activation in resistant *C. albicans* CA10 cells.

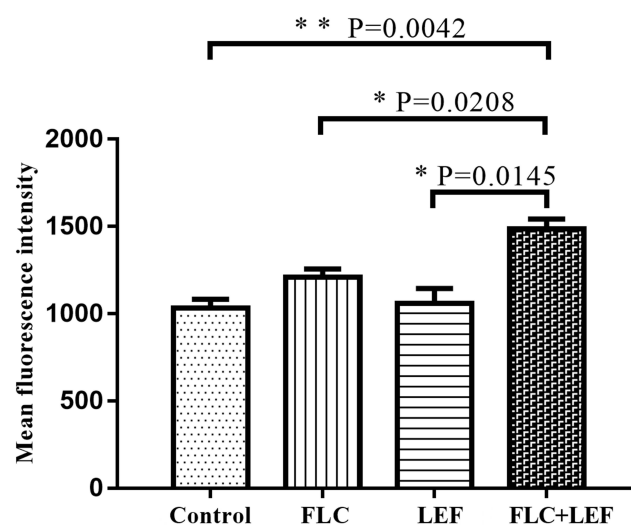


Figure 3 Flow cytometric analysis of ROS accumulation using DCFH-DA. CA10 cells were treated with different drugs (1 $\mu\text{g/mL}$ for FLC and 64 $\mu\text{g/mL}$ for LEF) for 4 h and then stained with DCFH-DA for 30 min. CA10 cells without drug treatment were used as the control. The change in intracellular ROS was shown by the fluorescence intensity of DCFH-DA. Values are the mean ($n = 3$) $\pm$ SD (* $p < 0.05$, ** $p < 0.01$).

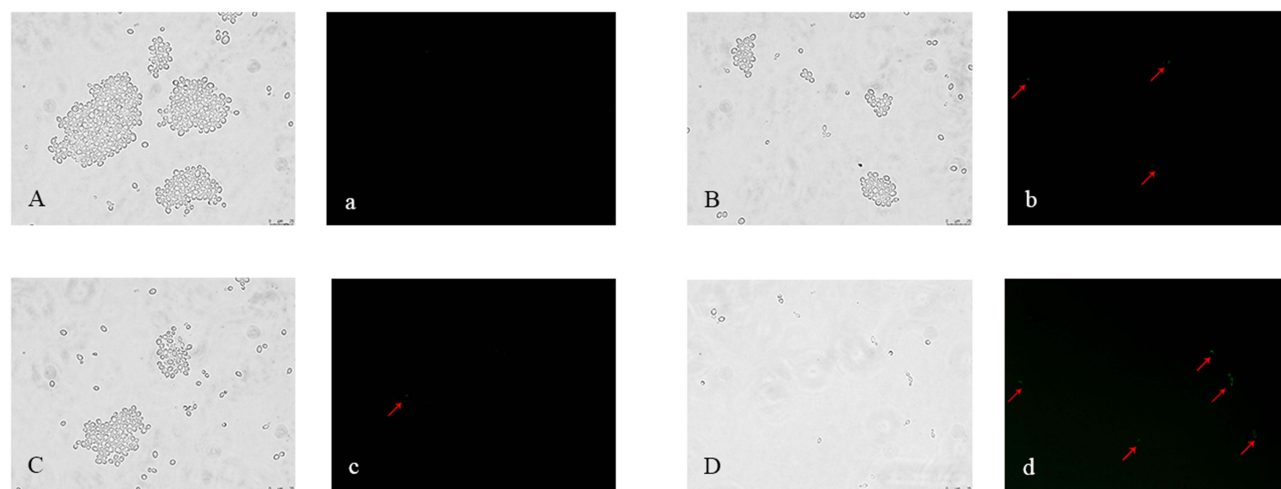


Figure 4 Fluorometric analysis of metacaspase activity. CA10 cells with FITC-VAD-FMK staining were observed under a fluorescent microscope after treatment with FLC (1 $\mu\text{g/mL}$), LEF (64 $\mu\text{g/mL}$), and a combination of FLC (1 $\mu\text{g/mL}$) with LEF (64 $\mu\text{g/mL}$). CA10 cells without drug treatment were used as the control. The photographs were collected from the most representative example in three independent experiments. (A, a) Control; (B, b) Cells exposed to FLC; (C, c) Cells exposed to LEF; (D, d) Cells exposed to FLC+LEF.

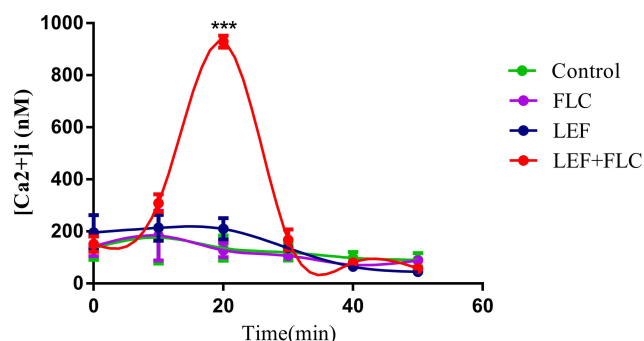


Figure 5 Flow cytometric analysis of $[\text{Ca}^{2+}]_i$ using Fluo-3/AM. CA10 cells with Fluo-3/AM staining were analyzed by flow cytometry after treatments with different drugs (no drug for the control, 1 $\mu\text{g/mL}$ for FLC, 64 $\mu\text{g/mL}$ for LEF, and 1 $\mu\text{g/mL}$ FLC + 64 $\mu\text{g/mL}$ LEF). Values are the mean ($n = 3$) $\pm$ SD (***) ($p < 0.001$).

Treatment with FLC+LEF Increases $[\text{Ca}^{2+}]_i$

As one of the most important signaling messengers in cells, Ca^{2+} plays an important role in many organisms. Our previous work demonstrated that $[\text{Ca}^{2+}]_i$ can be closely associated with drug resistance in fungi.^{21,25} Moreover, $[\text{Ca}^{2+}]_i$ acts as an initiator of apoptosis.²⁶ In this study, Fluo-3AM was used to measure $[\text{Ca}^{2+}]_i$ levels in resistant *C. albicans* cells. $[\text{Ca}^{2+}]_i$ was significantly increased in cells treated with the combination of LEF and FLC (Figure 5) at 20 min ($P < 0.001$). Our results indicated that the synergistic mechanisms of this drug combination might be associated with the unexpected movement of $[\text{Ca}^{2+}]_i$.

Discussion

Triazoles have been applied in the clinic for over 50 years. Over the years, the application of triazoles has been limited by the resistance of *C. albicans*. The general resistance of *C. albicans* to the available antifungal drugs and the emergence of multidrug-resistant strains make urgent the need to develop novel effective antifungal approaches. Seeking out new compounds with antifungal activity from a wide range of natural products, including essential oils, can be a means to combat resistant *C. albicans*.^{27–29} On the other hand, drug repurposing is also an anticipative chemotherapeutic strategy that serves to combat the resistance of *C. albicans*. Non-antifungal drugs, as sensitizers of existing antifungal drugs, can combined with existing antifungal drugs to act synergistically against drug-resistant fungi, which has attracted wide attention as one of the forms of drug repurposing. Synergy implies a rapid increase in the antifungal effects of two

agents acting together. The synergistic effects of combining agents have been highlighted as a novel antifungal approach. The combination strategy allows each individual drug to exert its ideal efficacy with very low MIC. Much effort has been expended to identify adjuvants of antifungal drugs from pharmacologically distinct families. To date, combinations of a range of commonly used antifungal drugs with various non-antifungal drugs or compounds have been found to show synergistic effects in combating resistant *C. albicans*. Inspired by the synergistic antifungal effects of immunosuppressants plus antifungal drugs, this study was primarily conducted to investigate the effects of LEF, an immunomodulator, in combination with triazoles and to determine their mode of action against *Candida* strains. No synergistic effect was found for these drug combinations against susceptible *C. albicans* strains, susceptible NAC strains, or resistant NAC strains. However, we were surprised that LEF acts synergistically with each triazole against two tested resistant *C. albicans* strains in vitro, as interpreted by the FICI model. LEF decreased the MIC of triazoles approximately 1, 024–2, 048 times in this study, indicating its great potential as an adjuvant for triazoles to reverse the resistance of *C. albicans*. Many experiments are needed to explain this phenomenon. When studying the synergistic mechanisms, FLC is selected as the representative of triazole because of its advantages of low price and wide application. Besides, we randomly selected CA10 from these two resistant *C. albicans* strains for further exploration of the underlying mechanisms of the drug combination FLC+LEF, considering that the MIC of CA10 and CA16 was the same when exposed to these two drugs.

In this study, we explored several synergistic mechanisms, including traditional mechanisms (eg efflux pumps, morphological transition) and noncanonical mechanisms (eg apoptosis, $[Ca^{2+}]_i$). *C. albicans*, as a polymorphic fungus, resides in host niches in both yeast and hypha forms. *C. albicans* yeasts can form hyphae both in planktonic cultures and during the maturation step of biofilm formation.³⁰ The formation of *C. albicans* biofilm can lead to strong resistance to conventional antifungal agents.^{31,32} As the most closely related virulence factor of biofilm, hyphae formed by *C. albicans* undoubtedly play a central role in the resistance of *C. albicans*.^{33,34} Defining the effect of FLC+LEF on the morphogenesis of resistant *C. albicans* is critical for developing targeted fungal therapeutics to prevent resistant *C. albicans* colonization and pathogenesis. Accordingly, the effect of FLC+LEF on the growth of *C. albicans* hyphae was determined in this study. As expected, the results in our study indirectly verified the role of morphogenesis in fungal resistance, and demonstrated that FLC+LEF could obviously inhibit the yeast-to-hypha transition of resistant *C. albicans*.

The overexpression of efflux pumps, one of the canonical mechanisms in *C. albicans* resistance, is among the culprits of antifungal agent resistance in recent decades. *C. albicans* with enhanced efflux pumps shows resistance to triazoles, and inhibitory strategies on the activity of efflux pumps are being explored. The activity of efflux pumps in triazole-resistant *C. albicans*, especially Cdr 1, can be intuitively reflected by the intracellular accumulation of Rh6G, a fluorescent alternative to triazoles.³⁵ This study indicated that the addition of LEF could significantly suppress the efflux of triazoles, which can be indicated by the fluorescence intensity of Rh6G (Figure 2). These findings demonstrated that the synergism between LEF and triazoles may be related to the elevated intracellular triazoles in resistant *C. albicans*.

Recently, inducing apoptosis has been regarded as a vital approach to combatting *C. albicans*. For example, plagiogchin E induces apoptosis in *C. albicans* cells through a ROS/metacaspase-dependent pathway.³⁶ Amentoflavone triggers apoptosis in *C. albicans* cells through a $\bullet OH$ -induced mitochondria-dependent pathway.³⁷ Researchers found that fungi do not completely recapitulate the mammalian apoptotic system.³⁸ The possible architectural differences between the apoptotic mechanisms of fungi and mammalian cells may open the door for designing new antifungal agents to solve the problem of antifungal resistance. ROS is a major mediating factor of cell apoptosis in fungi. ROS can oxidize intracellular biological macromolecules, cause cell damage, and activate metacaspase/Mca1 and cause cell apoptosis in *C. albicans*.^{39,40} Metacaspase/Mca1 is located in downstream of the apoptosis pathway, and most of the apoptotic processes induce apoptosis by activating metacaspase/Mca1. Metacaspase/Mca1 has also been described as a key protease for apoptosis in *C. albicans*.⁴¹ In addition, Ca^{2+} is a key regulator not only of antifungal resistance but also of cell apoptosis. Studies have proven that increased $[Ca^{2+}]_i$ can promote ROS generation and then activate the apoptotic pathway.⁴² Besides, the growth of hyphae is also closely connected to ROS production. It is proved that increased intracellular ROS can lead to filamentation defects of *C. albicans*.^{43,44} Pasrija et al showed that *erg1* mutant *C. albicans* strains could not produce hyphae, and this mutation reduced the drug efflux activity of *C. albicans*, which indirectly indicates the relationship between yeast-to-hypha transition and efflux pumps.⁴⁵ Considering our current results and the

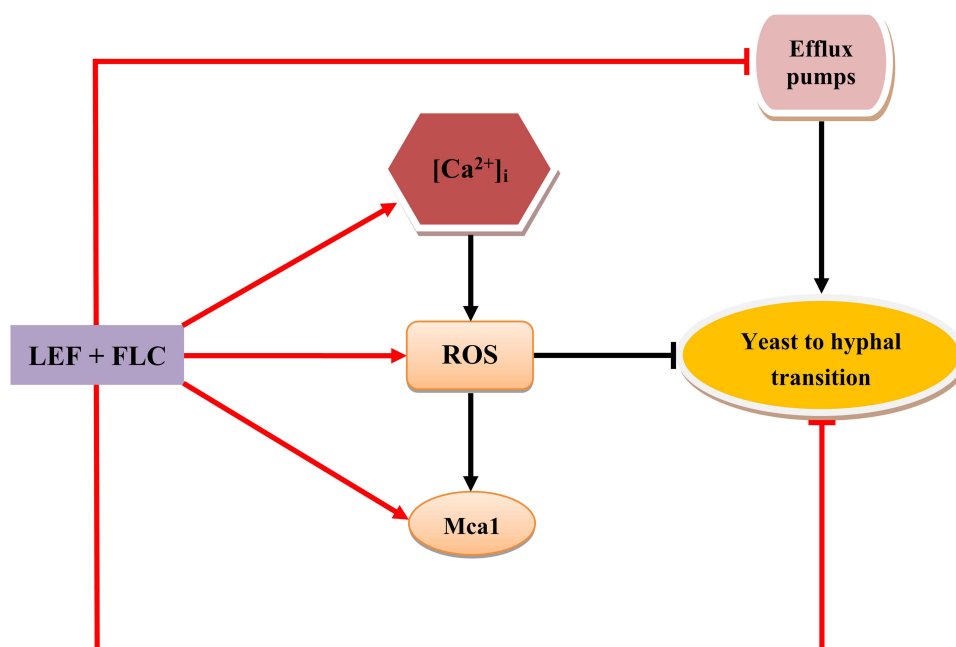


Figure 6 Hypothesis of the possible synergistic antifungal mechanisms of FLC + LEF. Arrow with flat head represents an inhibitory effect, arrow with cusp represents an activation, red arrow represents the results from our current study, and black represents the proven effects from previous literatures.

previous studies mentioned above, we have reason to suspect that the ROS-mediated apoptosis pathway plays an important role in antifungal drug resistance, and the ROS-mediated apoptosis pathway is likely to be the central part for LEF + FLC reversing *C. albicans* resistance (Figure 6). One of the shortcomings of this study is that it does not apply more resistant *C. albicans* strains to expand the scope of the study, which is what we want to continue to do in the future.

Conclusion

In conclusion, we found a novel drug combination, LEF+triazoles, against resistant *C. albicans*. In summary, this study first confirmed the synergistic antifungal effects of LEF in combination with triazoles against planktonic cells of resistant *C. albicans* in vitro. Further study concluded that the synergistic mechanisms resulted from multiple factors, mainly apoptosis. With a better understanding of the underlying synergistic mechanisms, this study provides a theoretical basis for the antifungal application of these drug combinations.

It also provides a reference for the study of antifungal drugs. Nevertheless, further explorations are still required to shed light on the molecular mechanisms of these drug combinations against resistant *C. albicans*. This study can also be an encouraging example of exploring new approaches against resistant *C. albicans*.

Abbreviations

LEF, Leflunomide; FLC, Fluconazole; ITR, Itraconazole; VRC, Voriconazole; MIC, Minimum inhibitory concentration; FICI, Fractional inhibitory concentration index; SMIC, Sessile minimum inhibitory concentration; CA, *Candida albicans*; CG, *Candida glabrata*; CK, *Candida krusei*.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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