Azole-based compounds as antiamoebic agents: a perspective using theoretical calculations†

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Diseases caused by protozoal organisms are responsible for significant mortality and morbidity worldwide. Amoebiasis caused by *Entamoeba histolytica* is an example of such diseases. In the quest for safe and effective antiamoebic agents, several heterocyclic moieties have been reported, out of which members of the azole family (dioxazole, pyrazoline, tetrazole, triazole and thiazolidinone derivatives) have attracted wide attention. This class of heterocyclic compounds have emerged as potential chemotherapeutic agents exhibiting promising antiamoebic activity with a non-cytotoxic nature. In the present article, some important breakthroughs in this area have been discussed. To get an insight at the supramolecular level, computational studies like Lipinski’s and DFT studies were carried out. Potent activity, chemical potential and hardness of the active compounds based on theoretical calculations were explained. The DFT study indicated that the LUMO energy level should lie between \(-1.34\) and \(-0.54\) eV to show high activity. We also observed that the LUMO level was mainly distributed over the 2-methyl 5-nitro imidazole ring in most of the active compounds.

1. Introduction

Protozoans, a eukaryotic unicellular organism, have the capability to destroy a multicellular organism by causing infectious diseases. Several ailments like malaria, giardiasis, amoebiasis, chagas, sleeping sickness and amoebic dysentery etc. have been associated with this class of organism, which affects a large number of populations. Amongst all, malaria and amoebiasis are the most common ones, which can be seen in all parts of world, especially in developing and underdeveloped countries.¹ ² Amoebiasis, caused by the species *Entamoeba histolytica* (*E. histolytica*) is the third most life-threatening disease after

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malaria and schistosomias. Although it is non-symptomatic in most of the cases, it infects over 50 million people per annum leading to 50 000 to 100 000 deaths annually. Areas with high rates of amoebic infection incidence include India, Africa, Mexico, central and South America and Australia. In addition to amoebic infections, they are also a potential reservoir for other bacteria. The parasite exists in two forms: an infective cyst form (that can survive outside the body) and a motile pathogenic trophozoite form (that do not persist outside the body). The infective cyst form enters into the human body through food or water contaminated with fecal matters and liberate as trophozoites in the intestinal lumen. Then the trophozoites either invade and ulcerate the mucosa of the large intestine or simply feed on intestinal bacteria. However, remains in the colon as harmless commensally, but after a period of time it becomes devastating for human being causing dysentery, colitis, liver abscess, hemorrhagic colitis and extra intestinal abscess and amoebic brain abscess.

To curb this disease, drugs of both natural and synthetic origin (Chart 1) are being used. In spite of excellent activity profile with high usage and demands of some common drugs like metronidazole (1), tinidazole (2), ornidazole (3), secnidazole (4), emetine (5), iodoquinol (6), diloxanidefuroate (7) and paromomycin (8) (Chart 1), side effects associated with these drugs compelled researchers to think for a better alternative. In this context, several attempts have been made to synthesize/isolate new drug with same/better activity profile with no/less toxicity. Interestingly, some new syntheticazole-based molecules emerged as a potential candidate and are knocking the door to enter to the market (Chart 2).

Considering the importance of this class of molecule, we present here some recent advances made in the synthesis and biological activity ofazole-based antiamoebic agents. Furthermore, a theoretical study was also carried out to make a rationale for the design of new drug. Since computational studies play an important role in the drug discovery due to low cost, quick and acceptable results, the outcome of the present finding will be helpful for the researchers working in this area.

2. Mechanism of antiamoebic drugs

For bacterial infections and pathogenic protozoan parasites, 2-methyl 5-nitro imidazole based drugs are being used for last five decades. Currently, 2-methyl 5-nitro imidazole derivatives in market are metronidazole (1), tinidazole (2), ornidazole (3) and secnidazole (4) and are highly recommended for the treatment of different stages of amoebiasis. Particularly metronidazole (1), tinidazole (2), ornidazole (3) and secnidazole (4) are the main synthetic drugs. The mechanism of action of 5-nitroimidazole derived drugs is based on the reduction of nitro group by nitro reductase enzyme like thioredoxin reductase (TrxR) or ferrodoxin. The resulting nitro radical anion is a single-electron transfer reduction product, which further undergoes reduction to yield highly reactive nitroso species (Fig. 1). This species then binds to genetic materials/proteins/other bio-molecules to inhibit the activity of .

Similarly, tinidazole (2), a structural analogue of MNZ, is known to act by reducing itself to cytotoxic intermediates that covalently bind to DNA, causing irreversible damage. Emetine (5) is an alkaloid originally extracted from Ipecac roots. It kills trophozoites mainly by inhibiting protein synthesis by blocking
translocation of the peptidyl-tRNA from acceptor to donor site on the ribosome.\(^{28-30}\)

3. Limitations of current antiamoebic drugs

During the last 50 years, numbers of compounds possessing amoebicidal activity have been isolated and synthesized.\(^{17}\) Most of them are being in use either as single agent/in combination with antibiotics or other medications.\(^{17,28,31}\) Chemically, most of the agents are derivatives of imidazoles, alkaloids, furan and quinolines. Chart 1 represents some of the main drugs used for protozoal infection. The drugs used to treat amoebiasis are classified as tissue amoebicides and luminal amoebicides, depending upon the site of infection.\(^{13,32,33}\) Metronidazole (1), tinidazole (2), ornidazole (3), secnidazole (4), emetine (5) and dehydroemetine are some of the tissue amoebicides, which kill amoeba in host tissue and organ.\(^{24}\) Side-effects of MNZ (1) includes burning/numbness in feet or hands, confusion, dizziness, drowsiness, fever, nausea, headache, metallic taste, dry mouth, glossitis, urticaria, pruritus, urethral burning and dark colored urine etc.\(^{35-38}\) Some studies have reported that this drug induces encephalopathy,\(^{39,40}\) shows genotoxicity and carcinogenicity too.\(^{41,42}\) Some recent reports have also demonstrated the \textit{in vitro} generation of strains resistant to MNZ and other drugs.\(^{28,41}\) Tinidazole (2) shares same pharmacological profile and toxicity with MNZ like bitter taste, nausea, abdominal discomfort, anorexia, vomiting, and fatiguelessness. However, its toxicity persists for less time than MNZ.\(^{27}\) Similarly, patients treated with secnidazole (4) were reported to feel nausea, gastralgia, change of taste, stomatitis, urticaria, rashes, leucopenia and others.\(^{44}\) However, a detailed scientific study on human beings for secnidazole (4) side effects is not available, but this drug has been suggested as category C drugs, which means it may have adverse effect on the fetus.\(^{45}\) Severe side effects of emetine (5) include cardiotoxicity, adrenergic (\(\alpha_2\)) blocking activity, inhibition of dipeptidyl aminopeptidase IV etc.\(^{30,46,47}\) To overcome these limitations, several new molecules were reported. However, new emetine derivatives/analogues were less toxic than the parent drug emetine itself, the biological activities of emetine derivatives/analogues were not so high so that it could be employed for clinical purposes. For a range of emetine derivatives/analogues, readers are suggested to read extensive reviews published on this topic.\(^{17,39,46}\)

On the other hand, currently used luminal agents are ornidazole (3), iodoquinol (6) and diloxanidefuroate (7) which are active only in intestinal lumen.\(^{34}\) However, in majority of cases, nitro imidazole-based tissue amoebicide could effectively control the epidemic, but in some cases, it become necessary to administer nitro imidazole-based tissue amoebicide followed by paromomycin or the second line drug diloxanidefuroate (7) to take care of luminal infection.\(^{48,49}\) Similar to the tissue amoebicides, luminal amoebicides are also associated with toxicities and side effects. For example, the common side effect of paromomycin (8) is diarrhea, which causes trouble to both the patients and the physician. Overall, both classes of antiamoebic drugs are associated with one or more side effects including resistant development. These necessitate the development of novel drug with good therapeutic activity and less/no-risky side effects.

4. Heterocyclic azole based compounds with promising antiamoebic activity

Heterocyclic cores present in natural as well as synthetic world possess a diverse range of biological activities.\(^{50-54}\) The current treatment regimen of amoebiasis is itself full of heterocyclic molecules, mainly azole based. An important review by Singh \textit{et al.}\(^{17}\) elaborated the synthesis and amoebicidal activities of a range of molecules from different sources. However, we will be restricting ourselves here mainly to molecules bearing azole
moiety with excellent in vitro activity profile. Chart 2 shows some of the important recently reported synthetic azole based compounds possessing antiamoebic activity and their IC₅₀ values are given in Table ST1 (ESI†). In the pursuit of novel molecule, recently three MNZ–thiosalicylate conjugates (9a–c, Chart 2) were reported. These conjugates possessed IC₅₀ value

**Chart 2** Structure of recently reported antiamoebic agents ofazole family.
in the range of 0.015–0.028 μM, which was better than 1 (IC_{50} = 1.46 μM). The activity pattern of conjugates dictated that compound 9a having no oxygen atom (linked to sulphur atom) showed least activity, while 9b and 9c having oxygen atom linked to sulphur atom demonstrated the best. This was attributed to the increased electron density on the molecule. The cytotoxic assay of compounds against MCF-7 cell line demonstrated their non-toxic nature in the concentration range of 2.5–250 μM.

The biological potential of hydrazones and chalcones are well established.55–59 Drugs like dihydralazine, which is in use, is a well-known example of molecule having hydrazone moiety.59 On the other hand, nature is a rich source of chalcone containing molecule.60,61 To explore the potential of these two moieties as antimicrobial agent, Azam and co-workers reported some hydrazone derivatives of 1 (10a and b, Chart 2) along with their E. histolytica inhibition and cytotoxicity studies.62 They found that the activating group like methoxy (10b, Chart 2) displayed better antimicrobial activity than compound having electron donating methyl group (10a, Chart 2). However, comparatively, both of them showed better efficiency than 1. Chalcones (11a and b, Chart 2) were also found to be better inhibitors of E. histolytica than 1.64 The IC_{50} values for these two compounds were found to be 0.05 and 0.09 μM, which were much less than 1 (IC_{50} = 1.4 μM). Compound 11a retaining two chlorine atoms displayed better antimicrobial activity than compound 11b having a chlorine and a bromine atoms. Additionally, MTT assay against MCF-7 cell line depicts that these two compounds are non-toxic in concentration range 1.56–50 μM.

Dioxazole, bearing oxygen and nitrogen both, also displayed significant inhibitory activity against E. histolytica.65 It has been reported that the inclusion of electron donating group like methyl and methoxy in a bisisoxazole backbone significantly improves the antimicrobial activity.65 For example, compounds (12a and b, Chart 2) showed better activity than 1. The IC_{50} values of these two compounds were 1.05 μM and 1.01 μM, respectively. Furthermore, the cytotoxicity assay on H9c2 cardiac myoblasts revealed non-cytotoxic nature of the compounds (viability 82% and 89%, respectively, at 12.5 μg mL\(^{-1}\)). Quinoline and pyrazoline both are important pharmacophores which exhibits a range of biological activities.66,67 In order to observe the synergistic effects of these two scaffolds, a series of quinoline based pyrazoline derivatives (13a–d, Chart 2) were reported.68 In the series of eleven compounds, four compounds showed potent antiamoebic activity. The IC_{50} values of the compounds 13a, 13b, 13c and 13d (Chart 2) were 0.05, 0.31, 0.06 and 0.29 μM, respectively which was much more pronounced than 1 (IC_{50} = 1.84 μM). Compound 13a (Chart 2), having both electron donating and withdrawing groups showed best activity among the series. Compound 13b (Chart 2), having no functional group showed slightly lower activity. However, compound 13c (Chart 2) with electron donating methoxy group displayed second highest activity. Compound 13d (Chart 2), having electron withdrawing group chlorine, showed moderate activity. All these compounds were non-toxic against MCF-7 cell line in the concentration range 1.56–50 μM.

In spite of popularity of tetrazole among medicinal chemist for various biological activities,69 no attempts have ever been made by any groups to assess its amoebicidal activity. Considering this, some new tetrazole–pyrazoline hybrids were reported by Azam and co-workers.70 In the series of 15 compounds, four compounds (14a–d, Chart 2) showed good to moderate activity. IC_{50} values for compounds 14a–d were found to be in the range of 0.86–1.20 μM; more potent than standard 1 (IC_{50} = 1.80 μM). In the previous examples, we saw that electronic factor is one of the governing factors for amoebicidal activity, same have been observed here. For instance, mild electron donating group (methyl) at para position of benzene rings attached to pyrazoline (14a, Chart 2) exhibited better activity than the rests. The cytotoxic assay against HepG2 cell line depicts non-toxic nature of the compounds in the concentration range of 3.13–25 μM. In another work, Rawat and co-workers71 reported MNZ–triazole hybrids (15a–d, Chart 2) having IC_{50} values in the range of 0.008–0.08 μM. Especially the most active compound, 2-pyridyl-(1,2,3-triazolyl)metronidazole (15d, IC_{50} = 8.4 nm) seems to be very promising.

Thiazolidinone is one of the unique molecules which contain all the three heteroatoms (N, O, S) in one ring.72 It is known to display several pharmacological activities viz. antibacterial,73 fungicidal,74 antimicrobial,75–76 antiproliferative,77 antiviral,78 anticonvulsant79 and anticanicancer.68,80 In the view of its intriguing importance as biologically active scaffold, a very first report on amoebicidal activities of a series of thiazolidinone (16a–f) was reported.80 Screening of synthesized compounds against E. histolytica dictated that some of the molecules exhibited remarkable in vitro activity and was better than 1. The IC_{50} values of the compounds were found to be in the range of 0.11–0.64 μM. Among all the compounds in series, compound 16a showed lowest IC_{50} (0.11 μM). Cytotoxic assay on HepG2 cell line showed non-toxic nature of the compounds in the concentration range of 3.13–25 μM.
5. Correlation between drug-likeness-rule of five (Ro5) and in vitro activity

The study of drug-likeness gives an idea about the possibility of whether a molecule could act as a drug or not and is a very useful tool for the drug development. It has been reported, at least in many cases, molecules obeying the “Lipinski’s rules of Five (Ro5)” is likely to behave as drugs. According to the first rule, an ideal drug candidate should have log $P \leq 5$, where log $P$ is octanol–water partition co-efficient and describes the ability of a compound to dissolve into hydrophobic (non-aqueous)
or permeation is likely to happen if a molecule violates two or more of these rules.96

To check the possibility of discussed molecules as antiamoebic drug(s), we carried out an extensive study based on Ro5. The outcomes of the study for reported molecules as well as standards are summarized in Table ST1 (ESI†). The data given in table suggests that, except few, all other compounds follow Lipinski’s parameters and are potential candidates for further clinical studies. Among the reported synthetic molecules, 9a showed log P, HBA, HBD & MW of 2.4, 4, 0 and 321.3, respectively, while for compounds 9b, these values were log P = 0.92, HBA = 5; HBD = 0 & MW = 337.3 and for 9c it was log P = 1.03, HBA = 6, HBD = 0 and MW = 353.3. Upon inclusion of one oxygen to the S-atom in 9a, a significantly decrease in the partition co-efficient and increase in MW and HBA was observed in 9b. The pattern of activity (9b > 9c > 9a) among the compounds is strongly supporting the applicability of Ro5. Similar results were observed for compounds 15c and 15d, which showed activity in nanomolar concentration range. All these values along with their biological results dictate the possibility of these molecules as future antiamoebic drug and, thus, in vivo studies should be carried out.

Since it is easy to visualize and analyze data than other methods,99 we herein, also including a table (Table 1) showing drug property data in the form of simple color and shape. From the table, it is clear that all new compounds (9–16) including standard drugs (except 8, which is a natural product and falls under exception for Ro5) reasonably follow the criteria needed for a drug candidate. The number of RBs, which is also as a detrimental factor in the oral bioavailability, was under the upper limit. It has been reported that for a molecule to possess ≥20% oral bioavailability, it should not have more than 13 RBs.92 Similarly PSA, of which cut off value was ≤140 Å² (when RB ≤ 10) for ≥20% oral bio-availability93 was within the limit.

6. Relationship between frontier molecular orbitals (FMO) and IC₅₀ value of the compounds

We already discussed the Ro5 to predict the future of recently reported azole based molecules as drug candidates. To understand these properties further at supra-molecular level, we carried out frontier molecular orbitals (FMO) studies to ensure the effect of electronic distribution within molecule on biological activities (in this case, antiamoebic). It is important to note that molecules having smaller interfrontier orbitals are chemically more active and have lower kinetic stability.94–96 The highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of a molecule give significant information about the potency of biological activity. The ionization enthalpy is related to HOMO while the LUMO corresponds to electron affinity (electron gain enthalpy) of a molecule.97 The HOMO and LUMO energy values along with chemical potential and hardness of the standards (1–8, Chart 1) and recently reportedazole-based molecules (9–16, Chart 2) are given in Table ST2 (ESI†). Fig. SF1 (ESI†) depicts orbital
diagrams of 1–16 (Charts 1 & 2). The chemical potential of standard drugs (1–8, Chart 1) ranged from −5.69 to −4.91 eV. Interestingly, for recently reportedazole-based molecules (9–16, Chart 2) this range was −5.63 to −4.47 eV, which is much similar to the standard drugs. Adding to this, when we compared hardness of the standard drugs (1–8, Chart 1) with reported azole-based molecules (9–16, Chart 2), they were also very much similar (−4.48 to −3.11 eV for 1–8 vs. −4.38 to −2.96 eV for 9–16). When we tried to correlate activity of the compounds with the negative highest electron affinity, we found that compounds 9c, 15b, 15c, and 15d have highest affinity (−1.26, −1.32, −1.27 and −1.22 eV, respectively) and hence they should possess potent amoebicidal activity. In fact, we observe the same. Compounds 15a–d reported by Rawat and co-workers and compounds 9a–c reported by Azam and co-workers possessed excellent in vitro antiamoebic activity. Fig. 2 describes HOMO and LUMO orbitals of a standard drug (MNZ) and active synthetic compounds 9b and 15d. Fig. 2 and SF1 (ESI†) indicates that the HOMO-LUMO undergoes a shift from imidazole ring to the other rings upon derivatization, resulting in a dramatic change in biological activity of the molecules. In most of the active compounds (viz. 1, 9b, and 15d), the LUMO level was mainly distributed over 2-methyl 5-nitro imidazole ring, which is the backbone to express antiamoebic activity. This implies that the new MNZ based derivatives shows variation in IC50 value due to shifting of LUMO levels between 2-methyl 5-nitro imidazole ring and other aromatic rings carrying different functionality. Furthermore, due to this, a variation in nitro group reduction affinity cannot be ruled out.

Furthermore, we draw a plot between IC50 and LUMO energies (Fig. 3), to predict and set a limit for LUMO energy level, which a molecule should possess in order to show better activity. From figure, it is interesting to note that majority of the molecules, which we discussed in this paper (1–16), displayed LUMO energy between −1.34 to −0.54 eV. Thus, this value could be treated as limit while designing new antiamoebic agents.

7. Conclusion

Amoebiasis is one of the silent killers in developing and underdeveloped countries. However, the number of deaths caused by this disease is under the control, but it causing a considerable loss of health and economy. In addition to the current therapeutic regime, severalazole-based compounds have been reported with activity better than the standards. We have reviewed the potential of some new syntheticazole-based molecules as antiamoebic agents. Through theoretical studies, we observed that some of the newly reported azole based compounds deserve further clinical studies as their physico-chemical properties are similar or comparable with the currently employed drugs. DFT studies indicated that LUMO energy level should lie between −1.34 and −0.54 eV to show excellent activity. The HOMO-LUMO undergoes a shift from imidazole ring to the other rings upon derivatization, resulting in a dramatic change in biological activity of the molecules. In most of the active compounds, the LUMO level was mainly distributed over 2-methyl 5-nitro imidazole ring. Among the discussed, compounds 9a–c and 15b–d need special attention from the people working in this area. They obeyed the rules of drug likeliness to all extents. Hence, based on experimental in vitro results and theoretical calculations, we strongly support further in vivo studies of the above-said compounds to introduce new antiamoebic agents in the market.

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