

## Retraction

# Retracted: Exploring Drug Targets in Isoprenoid Biosynthetic Pathway for *Plasmodium falciparum*

### Biochemistry Research International

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*Biochemistry Research International* has retracted the article titled “Exploring Drug Targets in Isoprenoid Biosynthetic Pathway for *Plasmodium falciparum*” [1]. The article was found to contain a substantial amount of material from previously published articles [2–6], including the following sources:

- (i) Baichen Zhang, Kristin M. Watts, Dana Hodge, Lisa M. Kemp, David A. Hunstad, Leslie M. Hicks, Audrey R. Odom. “A Second Target of the Antimalarial and Antibacterial Agent Fosmidomycin Revealed by Cellular Metabolic Profiling”, *Biochemistry*, 2011. <https://doi.org/10.1021/bi200113y>. (Cited as reference 3)
- (ii) Cyrille Y. Botté, Faustine Dubar, Geoffrey I. McFadden, Eric Maréchal, Christophe Biot. “Plasmodium falciparum Apicoplast Drugs: Targets or Off-Targets?”, *Chemical Reviews*, 2011. <https://doi.org/10.1021/cr200258w>. (Not cited)
- (iii) J. Kipchirchir Bitok, Caren Freel Meyers. “2-Methyl-erythritol 4-Phosphate Enhances and Sustains Cyclodiphosphate Synthase IspF Activity”, *ACS Chemical Biology*, 2012. <https://doi.org/10.1021/cb300243w>. (Not cited)
- (iv) Fabiana Morandi Jordão, Emília Akemi Kimura, Alejandro Miguel Katzin. “Isoprenoid biosynthesis in the erythrocytic stages of *Plasmodium falciparum*”, *Memórias do Instituto Oswaldo Cruz*, 2011. <https://doi.org/10.1590/S0074-02762011000900018>. (Cited as reference 6)
- (v) Lisheng Deng, Jiasheng Diao, Pinhong Chen, Venugopal Pujari et al. “Inhibition of 1-Deoxy-D-Xylulose-5-Phosphate Reductoisomerase by Lipophilic

Phosphonates: SAR, QSAR, and Crystallographic Studies”, *Journal of Medicinal Chemistry*, 2011. <https://doi.org/10.1021/jm200363d>. (Not cited)

The authors disagree with this retraction.

### References

- [1] T. Qidwai, F. Jamal, M. Y. Khan, and B. Sharma, “Exploring Drug Targets in Isoprenoid Biosynthetic Pathway for *Plasmodium falciparum*,” *Biochemistry Research International*, vol. 2014, Article ID 657189, 12 pages, 2014.
- [2] B. Zhang, K. M. Watts, D. Hodge et al., “A second target of the antimalarial and antibacterial agent Fosmidomycin revealed by cellular metabolic profiling,” *Biochemistry*, vol. 50, 2011.
- [3] C. Y. Botté, F. Dubar, G. I. McFadden, E. Maréchal, and C. Biot, “Plasmodium falciparum Apicoplast Drugs: Targets or off-targets?” *Chemical Reviews*, 2011.
- [4] J. Kipchirchir Bitok and C. F. Myers, “2-methyl-erythritol 4-phosphate Enhances and Sustains cyclodiphosphate Synthase IspF activity,” *ACS Chemical Biology*, 2012.
- [5] F. M. Jordão, E. A. Kimura, and A. Miguel Katzin, “Isoprenoid biosynthesis in the erythrocytic stages of *Plasmodium falciparum*,” *Memórias do Instituto Oswaldo Cruz*, vol. 106, 2011.
- [6] L. Deng, J. Diao, P. Chen, and V. Pujari, “Inhibition of 1-deoxy-D-Xylulose-5-Phosphate Reductoisomerase by lipophilic Phosphonates: SAR, QSAR, and crystallographic Studies,” *Journal of Medicinal Chemistry*, 2011.

## Review Article

# Exploring Drug Targets in Isoprenoid Biosynthetic Pathway for *Plasmodium falciparum*

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Emergence of rapid drug resistance to existing antimalarial drugs in *Plasmodium falciparum* has created the need for prediction of novel targets as well as leads derived from original molecules with improved activity against a validated drug target. The malaria parasite has a plant plastid-like apicoplast. To overcome the problem of falciparum malaria, the metabolic pathways in parasite apicoplast have been used as antimalarial drug targets. Among several pathways in apicoplast, isoprenoid biosynthesis is one of the important pathways for parasite as its multiplication in human erythrocytes requires isoprenoids. Therefore targeting this pathway and exploring leads with improved activity is a highly attractive approach. This report has explored progress towards the study of proteins and inhibitors of isoprenoid biosynthesis pathway. For more comprehensive analysis, antimalarial drug-protein interaction has been covered.

## 1. Introduction

Falciparum malaria is a well-known major killer, causing approximately one million deaths per year and 300–500 million clinical cases [(WHO 2010) World malaria report. World Health Organization, Geneva]. The malaria parasite belongs to apicomplexan phylum and has a plastid-like structure “apicoplast.” The metabolic pathways in apicoplast differ from the host and therefore apicoplast opens up new possibilities of targeting *P. falciparum*. The isoprenoid metabolic pathway is crucial for the *P. falciparum*. In plants more than 30000 isoprenoids are known. However the number of isoprenoids in malaria parasites is low. Isoprenoid includes cholesterol, bile acids, steroid hormones, dolichol, ubiquinone, prenylated proteins, and a wide variety of plant terpenoids [1]. The isoprenoid compounds are widespread in the three domains of archaeobacteria, eubacteria, and eukaryotes. The “cyclisation reactions” are unknown in malaria parasites; however, rearrangements and oxidation of the carbon skeleton are responsible for the enormous structural diversity. Although they are

produced from the condensation of the same precursors in all organisms (isopentenyl pyrophosphate and dimethylallyl diphosphate), the evolutionary origin of their biosynthesis remains controversial. Currently, two different routes have been identified to biosynthesize isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP). The well-known mevalonate pathway in most eukaryotes include mammals, higher plants, and archaea and the 2-C-methyl-D-erythritol-4-phosphate (MEP) pathway, also known as 1-deoxy-D-xylulose-5-phosphate (DOXP) or nonmevalonate pathway, in bacteria and plant plastids, especially in several pathogenic microorganisms [2].

Antimicrobial drug resistance is the most common problem in the control and treatment of many serious infections, including *P. falciparum* malaria, tuberculosis, and other infectious diseases. The nonmevalonate pathway of isoprenoid biosynthesis is essential in eubacteria (not all) and *P. falciparum*. As this pathway is absent in humans, consequently there is a great interest in targeting the enzymes of non-mevalonate metabolism for antiparasitic drug development.

Fosmidomycin is a broad-spectrum antimicrobial agent and has been used in clinical trials of combination therapies for the treatment of malaria [3]. *In vitro*, fosmidomycin is known to inhibit the deoxyxylulose phosphate reductoisomerase (DXR) enzyme of isoprenoid biosynthesis from multiple pathogenic organisms. Isoprenoid metabolism proceeds through DXR even in the presence of fosmidomycin but is inhibited at the level of the downstream enzyme, methylerythritol phosphate cytidyltransferase (IspD). Overexpression of IspD in *E. coli* conferred fosmidomycin resistance, and fosmidomycin was found to inhibit IspD *in vitro* [3]. Under *in vivo* conditions fosmidomycin may inhibit IspD directly or may cause other changes within the cell that reduce IspD activity [3]. *Mycobacterium tuberculosis* synthesizes isoprenoids via the nonmevalonate or DOXP pathway. Previous work had demonstrated that three enzymes, namely, Dxr, IspD, and IspF, are all required for growth *in vitro*. The DOXP biosynthetic pathway of *M. tuberculosis* is specific and essential and represents an attractive potential target for the design of new antimycobacterial agents. The work by Brown et al. (2010) demonstrated that three enzymes in the pathway (Dxr, IspD, and IspF) are all required for *in vitro* growth of *M. tuberculosis* [4]. Most eubacteria (not all) synthesize their isoprenoids using the methylerythritol-4-phosphate pathway, whereas a minority uses the unrelated mevalonate pathway and only a few have both [5]. Isoprenoids are a large and highly diverse group of natural products with many functions and their synthesis is essential for the parasite's survival [6]. This paper attempts to cover the different enzymes involved in isoprenoid biosynthesis and their importance in *P. falciparum* and antimalarial drug against these enzymes. In addition, an insight into host-parasite genetic polymorphisms is also presented.

## 2. Scope of Apicoplast as Antimalarial Drug Target

The parasites such as *Plasmodium* spp., *Babesia* spp., *Toxoplasma gondii*, *Cryptosporidium* spp., *Isospora belli*, and *Cyclospora cayetanensis* infect humans [9]. With the exception of *Cryptosporidium* spp., these parasites possess apicoplast, a nonphotosynthetic plastid-like organelle. The apicoplast genome houses only 68 open reading frames (ORFs) for rRNAs, tRNAs, ribosomes, RNA polymerase, translational elongation factor (EF-Tu), ClpC chaperone, and Fe-S cluster protein (SufB) [1, 9]. Most of the proteins involved in the apicoplast metabolic pathways are encoded in the nucleus, synthesized in the cytoplasm, and subsequently imported into the apicoplast [2].

The apicoplast contains metabolic pathways critical for liver-stage and blood-stage development. During the blood stages, parasites lacking an apicoplast can grow in the presence of isopentenyl pyrophosphate, demonstrating that isoprenoids are the only metabolites produced in the apicoplast which are needed outside of the organelle. Two of the isoprenoid biosynthesis enzymes are predicted to rely on iron-sulfur (FeS) cluster cofactors; however, little is known about FeS cluster synthesis in the parasite or the roles that FeS

cluster proteins play in parasite biology [10]. In *P. falciparum*, the protein SufS and its partner SufE were found exclusively in the apicoplast and SufS was shown to have cysteine desulfurase activity in a complementation assay. IscS and its effector Isd11 were solely mitochondrial, suggesting that the Isc pathway cannot contribute to apicoplast FeS cluster synthesis. The Suf pathway was disrupted with a dominant negative mutant resulting in parasites that were only viable when supplemented with IPP. These parasites lacked the apicoplast organelle and its organellar genome—a phenotype not observed when isoprenoid biosynthesis was specifically inhibited with fosmidomycin. These results demonstrate that the Suf pathway is essential for parasite survival [10].

Fatty acid, isoprenoid, haem biosynthesis, Fe-S clusters, and DNA transactions are prominent pathways in apicoplast. The most important metabolic functions and the mevalonate independent 1-deoxy-D-xylulose-5-phosphate (DOXP) pathway of isoprenoid synthesis and the type II fatty acid synthesis system operate inside the apicoplast. Classical antibacterial drugs such as ciprofloxacin, tetracycline, doxycycline, clindamycin, and spiramycin inhibit the apicoplast-located gyrase and translation machinery, respectively, and are currently used for the treatment of infections with apicomplexan parasites. Fosmidomycin, an inhibitor of isoprenoid synthesis, was proven to be effective against acute falciparum malaria in clinical phase II studies. Fosmidomycin alone or in combination with clindamycin was evaluated for the treatment of acute uncomplicated falciparum malaria. Monotherapy using fosmidomycin led to a fast parasite clearance but was inefficient in radical elimination of the parasites [11]. Triclosan, an inhibitor of fatty acid synthesis, was active in a malaria mouse model. *In vitro* antimalarial activity was shown for inhibitors of peptide deformylase and the import of apicoplast-targeted proteins. In the drug discovery against *P. falciparum*, the presence of apicoplast has been a milestone [12].

## 3. Isoprenoid Biosynthesis

It is required for the production of isopentenyl pyrophosphate and dimethylallyl pyrophosphate that plays a role in the biosynthesis of molecules used in protein prenylation, cell membrane maintenance, hormones, protein anchoring, and N-glycosylation. Plants and apicomplexan protozoa such as malaria parasites have the ability to produce their isoprenoids by means of an alternative pathway (nonmevalonate pathway) which takes place in their plastids. Interestingly, most bacteria including important pathogens such as *M. tuberculosis* synthesize IPP and DMAPP via the nonmevalonate pathway.

**3.1. Nonmevalonate (MEP/DOXP Pathway).** Plants and apicomplexan protozoa such as malaria parasites produce their isoprenoids by utilizing an additional alternative pathway called the methylerythritol phosphate (MEP) or nonmevalonate pathway, which takes place in their plastids (Figure 1).

Higher plants possess the MEV pathway in the cytosol, in addition to the MEP pathway in the plastids. In contrast, the MEV pathway has not yet been detected in

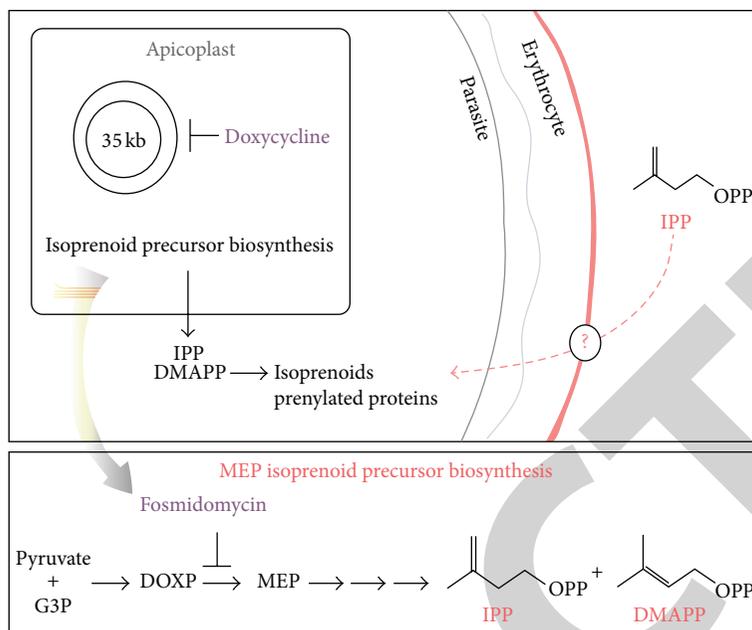


FIGURE 1: The role of the apicoplast in production of isoprenoid precursors, IPP and DMAPP, which are exported into the cytoplasm and used to synthesize small molecule isoprenoids and prenylated proteins. *P. falciparum* is unable to synthesize isoprenoid precursors either due to inhibition of the biosynthetic pathway by fosmidomycin or loss of the apicoplast following doxycycline inhibition which can be chemically rescued by addition of exogenous IPP. The exogenous IPP enters the host cell through unknown membrane transporters and fulfills the missing biosynthetic function [7].

the cytosol of apicomplexan parasites. The nonmevalonate pathway or 2-C-methyl-D-erythritol-4-phosphate/1-deoxy-D-xylulose-5-phosphate pathway (MEP/DOXP pathway) of isoprenoid biosynthesis is an alternative metabolic pathway leading to the formation of IPP and DMAPP [7]. The MEP pathway consists of 8 steps and 7 enzymes (Figures 2(a) and 2(b)).

**3.2. Enzymes of MEP Pathway.** Cassera et al. (2004) suggested that two genes encoding the enzymes of MEP pathway, namely, 1-deoxy-D-xylulose-5-phosphate synthase and 1-deoxy-D-xylulose-5-phosphate reductoisomerase, play a role in isoprenoid biosynthesis in *P. falciparum*. Fosmidomycin could inhibit the activity of 1-deoxy-D-xylulose-5-phosphate reductoisomerase [13]. The metabolite 1-deoxy-D-xylulose-5-phosphate is not only an intermediate of the MEP pathway for the biosynthesis of isopentenyl diphosphate but is also involved in the biosynthesis of thiamin (vitamin B1) and pyridoxal (vitamin B6) in plants and many microorganisms. An added advantage of targeting 1-deoxy-D-xylulose-5-phosphate synthase is its influence on vitamins B1 and B6 biosynthesis in malaria parasite [14].

Most of the downstream intermediates (1-deoxy-D-xylulose-5-phosphate, 2-C-methyl-D-erythritol-4-phosphate, 4-(cytidine-5-diphospho)-2-C-methyl-D-erythritol, 4-(cytidine-5-diphospho)-2-C-methyl-D-erythritol-2-phosphate, and 2-C-methyl-D-erythritol-2,4-cyclodiphosphate) of the MEP pathway in the three intraerythrocytic stages of *P. falciparum* have been unfolded [15]. The effect of fosmidomycin on the biosynthesis of each intermediate of this pathway

and isoprenoid biosynthesis (dolichols and ubiquinones) has been explored. MEP pathway is functionally active in all intraerythrocytic forms of *P. falciparum*, and *de novo* biosynthesis of pyridoxal in a protozoan has been reported [16]. Its absence in the human host makes both pathways potentially very attractive targets for antimalarial drug development.

Another enzyme of the nonmevalonate pathway, 1-deoxy-D-xylulose-5-phosphate reductoisomerase which is involved in the transformation of 1-deoxy-D-xylulose 5-phosphate to 2-C-methyl-D-erythritol-4-phosphate. DXR protein from the human malaria parasite *P. falciparum* (PfDXR) was overproduced in *Escherichia coli* and crystallized using the hanging-drop vapour-diffusion method in the presence of nicotinamide adenine dinucleotide (NADPH) [16]. Cassera et al. (2007) reported that, in *P. falciparum*, the formation of isopentenyl diphosphate and dimethylallyl diphosphate intermediates in the biosynthesis of isoprenoids and occurs via the methylerythritol phosphate pathway [17]. Fosmidomycin is a specific inhibitor of the 1-deoxy-D-xylulose-5-phosphate reductoisomerase. The effect of fosmidomycin on the levels of each intermediate and its metabolic requirement for the isoprenoid biosynthesis, such as dolichols and ubiquinones, throughout the intraerythrocytic cycle of *P. falciparum* have been analyzed. Fosmidomycin treatment resulted in a decrease of the intermediate levels in the MEP pathway as well as in ubiquinone and dolichol biosynthesis. The MEP pathway associated transcripts were modestly altered by the drug, indicating that the parasite is not strongly responsive at the transcriptional level. This was the first study

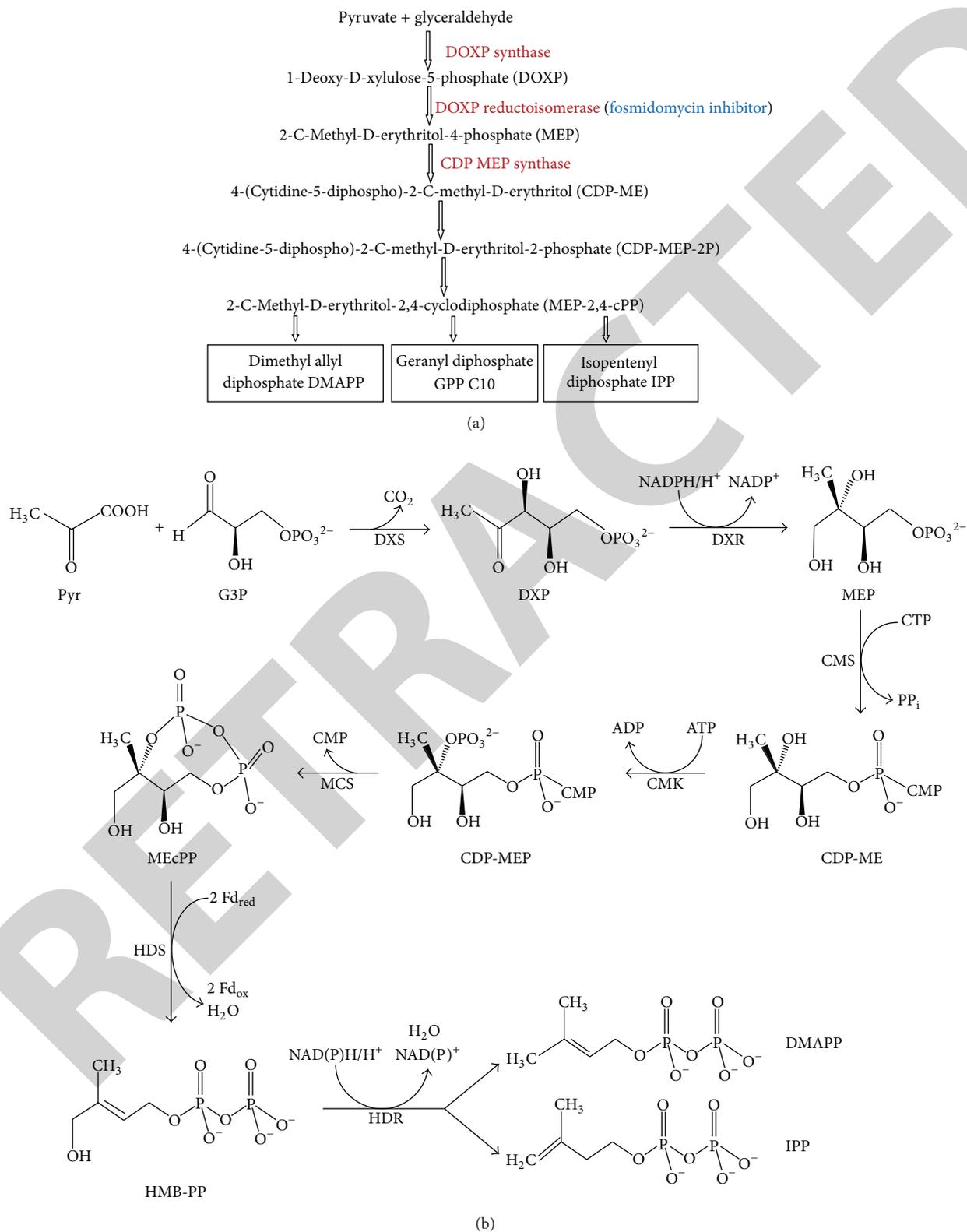


FIGURE 2: (a) Synthesis of isoprenoid compound by nonmevalonate pathway: a flow chart; (b) chemical reactions involved in biosynthesis of isoprenoid via nonmevalonate pathway.

that compares the effect of fosmidomycin on the metabolic and transcript profiles in *P. falciparum*, which has only the MEP pathway for isoprenoid biosynthesis.

**3.3. Dolichol Phosphate Mannose Synthase.** The intraerythrocytic stages of *P. falciparum* use dolichol and its phosphorylated derivatives as carrier lipids in biosynthesis of several glycoconjugates. Anchors and N-linked glycoproteins require dolichyl phosphate and dolichyl pyrophosphate as carriers of different monosaccharide constituents. Kimura et al. (1996) demonstrated the effect of N-linked glycoproteins on differentiation of intraerythrocytic stages of *P. falciparum* [18]. The reaction between dolichol phosphate (Dol-P) and guanosine diphosphate mannose (GDP-Man) to form dolichol-phosphate-mannose (Dol-P-Man) is catalyzed by dolichol phosphate mannose synthase (DPM) enzyme [19]. This molecule acts as mannose donor for N-glycosylation and glycosylphosphatidylinositol (GPI) biosynthesis. *P. falciparum* DPM1 (*Pfdpm1*) possesses a single predicted transmembrane region near the N-terminus but not the C-terminus. *Pfdpm1* was unable to complement a mouse mutant deficient in DPM but efficiently complemented the *Schizosaccharomyces pombe* fission yeast mutant, indicating a difference between fission yeast and mammalian DPM genes.

Many eukaryotic cells, such as yeast and a number of mammalian cells, are unable to incorporate more complex isoprenoid precursors such as FPP and GGPP. In contrast, intraerythrocytic forms of *P. falciparum* easily metabolise these compounds when they are added to the culture medium, permitting the subsequent identification of higher isoprenoids. Walter (1986) reported that dolichol kinase, a rate limiting enzyme for the supply with dolichyl monophosphate as glycosyl carrier lipid in *P. falciparum*, and inhibition of this enzyme (dolichol kinase) occurred by mefloquine [20]. The enzyme was found to be associated with the pellet fraction and to depend on cytidine triphosphate as phosphoryl donor. Couto et al. (1999) identified dolichol, dolichyl phosphate, and dolichyl pyrophosphate of 55 and 60 carbons (11/12 isoprenic units) [21]. Biochemical studies in *P. falciparum* indicated that, in addition to the pathway for synthesis of phosphatidylcholine from choline (CDP-choline pathway), the parasite synthesizes this major membrane phospholipid via an alternative pathway named the serine-decarboxylase-phosphoethanolamine-methyltransferase (SDPM) pathway using host serine and ethanolamine as precursors [22].

The pathogenic stages of *P. falciparum* are those that invade mature erythrocytes, which are devoid of internal organelles and incapable of *de novo* lipid biosynthesis. Despite this, *P. falciparum* undergoes dramatic morphological and metabolic developmental changes and asexually divides to form new daughter cells within a human erythrocyte [23]. This rapid multiplication of *P. falciparum* within host erythrocytes entails the active production of new plasma membranes in which phospholipids are the major architectural and functional components. Phosphatidylcholine (PtdCho)2 and phosphatidylethanolamine (PtdEtn) comprise 40–50% and 35–45%, respectively, of the parasite's total plasma membrane phospholipid content [24]. Genome data predicts

that *P. falciparum* possesses enzymatic pathways for the synthesis of all the necessary phospholipids from precursors transported from host milieu, such as serine, choline, inositol, glycerol, and fatty acids [24, 25]. The *PfPMT* gene in *P. falciparum* encodes the phosphoethanolamine methyltransferase that specifically methylates phosphoethanolamine to phosphocholine (p-Cho) via the SDPM pathway [26]. The studies show that *PfPMT* is important for membrane biogenesis, development, survival, and propagation of the parasite. Compounds that target *PfPMT* could thus be combined with those that specifically target choline transport, choline phosphorylation, or other steps of the CDP-choline pathway in order to completely block PtdCho biosynthesis and kill the parasite.

In *P. falciparum*, the biosynthesis of ubiquinone or coenzyme Q involves two major steps: synthesis of the benzoquinone by the shikimate pathway and synthesis of the isoprene side chain by the MEP pathway. The presence of dolichol and isoprenylated proteins has been detected in *P. falciparum*, but no studies are available about the biosynthesis of the isoprenic side chain attached to the benzoquinone ring of coenzyme Q. De Macedo et al. (2002) showed that *P. falciparum* synthesizes different homologs (coenzyme Q(8) and coenzyme Q(9)), depending on the given intermediate [27]. The authors also demonstrated that nerolidol treatment of *P. falciparum* parasites resulted in a reduced ability to synthesise CoQ and inhibited *P. falciparum* growth *in vitro*. Treatment with nerolidol arrested development of the intraerythrocytic stages of the parasites, indicating that the drug may have an antimalarial potential.

#### 4. Antimalarial Compounds against Isoprenoid Biosynthetic Pathway

Biosynthesis of several isoprenoids in *P. falciparum* was studied and terpenes (molecules with a similar chemical structure to the intermediates of the isoprenoids pathway) as potential antimalarial drugs were evaluated [28–30]. Different terpenes and S-farnesylthiosalicylic acid were tested on cultures of the intraerythrocytic stages of *P. falciparum*, and the 50% inhibitory concentration for each one was found. Farnesol, nerolidol, limonene, and linalool terpenes have been used against *P. falciparum* [30]. All the terpenes tested inhibited dolichol biosynthesis in the trophozoite and schizont stages. Farnesol, nerolidol, and linalool showed stronger inhibitory activity in the biosynthesis of the isoprenic side chain of the benzoquinone ring of ubiquinones in the schizont stage. The inhibitory effect of terpenes and S-farnesylthiosalicylic acid on the biosynthesis of both dolichol, the isoprenic side chain of ubiquinones, and the isoprenylation of proteins in the intraerythrocytic stages of *P. falciparum* appears to be specific, because overall protein biosynthesis was not affected.

A variety of proteins undergo posttranslational modification such as prenylation near the carboxyl terminus with farnesyl (C15) or geranylgeranyl (C20) groups. Protein farnesyltransferase (PFT) transfers the farnesyl group from farnesyl diphosphate to the SH of the cysteine near the C-terminus of proteins such as Ras. PFT inhibitors (PFTIs)

have been extensively developed as anticancer agents because of their ability to block tumor growth in experimental animals. PFTIs have been explored as antimalarial and antitrypanosome agents because these compounds are much more toxic to these parasites than to mammalian cells, and there are a large number of lead compounds which have been explored as part of the antiparasite drug discovery program [31]. MEP pathway inhibition with fosmidomycin reduces protein prenylation, confirming that *de novo* isoprenoid biosynthesis produces the isoprenyl substrates for protein prenylation. One important group of prenylated proteins is small GTPases, such as Rab family members, which mediate cellular vesicular trafficking [32].

Substituted tetrahydroquinolines (THQs) have been previously identified as inhibitors of mammalian protein farnesyltransferase. Fletcher et al. (2008) designed and synthesized a series of inhibitors that are selective for *P. falciparum* farnesyltransferase (PfPFT). Several PfPFT inhibitors have been found to inhibit the malarial enzyme with IC<sub>50</sub> values down to 1 nM, and that blocks the growth of *P. falciparum* in infected whole cells (erythrocytes) with ED<sub>50</sub> values down to 55 nM. Potent, *Plasmodium*-selective farnesyltransferase inhibitors that arrest the growth of malaria parasites have been explored [33]. A new synthetic pathway was devised to reach tetrasubstituted 3-arylthiophene 2-carboxylic acids in a three-step solid-phase synthesis. This very efficient methodology provided more than 20 new compounds that were evaluated for their ability to inhibit protein farnesyltransferase from different species as well as *Trypanosoma brucei* and *P. falciparum* proliferation [34].

Strong inhibition of *P. falciparum* PFT (PfPFT) by peptidomimetics illustrated the potential of targeting these enzymes in developing drug therapy for malaria. Ohkanda et al. (2001) have recently demonstrated the potency of a variety of other peptidomimetics as inhibitors of *P. falciparum* growth and PfPFT activity [35]. Moura et al. (2001) have also shown that the monoterpene, limonene, inhibits parasite development and prenylation of *P. falciparum* proteins [36]. The enzymes of the nonmevalonate pathway for isoprenoid biosynthesis are attractive targets for the development of novel drugs against malaria and tuberculosis.

Fosmidomycin and FR900098 (an *N*-acetyl derivative of fosmidomycin) are inhibitor of DOXP reductoisomerase which showed antimalarial activity *in vitro* and *in vivo* [15, 29] (Figure 3).

Reverse hydroxamate-based inhibitor for IspC enzyme was evaluated by Behrendt et al. (2011) [37]. Fosmidomycin has been proven to be efficient in the treatment of *P. falciparum* malaria by inhibiting 1-deoxy-D-xylulose-5-phosphate reductoisomerase (DXR), an enzyme of the non-mevalonate pathway, which is absent in humans (Figure 4).

1-Deoxy-D-xylulose-5-phosphate reductoisomerase (Dxr) represents an essential enzyme of the mevalonate-independent pathway of the isoprenoid biosynthesis. Using fosmidomycin as a specific inhibitor of Dxr, this enzyme was previously validated as target for the treatment of malaria and bacterial infections. The replacement of the formyl residue of fosmidomycin by spacious acyl residues yielded inhibitors active in the micromolar range. As predicted by

flexible docking, evidence was obtained for the formation of a hydrogen bond between an appropriately placed carbonyl group in the acyl residue and the main-chain NH of Met214 located in the flexible catalytic loop of the enzyme [38, 39]. Specific inhibition of enzymes of the nonmevalonate pathway is a promising strategy for the development of novel antiplasmodial drugs.  $\alpha$ -Aryl-substituted  $\beta$ -oxa isosteres of fosmidomycin with a reverse orientation of the hydroxamic acid group were synthesized and evaluated for their inhibitory activity against recombinant 1-deoxy-d-xylulose 5-phosphate reductoisomerase (IspC) of *Plasmodium falciparum* and for their *in vitro* antiplasmodial activity against chloroquine-sensitive and resistant strains of *P. falciparum*. The most active derivative inhibits IspC protein of *P. falciparum* (PfIspC) with an IC<sub>50</sub> value of 12 nM and shows potent *in vitro* antiplasmodial activity [40].

The structure-activity relationships for 43 inhibitors of 1-deoxyxylulose-5-phosphate (DOXP) reductoisomerase, derived from protein-based docking, ligand-based 3D QSAR, and a combination of both approaches as realized by AFMoC (adaptation of fields for molecular comparison) have been presented by Silber et al. (2005) [41]. A series of novel 3'-amido-3'-deoxy-N(6)-(1-naphthylmethyl) adenosines was synthesized applying a polymer-assisted solution phase (PASP) protocol and was tested for antimalarial activity versus the Dd2 strain of *Plasmodium falciparum*. Further, this series and 62 adenosine derivatives were analyzed regarding 1-deoxy-D-xylulose-5-phosphate reductoisomerase inhibition. Biological evaluations revealed that the investigated 3',N(6)-disubstituted adenosine derivatives displayed moderate but significant activity against the *P. falciparum* parasite in the low-micromolar range [42].

## 5. Genetic Polymorphism in *P. falciparum*

*P. falciparum* malaria is an example of evolutionary selection. Both host and parasite show the phenomenon of natural selection. Several polymorphisms in human host and parasite have been found. Table 1 shows details of genes involved in isoprenoid metabolism and their polymorphisms in *P. falciparum*. In the drug discovery process the polymorphisms in parasite genes encoding the target protein should be considered. In *P. falciparum* the genetic polymorphisms at 10 loci are considered potential targets for specific antimalarial vaccines [43]. The polymorphism is unevenly distributed among the loci; loci encoding proteins expressed on the surface of the sporozoite or the merozoite (AMA-1, CSP, LSA-1, MSP-1, MSP-2, and MSP-3) are more polymorphic than those expressed during the sexual stages or inside the parasite (EBA-175, Pfs25, PF48/45, and RAP-1). Comparison of synonymous and nonsynonymous substitutions indicates that natural selection may account for the polymorphism observed at seven of the 10 loci studied. This inference depends on the assumption that synonymous substitutions are neutral. The authors obtained evidence for an overall trend towards increasing A+T richness but no evidence of mutation. Although the neutrality of synonymous substitutions is not definitely established, this trend

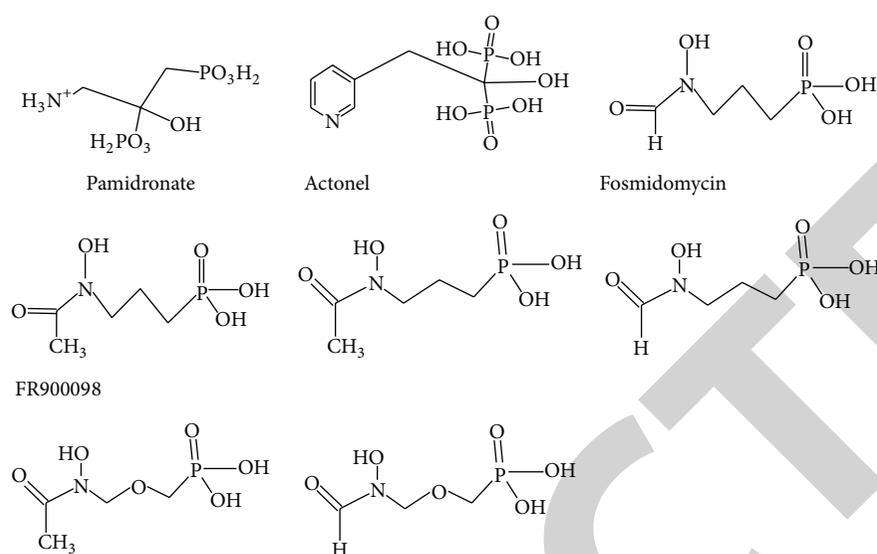


FIGURE 3: Structures of diphosphate and bisphosphonates (inhibitors of pathway) [8].

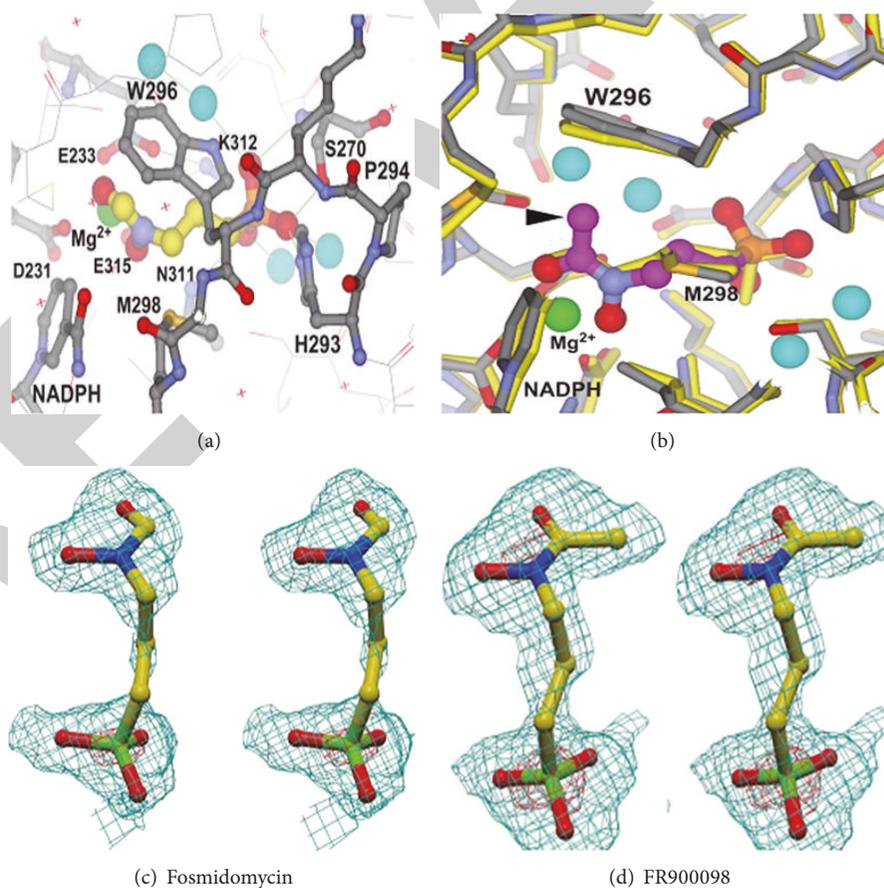


FIGURE 4: (a) Interaction of fosmidomycin with *PfDXR*. FR900098 complex. (b) The carbon atoms of the FR900098 molecule are shown in magenta, (c) fosmidomycin, and (d) FR900098.

TABLE 1: Details of genes involved in isoprenoid metabolism and their polymorphisms in *P. falciparum* 3D7.

Gene ID	Previous ID	Chromosome	Product description	Protein length	Nonsynonymous SNPs in all strains	Synonymous SNPs in all strains
PF3D7_0104400	PFA0225w	1	4-Hydroxy-3-methylbut-2-enyl diphosphate reductase (LytB)	535	3	3
PF3D7_0106900	PFA0340w	1	2-C-Methyl-D-erythritol 4-phosphate cytidyltransferase, putative (IspD)	734	6	2
PF3D7_0209300	PFB0420w	2	2-C-Methyl-D-erythritol 2,4-cyclodiphosphate synthase (IspF)	240	0	0
PF3D7_0318800	PFC0831w	3	Triosephosphate isomerase, putative	357	0	0
PF3D7_0503100	PFE0150c	5	4-Diphosphocytidyl-2c-methyl-D-erythritol kinase (CMK), putative	537	4	0
PF3D7_0508300	PFE0410w	5	Triose phosphate transporter (oTPT)	342	0	0
PF3D7_0530200	PFE1510c	5	Triose phosphate transporter (iTPT)	524	1	0
PF3D7_0623200	PFF1115w	6	Ferredoxin NADP reductase (FNR)	371	1	1
PF3D7_1022800	PF10_0221	10	4-Hydroxy-3-methylbut-2-en-1-yl diphosphate synthase (GcpE)	824	1	0
PF3D7_1037100	PF10_0363	10	Pyruvate kinase 2 (PykII)	745	2	1
PF3D7_1318100	MAL13P1.95	13	Ferredoxin, putative	194	2	0
PF3D7_1337200	MAL13P1.186	13	1-Deoxy-D-xylulose 5-phosphate synthase	1205	13	2
PF3D7_1439900	PF14_0378	14	Triosephosphate isomerase (TIM)	248	0	0
PF3D7_1467300	PF14_0641	14	1-Deoxy-D-xylulose 5-phosphate reductoisomerase (DOXR)	488	2	2

towards an A+T rich genome cannot explain the accumulation of substitutions at least in the case of four genes (AMA-1, CSP, LSA-1, and PF48/45) because the G → C transversions are more frequent than expected. Predicted polymorphisms in genes encoding isoprenoid biosynthesis may play an important role in drug response (Table 1).

Nonsynonymous single nucleotide polymorphisms in 4-hydroxy-3-methylbut-2-enyl diphosphate reductase (LytB), 2-C-methyl-D-erythritol 4-phosphate cytidyltransferase, putative (IspD), 1-deoxy-D-xylulose 5-phosphate synthase, 1-deoxy-D-xylulose 5-phosphate reductoisomerase (DOXR), and 4-diphosphocytidyl-2c-methyl-D-erythritol kinase (CMK) proteins may change the amino acids. Such change may affect the proteins and interaction with antimalarial drugs.

**5.1. DNA Sequence Variation(s) and Evolution.** Mutations or genetic variations that have ability to alter the activity or availability of transcription factors, as well as mutations that alter the *cis*-regulatory sequences (transcription factor binding sites) to which they bind, can change expression of gene and both types of changes contribute to evolution. Several studies have suggested that mutations affecting *cis*-regulatory activity (transcription factor binding site) are

the predominant source of expression divergence between species [44, 45]. Changes in gene expression often alter phenotypes; mutations that affect gene expression can affect fitness and contribute to adaptive evolution. DNA sequence variations reported in genes involved in dolichol pathway of *P. falciparum* were shown.

**5.2. DNA Sequence Variation and Drug Response.** In the genome different types of variations are reported such as copy number variations (CNV), microsatellite repeats (SSR), and single nucleotide polymorphisms (SNP) which are known to play role in regulation of gene expression. Presence of such variations in the transcription factor binding site (TFBS) may influence the binding of transcription factor to their respective binding sites and is responsible for the alteration of gene product in the cell. The presence of several polymorphisms in the upstream region gives rise to different haplotypes. These haplotypes in the transcription factor binding sites alter the interaction of transcription factor (TF) to TFBS and may cause transcriptional modification of gene, altering the level of protein. Genetic variation associated with increased susceptibility to complex diseases can elucidate genes and underlying biochemical mechanisms linked to disease onset

and progression. It has been suggested that when gene shows association with disease, the most common condition is that genetic variation or causal mutations alter an encoded protein sequence. But a significant number of undiscovered causal mutations may alter the regulation of gene transcription. However, it remains a challenge to separate causal genetic variations from linked neutral variations. One of the most important applications of genetic polymorphisms is the drug response. Earlier, we have detected that peoples from different ethnic backgrounds have shown different susceptibility/resistance to falciparum malaria [46, 47]. It has been clear from several studies that polymorphisms are important factor for determining the drug response. The most studied example of polymorphisms and drug response in the *P. falciparum* is the multidrug resistance gene (*pfmdr-1*) that contributes to variability and is known to play role in drug response. The peoples varying in the genotype at a particular locus may have different responses to a particular drug which is illustrated in Figure 5.

## 6. Discussion

It is very difficult to treat malaria because of the development of resistance of the parasite to antimalarial(s). Currently the main drug available is artemisinin (ART) and its derivatives and serious efforts are underway to develop ART-based combination therapies. The new pharmacophores attacking different targets in the parasite can bring in new strategies to combat malaria. Apart from efficacy, toxic side effects, pharmacokinetic compatibility, and potential to develop resistance would all be the major parameters in the eventual development of a successful drug. Therefore, all the targets and molecules discussed in this review are important.

Apicoplast itself contains a small circular genome, most of the proteome of this organelle is encoded in the nuclear genome, and the proteins are subsequently transported to the apicoplast. It is assumed to contain a number of unique metabolic pathways not found in the vertebrate host, making it an ideal “playground” for those interested in drug targets. The apicoplast contains metabolic pathways critical for liver-stage and blood-stage development. During the blood stages, parasites lacking an apicoplast can grow in the presence of isopentenyl pyrophosphate (IPP), demonstrating that isoprenoids are the only metabolites produced in the apicoplast which are needed outside of the organelle. Two of the enzymes involved in isoprenoid biosynthesis are predicted to rely on iron-sulfur (FeS) cluster cofactors [48].

Since the nonmevalonate pathway of isoprenoid biosynthesis is essential in eubacteria and *P. falciparum* and this pathway is not present in humans, there is a great interest in targeting the enzymes of nonmevalonate metabolism for antiparasitic drug development. Fosmidomycin is currently in clinical trials of combination therapies for the treatment of malaria [49]. Cell-penetrating peptides, such as oligoarginines, improved the intracellular delivery of the drug fosmidomycin [50]. Analogues of fosmidomycin that is substituted in both the C $\alpha$  and the hydroxamate positions have been found more potent than fosmidomycin in terms

of killing *P. falciparum* in an *in vitro* assay [51]. A screen of host cell proteins that might facilitate lipid scavenging by the parasite during the liver stage has pointed toward the surface-expressed cholesterol ester receptor, scavenger receptor class B type 1 (SR-BI) [42]. A decrease or complete loss of SR-BI surface availability via treatment with siRNA (short interfering RNA), antibodies, drugs, or gene deletion results in a reduction in parasite invasion and growth in hepatocytes [52, 53].

*P. falciparum* mitochondrion presents structural and physiological characteristics different from mitochondria in other eukaryotes [54]. One of the reasons is the adaptation of the parasite to different environments, in particular, the great differences in oxygen tension between the host and the mosquito. Mitochondrial role in the intraerythrocytic environment particularly focuses on mitochondrial metabolic pathways that relate to oxidative phosphorylation, including the tricarboxylic acid cycle, *de novo* pyrimidine biosynthesis via dihydroorotate dehydrogenase, and the particularities of the electron transport chain. Such unique particularities of parasite mitochondria could be promising targets for development of a new therapy. The elucidation of the role of this organelle in aerophilic respiratory metabolism and the association of antimalarial drugs with hyperbaric oxygen therapy might provide new treatments for infection by *P. falciparum*. Howe et al. (2013) demonstrate that protein prenylation depends on *de novo* isoprenoid biosynthesis in *P. falciparum* [32]. When isoprenoid biosynthesis is inhibited, the digestive food vacuole of the parasite is structurally and functionally disrupted. These results suggest that a key function of isoprenoids in malaria is protein prenylation and support a role for prenylated proteins, such as Rab GTPases, in FV maintenance.

Dolichol and its derivatives are the lipids discovered most recently in eukaryotic cells. They serve as inducers of membrane fusion. The DOXP pathway provides precursors for protein farnesylation. Plasmodial farnesyl transferase activity has unique biochemical features and inhibitors of this process have *in vitro* antimalarial activity [35, 55]. The resistance of malaria parasites to available drugs continues to grow, increasingly limiting our ability to control this serious disease. Recent increases in the pace of progress in this area will be helpful in the development of novel antimalarial therapies.

As outlined in this review, a number of pathways and inhibitory substances have already been identified which hold great promise for the future. With the completion of the *Plasmodium* genome project new biosynthetic routes in the apicoplast are discovered and efforts are on to explore them as candidate drug targets. The development of a number of genetic tools to validate these possible targets in transgenic parasites and also for drug screening purposes will have an enormous impetus on the development of drugs against this pathogen. The analysis of the utility of isoprenoid biosynthesis pathway in *P. falciparum* reveals that the proteins of this pathway might be important drug targets. The study of host genetic factors and polymorphisms in parasite isoprenoid biosynthetic genes will be helpful in the analysis of disease susceptibility and drug response.

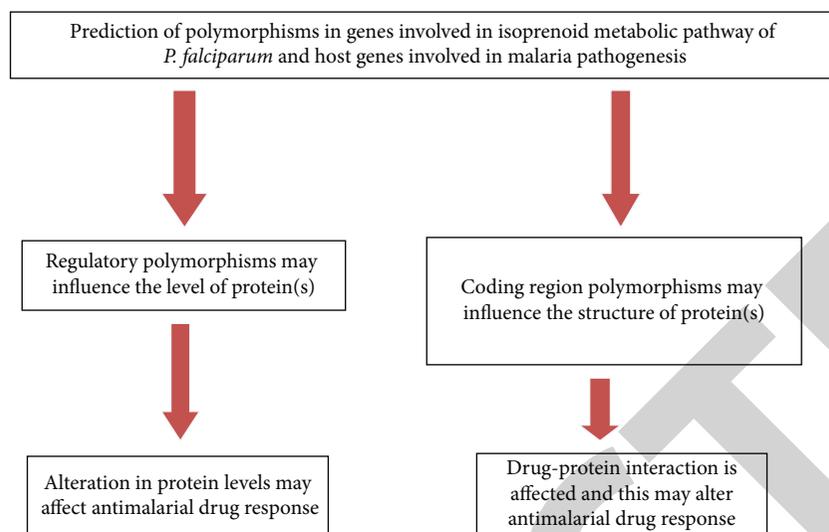


FIGURE 5: Diagrammatic representation of role of polymorphisms in drug response.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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## References

- [1] C. D. Poulter, "Bioorganic chemistry: a natural reunion of the physical and life sciences," *Journal of Organic Chemistry*, vol. 74, no. 7, pp. 2631–2645, 2009.
- [2] J. Lombard and D. Moreira, "Origins and early evolution of the mevalonate pathway of isoprenoid biosynthesis in the three domains of life," *Molecular Biology and Evolution*, vol. 28, no. 1, pp. 87–99, 2011.
- [3] B. Zhang, K. M. Watts, D. Hodge et al., "A second target of the antimalarial and antibacterial agent fosmidomycin revealed by cellular metabolic profiling," *Biochemistry*, vol. 50, no. 17, pp. 3570–3577, 2011.
- [4] A. C. Brown, M. Eberl, D. C. Crick, H. Jomaa, and T. Parish, "The nonmevalonate pathway of isoprenoid biosynthesis in *Mycobacterium tuberculosis* is essential and transcriptionally regulated by Dxs," *Journal of Bacteriology*, vol. 192, no. 9, pp. 2424–2433, 2010.
- [5] F. J. Sangari, J. Pérez-Gil, L. Carretero-Paulet, J. M. García-Lobo, and M. Rodríguez-Concepción, "A new family of enzymes catalyzing the first committed step of the methylerythritol 4-phosphate (MEP) pathway for isoprenoid biosynthesis in bacteria," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 107, no. 32, pp. 14081–14086, 2010.
- [6] F. M. Jordão, E. A. Kimura, and A. M. Katzin, "Isoprenoid biosynthesis in the erythrocytic stages of *Plasmodium falciparum*," *Memorias do Instituto Oswaldo Cruz*, vol. 106, no. 1, pp. 134–141, 2011.
- [7] W. Eisenreich, A. Bacher, D. Arigoni, and F. Rohdich, "Biosynthesis of isoprenoids via the non-mevalonate pathway," *Cellular and Molecular Life Sciences*, vol. 61, no. 12, pp. 1401–1426, 2004.
- [8] E. Oldfield, "Targeting isoprenoid biosynthesis for drug discovery: bench to bedside," *Accounts of Chemical Research*, vol. 43, no. 9, pp. 1216–1226, 2010.
- [9] J. Wiesner, A. Reichenberg, S. Heinrich, M. Schlitzer, and H. Jomaa, "The plastid-like organelle of apicomplexan parasites as drug target," *Current Pharmaceutical Design*, vol. 14, no. 9, pp. 855–871, 2008.
- [10] J. E. Gisselberg, T. A. Dellibovi-Ragheb, K. A. Matthews, G. Bosch, and S. T. Prigge, "The suf iron-sulfur cluster synthesis pathway is required for apicoplast maintenance in malaria parasites," *PLOS Pathogens*, vol. 9, no. 9, article e1003655, 2013.
- [11] J. Wiesner and H. Jomaa, "Isoprenoid biosynthesis of the apicoplast as drug target," *Current Drug Targets*, vol. 8, no. 1, pp. 3–13, 2007.
- [12] G. I. McFadden, "The apicoplast," *Protoplasma*, vol. 248, no. 4, pp. 641–650, 2011.
- [13] M. B. Cassera, F. C. Gozzo, F. L. D'Alexandri et al., "The methylerythritol phosphate pathway is functionally active in all intraerythrocytic stages of *Plasmodium falciparum*," *Journal of Biological Chemistry*, vol. 279, no. 50, pp. 51749–51759, 2004.
- [14] V. K. Singh and I. Ghosh, "Methylerythritol phosphate pathway to isoprenoids: kinetic modeling and in silico enzyme inhibitions in *Plasmodium falciparum*," *FEBS Letters*, vol. 587, no. 17, pp. 2806–2817, 2013.
- [15] H. Jomaa, J. Wiesner, S. Sanderbrand et al., "Inhibitors of the nonmevalonate pathway of isoprenoid biosynthesis as antimalarial drugs," *Science*, vol. 285, no. 5433, pp. 1573–1576, 1999.

- [16] T. Umeda, N. Tanaka, Y. Kusakabe, M. Nakanishi, Y. Kitade, and K. T. Nakamura, "Crystallization and preliminary X-ray crystallographic study of 1-deoxy-d-xylulose 5-Phosphate reductoisomerase from *Plasmodium falciparum*," *Acta Crystallographica Section F: Structural Biology and Crystallization Communications*, vol. 66, no. 3, pp. 330–332, 2010.
- [17] M. B. Cassera, E. F. Merino, V. J. Peres, E. A. Kimura, G. Wunderlich, and A. M. Katzin, "Effect of fosmidomycin on metabolic and transcript profiles of the methylerythritol phosphate pathway in *Plasmodium falciparum*," *Memorias do Instituto Oswaldo Cruz*, vol. 102, no. 3, pp. 377–383, 2007.
- [18] E. A. Kimura, A. S. Couto, V. J. Peres, O. L. Casal, and A. M. Katzin, "N-linked glycoproteins are related to schizogony of the intraerythrocytic stage in *Plasmodium falciparum*," *Journal of Biological Chemistry*, vol. 271, no. 24, pp. 14452–14461, 1996.
- [19] H. Shams-Eldin, C. S. de Macedo, S. Niehus et al., "*Plasmodium falciparum* dolichol phosphate mannose synthase represents a novel clade," *Biochemical and Biophysical Research Communications*, vol. 370, no. 3, pp. 388–393, 2008.
- [20] R. D. Walter, "*Plasmodium falciparum*: inhibition of dolichol kinase by mefloquine," *Experimental Parasitology*, vol. 62, no. 3, pp. 356–361, 1986.
- [21] A. S. Couto, E. A. Kimura, V. J. Peres, M. L. Uhrig, and A. M. Katzin, "Active isoprenoid pathway in the intra-erythrocytic stages of *Plasmodium falciparum*: presence of dolichols of 11 and 12 isoprene units," *Biochemical Journal*, vol. 341, no. 3, pp. 629–637, 1999.
- [22] W. H. Witola, K. El Bissati, G. Pessi, C. Xie, P. D. Roepe, and C. B. Mamoun, "Disruption of the *Plasmodium falciparum* PfPMT gene results in a complete loss of phosphatidylcholine biosynthesis via the serine-decarboxylase-phosphoethanolamine-methyltransferase pathway and severe growth and survival defects," *Journal of Biological Chemistry*, vol. 283, no. 41, pp. 27636–27643, 2008.
- [23] S. Krishna, "Malaria," *British Medical Journal*, vol. 315, no. 7110, pp. 730–732, 1997.
- [24] H. J. Vial, C. Ben Mamoun, and I. W. Sherman, "Plasmodium lipids: metabolism and function," in *Molecular Approaches to Malaria*, pp. 327–352, ASM Press, Washington, DC, USA, 2005.
- [25] G. G. Holz Jr., "Lipids and the malarial parasite," *Bulletin of the World Health Organization*, vol. 55, no. 2-3, pp. 237–248, 1977.
- [26] G. Pessi and C. Ben Mamoun, "Pathways for phosphatidylcholine biosynthesis: targets and strategies for antimalarial drugs," *Future Medicine Lipids*, vol. 1, no. 2, pp. 173–180, 2006.
- [27] C. S. De Macedo, M. L. Uhrig, E. A. Kimura, and A. M. Katzin, "Characterization of the isoprenoid chain of coenzyme Q in *Plasmodium falciparum*," *FEMS Microbiology Letters*, vol. 207, no. 1, pp. 13–20, 2002.
- [28] P. J. Proteau, "1-Deoxy-D-xylulose 5-phosphate reductoisomerase: an overview," *Bioorganic Chemistry*, vol. 32, no. 6, pp. 483–493, 2004.
- [29] S. Steinbacher, J. Kaiser, W. Eisenreich, R. Huber, A. Bacher, and F. Rohdich, "Structural basis of fosmidomycin action revealed by the complex with 2-C-methyl-D-erythritol 4-phosphate synthase (IspC): implications for the catalytic mechanism and antimalaria drug development," *Journal of Biological Chemistry*, vol. 278, no. 20, pp. 18401–18407, 2003.
- [30] H. R. Goulart, E. A. Kimura, V. J. Peres, A. S. Couto, F. A. A. Duarte, and A. M. Katzin, "Terpenes arrest parasite development and inhibit biosynthesis of isoprenoids in *Plasmodium falciparum*," *Antimicrobial Agents and Chemotherapy*, vol. 48, no. 7, pp. 2502–2509, 2004.
- [31] S. Olepu, P. K. Suryadevara, K. Rivas et al., "2-Oxo-tetrahydro-1,8-naphthyridines as selective inhibitors of malarial protein farnesyltransferase and as anti-malarials," *Bioorganic and Medicinal Chemistry Letters*, vol. 18, no. 2, pp. 494–497, 2008.
- [32] R. Howe, M. Kelly, J. Jimah, D. Hodge, and A. R. Odom, "Isoprenoid biosynthesis inhibition disrupts Rab5 localization and food vacuolar integrity in *Plasmodium falciparum*," *Eukaryotic Cell*, vol. 12, no. 2, pp. 215–223, 2013.
- [33] S. Fletcher, C. G. Cummings, K. Rivas et al., "Potent, plasmodium-selective farnesyltransferase inhibitors that arrest the growth of malaria parasites: structure-activity relationships of ethylenediamine-analogue scaffolds and homology model validation," *Journal of Medicinal Chemistry*, vol. 51, no. 17, pp. 5176–5197, 2008.
- [34] S. Lethu, D. Bosc, E. Mouray, P. Grellier, and J. Dubois, "New protein farnesyltransferase inhibitors in the 3-arylthiophene 2-carboxylic acid series: diversification of the aryl moiety by solid-phase synthesis," *Journal of Enzyme Inhibition and Medicinal Chemistry*, vol. 28, no. 1, pp. 163–171, 2013.
- [35] J. Ohkanda, J. W. Lockman, K. Yokoyama et al., "Peptidomimetic inhibitors of protein farnesyltransferase show potent antimalarial activity," *Bioorganic and Medicinal Chemistry Letters*, vol. 11, no. 6, pp. 761–764, 2001.
- [36] I. C. Moura, G. Wunderlich, M. L. Uhrig et al., "Limonene arrests parasite development and inhibits isoprenylation of proteins in *Plasmodium falciparum*," *Antimicrobial Agents and Chemotherapy*, vol. 45, no. 9, pp. 2553–2558, 2001.
- [37] C. T. Behrendt, A. Kunfermann, V. Illarionova et al., "Reverse fosmidomycin derivatives against the antimalarial drug target IspC (Dxr)," *Journal of Medicinal Chemistry*, vol. 54, no. 19, pp. 6796–6802, 2011.
- [38] T. Umeda, N. Tanaka, Y. Kusakabe, M. Nakanishi, Y. Kitade, and K. T. Nakamura, "Molecular basis of fosmidomycin's action on the human malaria parasite *Plasmodium falciparum*," *Scientific Reports*, vol. 1, article no. 9, 2011.
- [39] R. Ortman, J. Wiesner, K. Silber, G. Klebe, H. Jomaa, and M. Schlitzer, "Novel deoxyxylulosephosphate-reductoisomerase inhibitors: fosmidomycin derivatives with spacious acyl residues," *Archiv der Pharmazie*, vol. 340, no. 9, pp. 483–490, 2007.
- [40] K. Brucher, B. Illarionov, J. Held et al., " $\alpha$ -substituted  $\beta$ -Oxa isosteres of fosmidomycin: synthesis and biological evaluation," *Journal of Medicinal Chemistry*, vol. 55, no. 14, pp. 6566–6575, 2012.
- [41] K. Silber, P. Heidler, T. Kurz, and G. Klebe, "AFMoC enhances predictivity of 3D QSAR: a case study with DOXP-reductoisomerase," *Journal of Medicinal Chemistry*, vol. 48, no. 10, pp. 3547–3563, 2005.
- [42] C. Herforth, J. Wiesner, P. Heidler et al., "Antimalarial activity of N6-substituted adenosine derivatives—part 3," *Bioorganic and Medicinal Chemistry*, vol. 12, no. 4, pp. 755–762, 2004.
- [43] A. A. Escalante, A. A. Lal, and F. J. Ayala, "Genetic polymorphism and natural selection in the malaria parasite *Plasmodium falciparum*," *Genetics*, vol. 149, no. 1, pp. 189–202, 1998.
- [44] R. M. Graze, L. M. McIntyre, B. J. Main, M. L. Wayne, and S. V. Nuzhdin, "Regulatory divergence in *Drosophila melanogaster* and *D. simulans*, a genomewide analysis of allele-specific expression," *Genetics*, vol. 183, no. 2, pp. 547–561, 2009.

- [45] I. Tiroshauth, S. Reikhav, A. A. Levy, and N. Barkai, "A yeast hybrid provides insight into the evolution of gene expression regulation," *Science*, vol. 324, no. 5927, pp. 659–662, 2009.
- [46] S. Sinha, T. Qidwai, K. Kanchan et al., "Distinct cytokine profiles define clinical immune response to falciparum malaria in regions of high or low disease transmission," *European Cytokine Network*, vol. 21, no. 4, pp. 232–240, 2010.
- [47] S. Sinha, G. N. Jha, P. Anand et al., "CRI levels and gene polymorphisms exhibit differential association with falciparum malaria in regions of varying disease endemicity," *Human Immunology*, vol. 70, no. 4, pp. 244–250, 2009.
- [48] J. E. Gisselberg, T. A. Dellibovi-Ragheb, K. A. Matthews, G. Bosch, and S. T. Prigge, "The suf iron-sulfur cluster synthesis pathway is required for apicoplast maintenance in malaria parasites," *PLOS Pathogens*, vol. 9, no. 9, article e1003655, 2013.
- [49] F. Mi-Ichi, K. Kita, and T. Mitamura, "Intraerythrocytic *Plasmodium falciparum* utilize a broad range of serum-derived fatty acids with limited modification for their growth," *Parasitology*, vol. 133, no. 4, pp. 399–410, 2006.
- [50] C. Sparr, N. Purkayastha, B. Kolesinska et al., "Improved efficacy of fosmidomycin against *Plasmodium* and *Mycobacterium* species by combination with the cell-penetrating peptide octaarginine," *Antimicrob Agents Chemother*, vol. 57, no. 10, pp. 4689–4698, 2013.
- [51] A. M. Jansson, A. Więckowska, C. Björkelid et al., "DXR inhibition by potent mono- and disubstituted fosmidomycin analogues," *Journal of Medicinal Chemistry*, vol. 56, no. 15, pp. 6190–6199, 2013.
- [52] C. D. Rodrigues, M. Hannus, M. Prudêncio et al., "Host scavenger receptor SR-BI plays a dual role in the establishment of Malaria parasite liver infection," *Cell Host and Microbe*, vol. 4, no. 3, pp. 271–282, 2008.
- [53] S. Yalaoui, T. Huby, J.-F. Franetich et al., "Scavenger receptor BI boosts hepatocyte permissiveness to *Plasmodium* infection," *Cell Host and Microbe*, vol. 4, no. 3, pp. 283–292, 2008.
- [54] M. Torrentino-Madamet, J. Desplans, C. Travaillé, Y. Jammes, and D. Parzy, "Microaerophilic respiratory metabolism of *Plasmodium falciparum* mitochondrion as a drug target," *Current Molecular Medicine*, vol. 10, no. 1, pp. 29–46, 2010.
- [55] D. Chakrabarti, T. D. Silva, J. Barger et al., "Protein farnesyltransferase and protein prenylation in *Plasmodium falciparum*," *Journal of Biological Chemistry*, vol. 277, no. 44, pp. 42066–42073, 2002.