

**ORIGINAL ARTICLE****Identification of Prognostic and Susceptibility Markers in Chronic Myeloid Leukemia Using Next Generation Sequencing****Yogender Shokeen<sup>1\*</sup>, Neeta Raj Sharma<sup>3</sup>, Abhishek Vats<sup>2</sup>, Vibha Taneja<sup>2</sup>, Sachin Minhas<sup>1</sup>, Mayank Jauhri<sup>1</sup>, Satish Sankaran<sup>4</sup>, Shyam Aggarwal<sup>1</sup>****OPEN ACCESS**

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**Affiliation and Correspondence:**

<sup>1</sup>Department of Medical Oncology, Sir Ganga Ram Hospital, Rajinder Nagar, Delhi, India

<sup>2</sup>Department of Research, Sir Ganga Ram Hospital, Rajinder Nagar, Delhi, India

<sup>3</sup>Department of Pediatrics and Child Health and Pediatric Emergency Consultant, School of Medicine, Addis Ababa University, Ethiopia

<sup>4</sup>School of Bio-Engineering and Biosciences, Lovely Professional University, Jalandhar, Punjab, India

<sup>5</sup>Strand Center for Genomics and Personalized Medicine. UAS Alumini Building, Veterinary College Campus, Bellary Road, Hebbal, Bangalore, India

\*Email: [yogendershokeen@yahoo.co.in](mailto:yogendershokeen@yahoo.co.in)

**ABSTRACT**

**BACKGROUND:** Incidence of Chronic Myeloid Leukemia (CML) is continuously increasing and expected to reach 100,000 patients every year by 2030. Though the discovery of Imatinib Mesylate (IM) has brought a paradigm shift in CML treatment, 20% patients show resistance to this tyrosine kinase inhibitor (TKI). Therefore, it is important to identify markers, which can predict the occurrence and prognosis of CML. Clinical Exome Sequencing, panel of more than 4800 genes, was performed in CML patients to identify prognostic and susceptibility markers in CML.

**METHODS:** Enrolled CML patients (n=18) were segregated as IM responders (n=10) and IM failures (n=8) as per European Leukemia Net (ELN), 2013 guidelines. Healthy controls (n=5) were also enrolled. DNA from blood of subjects was subjected to Next Generation Sequencing. Rare mutations present in one patient group and absent in another group were considered as prognostic markers, whereas mutations present in more than 50% patients were considered as susceptibility markers.

**RESULT:** Mutations in genes associated with cancer related functions were found in different patient groups. Four variants: rs116201358, rs4014596, rs52897880 and rs2274329 in C8A, UNC93B1, APOH and CA6 genes, respectively, were present in IM responders; whereas rs4945 in MFG8 was present in IM failures. Mutations in HLA-DRB1 (rs17878951), HLA-DRB5 (rs137863146), RPHN2 (rs193179333), CYP2F1 (rs116958555), KCNJ12 (rs76684759) and FUT3 (rs151218854) were present as susceptibility markers.

**CONCLUSION:** The potential genetic markers discovered in this study can help in predicting response to IM as frontline therapy. Susceptibility markers may also be used as panel for individuals prone to have CML.

**KEYWORDS:** Chronic Myeloid Leukemia, Genetic Markers, Next Generation Sequencing (NGS)

## INTRODUCTION

Incidence of Chronic Myeloid Leukemia in the United States is 1.6 per 100,000 of population, accounting approximately for 5,430 cases annually. The estimated prevalence in the US is around 25,000–30,000, which is expected to reach around 105,000 by the year 2030 (1). Its incidence in India is between 0.8–2.2 per 100,000 per annum (2). According to the current estimate, the world is expected to have 100,000 newly diagnosed CML patients per year, leading this chronic disorder into a serious health problem (3). Hence, the markers, with potential to detect individuals prone to have CML, are very important to control rising incidence.

According to the World Health Organization guidelines, CML is diagnosed with the presence of BCR-ABL gene, which is a reciprocal translocation between chromosome 9 and chromosome 22. Development of BCR-ABL inhibitor, Imatinib Mesylate (IM), spectacularly changed the prognosis with obstruction of its tyrosine kinase activity and impeding its further downstream signaling. The drug has high efficacy rates: the major molecular response (MMR) of IM as first line therapy at 12 months is 22%, which increases to 44% at 24 months (4). After 2 years of IM therapy, 40% of the patients achieve complete molecular response (CMR), which further increases to 81% at 10 years of treatment (5). Despite this commendable drug discovery, approximately 20% of the patients show resistance following treatment with this TKI therapy (6). European Leukemia Net (ELN) 2013 recommendations suggest that CML patients on first line TKI therapy can be segregated as responders or failures, where responders should continue with the regimen and failure are advised to change the treatment to either more potent TKI or dose escalation (7). Though prognostic scores (SOKAL and EUTOS) are available for estimation of outcomes, they have failed for several clinical conclusions (8,9). Therefore, genetic markers, with better reliability and accuracy, are required for estimation of prognosis and planning of personalized medicine in CML. In the present study, we performed clinical exome

sequencing in CML patients to search potential prognostic markers for IM response and susceptibility markers for CML.

## MATERIALS AND METHODS

**Subjects:** The study was conducted after obtaining approval from the Ethics Committee of Sir Ganga Ram Hospital, a super specialty tertiary care centre in Delhi (India). Informed consent was taken from each subject before enrollment in the study. Adult patients (>18 years) diagnosed with CML were enrolled. Diagnosis of CML was confirmed by reverse transcription polymerase chain reaction (RT-PCR) for BCR-ABL fusion gene and fluorescent in situ hybridization (FISH) for translocation (9,22). Enrolled patients were classified as responders and resistant as per ELN, 2013 criteria. According to ELN 2013 criteria, CML patients with  $\leq 10\%$  BCR-ABL or 35% Ph chromosome are considered as responders after 3 months of TKI treatment, whereas patients without complete hematological response or 95% Ph chromosome are considered as resistant. After 6 months of treatment, the criteria changes to presence of  $< 1\%$  BCR-ABL or 0% Ph chromosome for response and for resistance  $> 10\%$  BCR-ABL or 35% Ph chromosome. Patients harboring  $< 0.1\%$  BCR-ABL or are referred as responders and patients with  $> 1\%$  BCR-ABL as resistant after 12 months of treatment. Beyond 12 months of TKI treatment, loss of CHR, CMR or MMR is considered as resistance, whereas presence of  $< 1\%$  BCR-ABL is considered as optimal response. MMR is defined as presence of  $\leq 0.1\%$  BCR-ABL for the present study. Patients not achieving MMR at 18 months of IM treatment were regarded as suboptimal responders, whereas increase in BCR-ABL% at any time line compared to previous observation was considered as loss of molecular response and disease relapse (7). Healthy subjects with no known history of malignancy and above 18 years of age were also enrolled as controls.

Peripheral blood sample from both patients and controls was obtained in EDTA vials after taking informed consent. DNA was extracted (Nucleospin, Macheley-Nager, Germany) and was subjected to sequencing.

### Clinical exome sequencing

**Next generation sequencing:** A targeted panel (TruSight One, Illumina, USA) with probes covering all coding exons and essential splice

sites of >4800 clinically relevant genes was used for sequencing the DNA samples using Illumina's TruSight technology (Illumina, USA). The target size for this is panel 12 Mb and designed based on the information in the Human Gene Mutation Database (HGMD), the Online Mendelian Inheritance in Man (OMIM) catalogue, GeneTests.org, Illumina TruSight sequencing panels, etc.

DNA (50 ng) is taken for library preparation. TruSight One library preparation uses transposon based shearing of the genomic DNA. A limited cycle PCR step allows the incorporation of adaptors, platform-specific tags and barcodes to prepare the libraries. The tagged and amplified sample libraries were analyzed for quality using BioAnalyzer (Agilent, USA) and quantified using Qubit. And, 500 ng of each library was pooled and hybridized to biotinylated probes. The hybridized target DNA fragments were pulled down using streptavidin beads and two successive enrichment steps were performed to optimize the regions of interest. Target libraries were amplified using loaded for sequencing on the MiSeq or HiSeq (Illumina, USA) to obtain ~3 GB per sample.

**Sequence analysis:** The trimmed FASTQ files were generated using MiSeq Reporter from Illumina for MiSeq data and Casava software for HiSeq data. The reads were aligned against the whole genome build hg19 using STRAND® NGS V2.1.6 (Strand LifeSciences Pvt. Ltd., Bangalore). Five base pairs from the 3' end were trimmed, as 3' end were bases with quality below 10. Reads which had lengths less than 25 bp after trimming were not considered for alignment. A maximum of 5 matches of alignment score at least 90% were computed. Reads that failed QC (quality control), reads with average quality less than 20, reads with ambiguous characters were all filtered out. The STRAND® NGS variant caller was used to detect variants at locations in the target regions covered by a minimum of 10 reads with at least 2 variant reads. Variants with a decibel score of at least 50 were reported.

**Interpretation:** Interpretation of the variant data was done using the StrandOmics software, V1.9. The variant annotation engine includes different algorithms to identify variant impact on gene using public content (HGMD, ClinVar, OMIM, HPO, links to dbSNP, 1000 Genomes, Exome Variant Server) and proprietary content (curated variant records).

**Statistical analysis:** Statistical analyses were performed using SPSS for Windows 16 (SPSS, Chicago IL, USA). Non-parametric data is presented as median with standard deviation (SD). Statistical significance of differences of quantitative data was determined using Mann-Whitney U test. P-value of less than 0.05 was considered to be significant.

**Ethics statement:** The study and informed consent forms were reviewed and approved by the Ethics Committee of Sir Ganga Ram Hospital, Delhi, India (EC No.: EC/11/12/439). All procedures performed in the this study were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration

## RESULTS

**Subjects:** Eighteen patients and five healthy controls were enrolled in the study. Mean (SD) age of patients was 42.11 (12.76) years, whereas that of controls was 38.40 (12.76) years ( $p = 0.570$ ). All the patients were in chronic phase at the time of diagnosis. The IM responder group had 10 patients (55.55%), while 8 patients (44.45%) were in IM failure group. Patient no.4 and patient no.5 were included in responder group despite having >1% of BCR-ABL as the patients were responding well to IM therapy. Reduction in BCR-ABL percentage (compared to time of diagnosis) from 9.8% to 1.3% in patient no.4 and from 8.6% to 1% in patient no.5 was observed in span of 4 months and 5.5 months respectively. The mean (SD) age of the responder group was 35.1 (6.74) years, whereas failure was 50.88(13.36) years ( $p = 0.05$ ).

**Genetic markers:** Our main objective was to detect prognostic and susceptibility markers. The criterion for genetic variants to be considered as marker was presence in at least 50% patients of one group and absence in all patients of the opposite group, whereas mutations present in more than 50% ( $\geq 9$ ) of CML patients were considered as susceptibility markers. Only rare mutations, which were not present in healthy population of Asia, Europe and

Africa as per HapMap project, were considered. The shortlisted mutations were annotated manually with GeneCards and Kegg pathways for their functions (Table 3). Important genetic information about discovered mutations is given in Table 1.

**Table 1:** Genetic information of potential markers discovered in CML patients

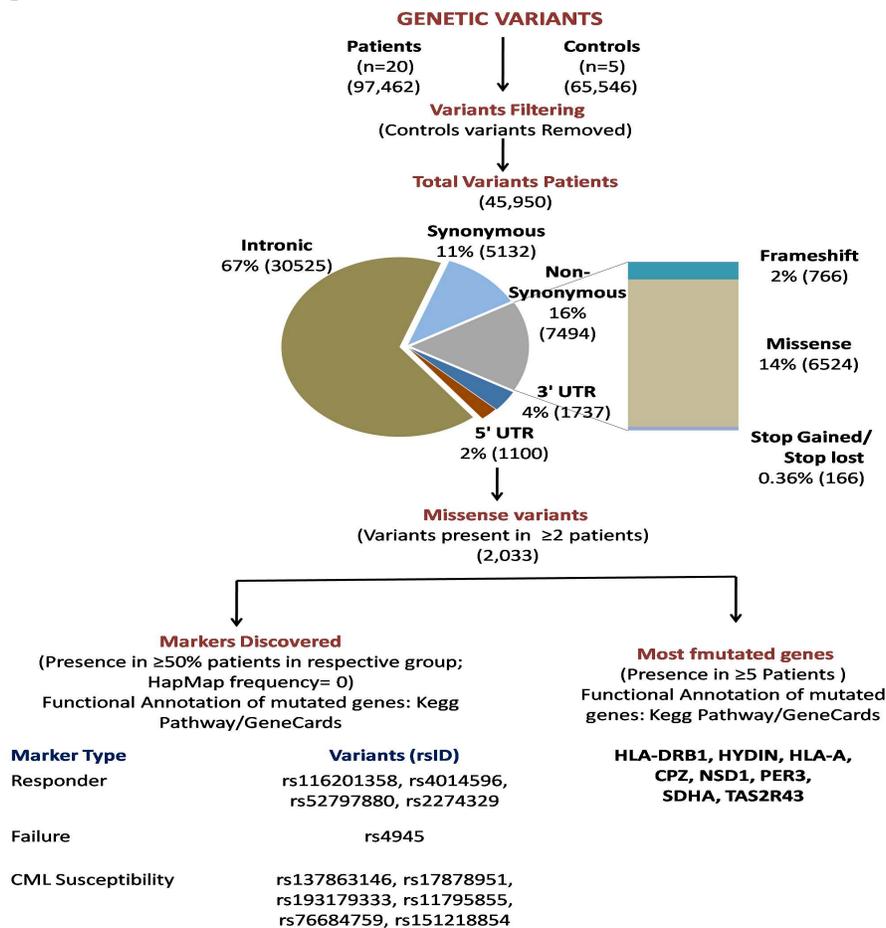
Mutation	Gene	Allele	Accession No.	Chromosomal Position <sup>ε</sup>	Codon	Amino Acid change	CpG islands <sup>▲</sup>
<b>Markers for IM Responder</b>							
c.107C>A (rs116201358)	C8A	A/C	NM_000562.2	1; 57333311	GCA-GAA	p.36Ala>Glu	None
c.1494G>A (rs4014596)	UNC93B1	C/T	NM_030930.2	11; 67759316	GTG-ATG	p.499Val>Met	67758155-67759445
c.422T>C (rs52797880)	APOH	A/G	NM_000042.2	17; 64216854	ATC-ACC	p.141Ile>Thr	None
c.209G>C (rs2274329)	CA6	C/G	NM_001215.3	1; 9009451	GGC-GCC	p.70Gly>Ala	None
<b>Marker for IM Failures</b>							
c.7C>A (rs4945)	MFGE8	G/T	NM_001114614.1	15; 89456544	CGC-AGC	p.3Arg>Ser	89456225-89456830
<b>CML Susceptibility Marker</b>							
c.181T>C (rs137863146)	HLA-DRB5	G/G	NM_002125.3	6; 32489871	TAT-CAT	p.61Tyr>His	32489743-32490128
c.200T>C (rs17878951)	HLA-DRB1	A/G	NM_002124.3	6; 32552056	GTG-GCG	p.67Val>Ala	32551852-32552331
c.1070A>T (rs193179333)	RHPN2	A/T	NM_033103.4	19; 33493188	CAC-CTC	p.357His>Leu	None
c.798G>C (rs117958555)	CYP2F1	C/G	NM_000774.3	19; 41628014	CAG-CAC	p.266Gln>His	None
c.785T>G (rs76684759)	KCNJ12	G/T	NM_021012.4	17; 21319439	ATC-AGC	p.262Ile>Ser	21318651-21320041
c.1007A>C (rs151218854)	FUT3	G/T	NM_000149.3	19; 5843844	GAT-GCT	p.336Asp>Ala	None

<sup>ε</sup>Chromosomal Position = Chromosome no.; nucleotide position, <sup>▲</sup>CpG = Cytosine phosphate Guanine

**Clinical exome analysis:** Data was uploaded to SeattleSeq Annotation 141 (<http://snp.gs.washington.edu/SeattleSeqAnnotation141>) for annotation. Analysis of patients and controls was done separately. All the variants present in the control group were aligned in one table and all variants of patients group were aligned in another table. In total, 97,462 variants in patients and 65,546 variants in controls were found. After filtration of common variants, 45,950 variants were selected exclusively in the patient group. The distribution of genetic variants in the patient group included 30,525 intronic, 2,837 variants were in untranslated regions (3'UTR = 1,737 and 5' UTR = 1,100), 5,132 variations were synonymous and 7,494 variants were non-synonymous. Non-synonymous mutations were further segregated as 6,524 missense mutations,

766 frame-shift and 166 stop gained/stop lost mutations (Figure 1). We targeted only missense mutations, as these mutations play a central role in altering phenotype of the gene at protein level.

**Variant analysis of significant genes:** Total 2,033 missense variants were common in at least 2 patients, and only 273 variants were left after considering the variants present in more than 25% ( $\geq 5$ ) patients. These variants were further analyzed for molecular pathway and functional correlation with CML. All the mutations observed were subjected to Kyoto Encyclopedia for Genes and Genomics (Kegg) pathways and GeneCards to identify the cellular pathway and functions associated with the mutated genes. We focused on the genes which were most frequently mutated in this group.



**Figure 1:** Work flow of clinical exome data interpretation to define potential prognostic and susceptibility markers in CML cohort.

**Prognostic marker variants:** We discovered rs116201358 (c.107C>A) in C8A, rs4014596 (c.149G>A) in UNC93B1, rs52797880 (c.422T>C) in APOH and rs2274329 (c.209G>C) in CA6 as markers for good response as mutations were present in responding patients only.

Amongst these mutations, rs116201358 (c.107C>A) and rs2274329 (c.209G>C) are expected to be most damaging (PolyPhan score: 0.994 and 1 respectively), while rs4014596 (c.149G>A) was moderately damaging (Table 2).

In the treatment failure group, rs4945 (c.7C>A) in MFGE8 was discovered. The mutation lies in conserved region and expected to be moderately damaging (SIFT: 0.00, PolyPhan score: 0.65) (Table 2).

HLA-DRB1 and HYDIN had 5 variants each, whereas HLA-A had 4 variants (Supplementary Table 2). These genes demonstrated maximum number of variants among all the genes. Apart from these candidate genes, CPZ, NSD1, PER3, SDHA and TAS2R43 had 3 mutations each (Supplementary Table 2). All the remaining genes had either 1 or 2 variation.

Table 2: Damaging potential of candidate variants related to CML prognosis and susceptibility.

Mutation	Gene	Allele	MAF <sup>▲</sup> (dbsnp)	Mutation scoring				Patients (n <sup>#</sup> )		
				SIFT <sup>€</sup>	PolyPhan	Grantham	GERP <sup>¶</sup>	Responders (n=10)	Failures (n=8)	Total (n=18)
<b>Markers for IM Responder</b>										
c.107C>A (rs116201358)	C8A	A/C	0.021	0.00	0.994	107	5.09	5	0	5
c.1494G>A (rs4014596)	UNC93B1	C/T	0.048	0.00	0.744	21	2.8	5	0	5
c.422T>C (rs52797880)	APOH	A/G	0.066	0.00	0	89	3.37	5	0	5
c.209G>C (rs2274329)	CA6	C/G	0.0004	0.00	1	60	3.39	5	0	5
<b>Marker for IM Failures</b>										
c.7C>A (rs4945)	MFGE8	G/T	0.435	0.00	0.065	110	-0.479	0	4	4
<b>CML Susceptibility Marker</b>										
c.181T>C (rs137863146)	HLA-DRB5	G/G	0.011	0.00	0.021	83	1.02	7	5	12
c.200T>C (rs17878951)	HLA-DRB1	A/G	NA	0.00	0	64	-0.433	9	6	15
c.1070A>T (rs193179333)	RHPN2	A/T	0.031	0.00	0.989	99	4.61	6	4	10
c.798G>C (rs117958555)	CYP2F1	C/G	0.008	0.00	0.994	24	-4.65	7	2	9
c.785T>G (rs76684759)	KCNJ12	G/T	0.197	0.00	0.999	142	5.43	7	5	12
c.1007A>C (rs151218854)	FUT3	G/T	0.002	0.00	0	126	-4.57	6	5	11

<sup>▲</sup>MAF = Minor allele frequency of variant according to dbsnp (NCBI), <sup>€</sup>SIFT = Sorting Intolerant From Tolerant, <sup>¶</sup>GERP = Genomic Evolutionary Rate Profiling, <sup>#</sup>n = total number of patients in respective

**Susceptibility marker:** HLA family genes HLA-DRB1 had rs17878951 (c.200T>C) and HLA-DRB5 had rs137863146. Other mutations observed in our cohort as CML susceptibility markers were rs193179333 in RHPN2, rs117958555 in CYP2F1, rs76684759 in KCNJ12 and rs151218854 in FUT3. Among these mutations, rs193179333, rs117958555 and rs76684759 were most deleterious as per SIFT, PolyPhan, Grantham and GERP scoring (Table 2).

**Supplementary Table 2:** Summary of most mutated genes (in  $\geq 5$  CML patients) revealing effected pathway and functions in CML.

Genes	Mutations (rsID <sup>▲</sup> )	No. of Patients (n <sup>€</sup> =18)	Associated Pathways/ Functions
HLA-DRB1	rs17885382	6	hsa04514:Cell Adhesion Molecules(CAMs); hsa04612:Antigen Processing and Presentation; hsa04640:Hematopoietic Cell Lineage; hsa04672:Intestinal Immune Network For IgA Production; hsa04940:Type I Diabetes Mellitus; hsa05140:Leishmaniasis; hsa05310:Asthma; hsa05320:AutoimmuneThyroid Disease; hsa05322:Systemic Lupus Erythematosus; hsa05330:Allograft Rejection; hsa05332:Graft-versus-host Disease; hsa05416:Viral Myocarditis (Kegg Pathways)
	rs17878951	15	
	rs9269951	8	
	rs11554462	8	
	c.239C>G	8	
HYDIN	rs147394921	8	Involved in cilia motility. Mutations in this gene cause of autosomal recessive primary ciliary dyskinesia-5. (GeneCards)
	rs201356436	7	
	rs202145987	5	
	rs117922041	6	
	rs148896798	7	
HLA-A	rs1059455	6	hsa04144:Endocytosis; hsa04514:Cell Adhesion Molecules (CAMs); hsa04612:Antigen Processing And Presentation; hsa04650:Natural Killer Cell Mediated Cytotoxicity; hsa04940:Type I Diabetes Mellitus; hsa05320:Autoimmune Thyroid Disease; hsa05330:Allograft Rejection; hsa05332: Graft-versus-host Disease; hsa05416:Viral Myocarditis (Kegg Pathways)
	rs199474430	8	
	rs1136949	8	
	rs1137160	8	
CPZ	rs79736750	6	Encodes Carboxypeptidase Z., has carboxypeptidase activity towards substrates with basic C-terminal residues (GeneCards).
	rs35993494	6	
	rs34964084	5	
NSD1	rs35848863	7	hsa00310:Lysine Degradation (Kegg Pathways)
	rs34165241	7	
	78247455	5	
PER3	rs10462020	7	hsa04710:Circadian Rhythm-Mammal (Kegg Pathways)
	rs10462021	7	
	rs2640909	10	
SDHA	rs1042052	5	hsa00020:Citrate Cycle (TCACycle); hsa00190:Oxidative Phosphorylation; hsa01100:Metabolic Pathways; hsa05010:Alzheimer's Disease; hsa05012: Parkinson's Disease; hsa05016: Huntington's Disease (Kegg Pathways)
	rs10426960	6	
	rs10426962	6	
TAS2R43	rs111846092	10	hsa04742:Taste Transduction (Kegg Pathways)
	rs200533679	7	
	rs201618803	9	

<sup>▲</sup>rsID = rsiD provided in DBSNP (NCBI), <sup>€</sup>n = total number of patients enrolled

Table 3: Functional annotation of genes having potential markers using Kegg pathways and Gene Cards.

Gene	Patients <sup>▲</sup>	Associated Pathways/Functions
<b>Genes of Responder Markers</b>		
C8A	P2, P3, P4, P5, P8	hsa04610:Complement And Coagulation Cascades; hsa05020:Prion Diseases; hsa05322:Systemic Lupus Erythematosus (Kegg Pathways)
UNC93B1	P2, P3, P4, P5, P7	Regulates toll-like receptor Signaling. Protein deficiency associated with herpes simplex encephalitis. (GeneCard)
APOH	P4, P5, P6, P8, P10	Associated with lipoprotein metabolism, coagulation, and the production of antiphospholipid autoantibodies. (GeneCard)
CA6	P3, P4, P5, P7, 10	hsa00910:Nitrogen Metabolism. (Kegg Pathways)
<b>Gene of Failure Marker</b>		
MFGE8	P11, P13, P16, P18	Encodes Lectadherin, involved in phagocytosis of apoptotic cells. Implicated in healing, autoimmune disease and cancer. (GeneCard)
<b>Genes of Susceptibility Markers</b>		
HLA-DRB5	hsa04514: Cell Adhesion Molecules (CAMs); hsa04612:Antigen Processing And Presentation; hsa04640:Hematopoietic Cell Lineage; hsa04672:Intestinal Immune Network For IgA Production; hsa04940:Type I Diabetes Mellitus; hsa05140:Leishmaniasis; hsa05310:Asthma; hsa05320:Autoimmune Thyroid Disease; hsa05322:Systemic Lupus Erythematosus; hsa05330:Allograft Rejection; hsa05332:Graft-versus-host Disease; hsa05416:Viral Myocarditis. (Kegg Pathways)	
HLA-DRB1	hsa04514:CellAdhesionMolecules(CAMs); hsa04612:Antigen Processing And Presentation; hsa04640:Hematopoietic Cell Lineage; hsa04672:Intestinal Immune Network For IgA Production; hsa04940:Type I Diabetes Mellitus; hsa05140:Leishmaniasis; hsa05310:Asthma; hsa05320:Autoimmune Thyroid Disease; hsa05322:Systemic Lupus Erythematosus; hsa05330:Allograft Rejection; hsa05332:Graft-versus-host Disease; hsa05416:Viral Myocarditis (Kegg Pathways)	
RHPN2	Encodes Rho-GTPase binding protein. Involved in actin cytoskeleton. (GeneCard).	
CYP2F1	hsa00980:Metabolism of Xenobiotics By Cytochrome P450 (Kegg Pathways)	
KCNJ12	Encodes K <sup>+</sup> channels. (GeneCard)	
FUT3	hsa00601:Glycosphingolipid Biosynthesis Lacto And Neolacto Series; hsa01100:Metabolic Pathways (Kegg Pathways)	

▲ Patients= patients having mutation of respective gene

## DISCUSSION

The discovery of Imatinib Mesylate in drastically changed the scenario of CML treatment. Despite the paradigm shift in prognosis, around 20% of patients fail to achieve expected remission (6). Increasing incidence of CML will soon convert it into a serious medical problem. Therefore, discovery of more prognostic markers which will help in proper outcome estimation and planning for personalized CML treatment is required. Susceptibility markers are also needed to control increasing incidence of CML. The susceptibility markers identified have been reported for the first

time in the present study. Therefore, these findings are required to be validated in larger cohort of CML patients. Once validated, these markers can be tested in high risk population, which is more prone to develop CML (10,11). In search of the potential prognostic and susceptibility markers, we performed NGS in 18 CML patients, classified as responders and failures. In the responder group, recommended time line for analysis (3 months and 6 months) was customized in case of 2 patients to detect BCR-ABL% for research purpose. Change in the time line of BCR-ABL analysis of patients for research purpose was one of the limitations of the study.

The key objective of the study was to find missense variants, capable of predicting the outcome of patients treated with Imatinib Mesylate as frontline therapy and potential markers to detect healthy individuals prone to have CML. As per the criterion for prognostic markers, we demonstrated mutations in 5 genes as markers. Out of these 5 variations observed, mutation in MFG-E8 was in the failure group, whereas 4 mutations, discovered in the responders, were in genes C8A, UNC93B1, APOH and CA6.

**Prognostic markers:** MFG-E8 (Milk Fat Globule–Epidermal growth factor-8), is primarily responsible for production of membrane glycoprotein lactadherin, which promotes phagocytosis of apoptotic cells. In melanoma cells, MEG-E8 promotes progression by triggering epithelial to mesenchymal transition, stimulated invasion and immune suppression, whereas the high expression is linked with disease progression in oral cancer, breast cancer, prostate cancer and colon cancer (12-16). As this gene was found to be involved in the progression of many cancers, rs4945, discovered in our study was also expected to be associated with IM treatment failure in CML.

Complement component 8-alpha (C8A), encodes alpha subunit of C8. C8A participates in the formation of membrane attack complex (MAC). Elevated RNA levels of C8A gene were associated with better prognosis of Hepatocellular carcinoma (17) and in breast cancer patients, treated with trastuzumab (18). We found a deleterious mutation, rs116201358 in the responders, which seems to be related with better treatment outcome similar to elevated expression in earlier studies.

UNC93B1 (Unc-93 homolog B1) is involved in regulation of toll like receptor signaling. The encoded protein traffics nucleotide sensing receptors to endolysosomes from endoplasmic receptor. It is an IFN1 signature gene, induced by chemotherapy cyclophosphamide. IFN1 has recently been found involved in inducing anti-tumor immunity (19). Impaired UNC93B1 dependent immunity is also associated herpes simplex virus 1 encephalitis (HSE) pathogenesis

in children (20). We observed that the presence of mutation rs4014596 in the majority of the responder patients associates it with better prognosis, due to potential role in anti-tumor immunity.

APOH (Apolipoprotein H) is linked with several pathways including lipoprotein metabolism, coagulation and the production of antiphospholipid antibodies. Its elevated serum levels were found to be associated with incidence of colorectal cancer (21), better prognosis in Estrogen Receptor negative (ER-ve) breast cancer (22) and acute myeloid leukemia (23). We observed mutation rs52797880 in IM the responding cohort, which corroborated with the previous findings correlating elevated serum levels with better prognosis in breast cancer and AML.

Carbonic Anhydrase 6 (CA6) is a protein involved in reversible hydration of carbon-dioxide in saliva. Strong expression of this gene is associated with serous adenocarcinomas of ovary and endometrium (24,25), in carcinomas of breast, pancreas, urothelium and cancers of renal and pulmonary origin (26). In our cohort, 60% of the responding patients had mutation rs2274329, which makes it a potential candidate as marker for better prognosis

Co-occurrence of different genetic variants in an individual or a group of patients is considered as haplotype marker (27). In this study, we observed the co-existence of rs116201358 with rs4014596 and rs4014596 with rs2274329 in 4 and 3 IM responding patients respectively (Table 3). This observation suggests that coexistence of mentioned variants can be a potential haplotypes for good prognosis in CML patients.

**Susceptibility markers:** In our search for CML susceptibility markers, we observed rs17878951 and rs137863146 in HLA-DRB1 (Major Histocompatibility Complex Class II, DR Beta1) and HLA-DRB5 in our cohort. Both of the genes are participants of Interferon-gamma and CXCR4 signaling and play a key role in antigen presentation. Variants of HLA-DRB1 were found to be associated with incidence of CML in different populations throughout the world (28-32), and overexpression of HLA-DRB5 is a

potential susceptibility marker of Lung cancer (33), whereas the genetic variants are markers for CLL (34) and breast cancer (35). Another variant (rs193179333) of RHPN2 (Rhopilin Rho GTPase Binding Protein 2) gene, which codes for Ras Homologous (Rho)-GTPase binding protein, was observed in 10 CML patients of our cohort. The RHPN2 binds to GDP and GTP bound RhoA and RhoB, involved in organization of actin cytoskeleton. Mutations of RHPN2 are linked with suspicion of colorectal cancer incidence (36), prognosis of lung adenocarcinoma and malignant glioma (37,38). The polymorphism of CYP2F1 (Cytochrome P450 family 2 subfamily F member 1) gene is linked to lung cancer in different ethnicities (39), whereas differential expression are associated with prognosis of ovarian and breast cancer (40-42). In this study, rs117958555 was found in the majority of CML patients, which hints at being a susceptibility marker. In normal circumstances, it is involved in drug metabolism, hence genetic change in the gene can be possibly related to pathogenesis of CML. However, FUT3 (Fucosyltransferase 3) is involved in embryogenesis, tissue differentiation, tumor metastasis and inflammation. Incidences of gastro-intestinal and breast cancer are linked to FUT3 genetic variations (43,44). Similarly, we also discovered rs151218854 in FUT3 related to incidence of CML. We also observed another mutation rs76684759 in KCNJ12 (Potassium Voltage-Gated Channel Subfamily J Member 12), Normal KCNJ12 gene is involved in cardiac inward rectifier current (IK1). Its association with any type of cancer is not reported to the best of our knowledge, but we observed rs76684759 in more than 70% of our patients. The mutation is present in conserved region (SIFT Score: 0) and highly damaging (PolyPhen : 0.999).

In conclusion, we discovered 11 missense mutations, as potential prognostic and susceptibility markers. Variants in C8A, UNC93B1, APOH and C6A genes were found in IM responders whereas variant of MFGE8 was present in IM failures. Susceptibility markers were discovered in HLA-DRB1, HLA-DRB5, RHPN2, CYP2F1, KCNJ12 and FUT3. All the

genes were associated with cancer. The study is a step forward to discovering reliable markers for selecting individuals prone to CML and estimate the outcome of treatment. The findings of the study can be useful in individualizing cancer treatment after validation of discovered mutations in larger cohort at genetic and functional level.

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