



**HAL**  
open science

## **Cytogenetic and molecular abnormalities in Waldenström's macroglobulinemia patients: correlations and prognostic impact**

Daphné Krzisch, Nayara Guedes, Clémentine Boccon-Gibod, Marine Baron,  
Clotilde Bravetti, Frédéric Davi, Marine Armand, Luce Smagghe, Jonathan  
Caron, Olivier A Bernard, et al.

### ► **To cite this version:**

Daphné Krzisch, Nayara Guedes, Clémentine Boccon-Gibod, Marine Baron, Clotilde Bravetti, et al..  
Cytogenetic and molecular abnormalities in Waldenström's macroglobulinemia patients: correlations  
and prognostic impact. *American Journal of Hematology*, 2021, 10.1002/ajh.26339 . hal-03359604

**HAL Id: hal-03359604**

**<https://hal.sorbonne-universite.fr/hal-03359604v1>**

Submitted on 30 Sep 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## **Cytogenetic and molecular abnormalities in Waldenström's macroglobulinemia patients: correlations and prognostic impact**

Daphné Krzisch<sup>1,2</sup>, Nayara Guedes<sup>1</sup>, Clémentine Boccon-Gibod<sup>1</sup>, Marine Baron<sup>1</sup>, Clotilde Bravetti<sup>3</sup>, Frédéric Davi<sup>3</sup>, Marine Armand<sup>3</sup>, Luce Smagghé<sup>4</sup>, Jonathan Caron<sup>2</sup>, Olivier A. Bernard<sup>7</sup>, Santos Susin<sup>2</sup>, Elise Chapiro<sup>2,4</sup>, Véronique Leblond<sup>1</sup>, Florence Nguyen-Khac<sup>2,4,\*</sup>, Damien Roos-Weil<sup>1,2,\*</sup>, on behalf the FILO (French Innovative Leukemia Organization) group

### **Affiliations:**

1. Sorbonne Université, Service d'Hématologie Clinique, Hôpital Pitié-Salpêtrière, APHP, Paris, France
2. Centre de Recherche des Cordeliers, INSERM, Cell Death and Drug Resistance in Lymphoproliferative Disorders Team, Sorbonne Université, Université Sorbonne Paris Cité, Université Paris Descartes, Université Paris Diderot, F-75006 Paris, France.
3. Sorbonne Université, Biologie moléculaire, Hôpital Pitié-Salpêtrière, APHP, Paris, France
4. Sorbonne Université, Unité de Cytogénétique, Hôpital Pitié-Salpêtrière, APHP, Paris, France
5. Université Paris-Saclay, Gustave Roussy, INSERM, Villejuif, France

**Running title:** Cytogenetic and molecular abnormalities in WM

**Key words:** Waldenström, prognosis, cytogenetic abnormalities, mutations, complex karyotype

**Correspondance:** Damien Roos-Weil, MD, PhD, Sorbonne Université, AP-HP, Hôpital Pitié-Salpêtrière, Service d'Hématologie Clinique, 47-83 Bd de l'Hôpital 75651 Paris Cedex, France, Phone: + 33.1.42161596, Fax: + 33.1.42162848; email: [damien.roosweil@aphp.fr](mailto:damien.roosweil@aphp.fr). Florence Nguyen-Khac, MD, PhD, Sorbonne Université, AP-HP, Hôpital Pitié-Salpêtrière, Service d'Hématologie Biologique, 47-83 Bd de l'Hôpital 75651 Paris Cedex, France, Phone: + 33.1.42162460, Fax: + 33.1.42162453; email: [florence.nguyen-khac@aphp.fr](mailto:florence.nguyen-khac@aphp.fr).

Abstract word count: 245

Text word count: 3778

Figures: 3

Tables: 2

Supplemental tables: 13

Supplemental figures: 2

References: 41

## Abstract

While Waldenström macroglobulinemia (WM) is characterized by an almost unifying mutation in *MYD88*, clinical presentation at diagnosis and response to therapy can be widely different among WM patients. Current prognostic tools only partially address this clinical heterogeneity. Limited data compiling both molecular and cytogenetic information have been used in risk prognostication in WM. To investigate the clinical impact of genetic alterations in WM, we evaluated cytogenetic and molecular abnormalities by chromosome banding analyses (CBA), FISH and targeted NGS in a retrospective cohort of 239 WM patients, including 187 patients treated by first-line **chemotherapy or immunochemotherapy**. Most frequent mutations were identified in *MYD88* (93%), *CXCR4* (29%), *MLL2* (11%), *ARID1A* (8%), *TP53* (8%), *CD79A/B* (6%), *TBL1XR1* (4%) and *SPI1* (4%). The median number of cytogenetic abnormalities was two (range, 0-22). Main cytogenetic abnormalities were 6q deletion (del6q) (27%), trisomy 4 (tri4) (12%), tri18 (11%), del13q (11%), tri12 (7.5%) and del17p (7%). Complex karyotype (CK) was observed in 15% (n=31) of cases, including 5% (n=12) of highly CK (high-CK). *TP53* abnormalities (*TP53*abn) were present in 15% of evaluable patients. *TP53*abn and del6q were associated with CK/high-CK ( $P<0.05$ ). **Fifty-three percent of patients with hyperviscosity harbored *CXCR4* mutations. Cytogenetic and molecular abnormalities did not significantly impact time to first treatment and response to therapy.** Prognostic factors associated with shorter PFS were del6q ( $P=0.01$ ), *TP53*abn ( $P=0.002$ ) and high-CK ( $P=0.01$ ). These same factors as well as IPSSWM, tri4, *CXCR4* frameshift and *SPI1* mutations were significantly associated with lower OS ( $P<0.05$ ). These results argue for integration of both cytogenetic and molecular screening in evaluation of first-line WM patients.

## Introduction

Waldenström's macroglobulinemia (WM) is a rare mature B-cell lymphoproliferative disorder characterized by the presence of serum monoclonal IgM associated with bone marrow infiltration by lymphoplasmacytic cells<sup>1</sup>. WM is a mostly indolent but still incurable disease for which there is a wide clinical heterogeneity. Some patients never require treatment while others have symptomatic disease upon diagnosis harboring hyperviscosity syndrome, bulky adenopathy and/or profound cytopenias and rapidly relapse after first-line (1L) immunochemotherapy. Different biomarkers have been developed to predict this heterogeneity. The International Prognostic Scoring System for WM (IPSSWM) and its revised version used simple clinical and biological parameters to stratify patients into, respectively, three and five distinct risk prognostic groups that are highly correlated with overall survival (OS)<sup>2,3</sup>. As observed in several other B-cell malignancies, it has been suggested that acquired cytogenetic and molecular abnormalities could also provide prognostic value in WM but it is still a matter of debate. Cytogenetic abnormalities identified in WM include deletion of the long arm of chromosome 6 (del6q) (20-40%), del13q (10-15%), trisomy 18 (tri18) (10%), tri4 (8%) and deletion of the short arm of chromosome 17 (del17p) (8%)<sup>4-6</sup>. Only few data exist regarding the impact of cytogenetic abnormalities in WM but shorter progression-free survival (PFS) has been reported for del17p patients<sup>4</sup>. Next-generation sequencing (NGS) studies revealed that the most common somatic mutations were activating mutations in *MYD88* and *CXCR4* genes, present in respectively more than 90% and 30% of WM patients. Both these mutations have been associated with specific clinical and biological presentation at diagnosis<sup>7</sup>, along with prognosis in some studies<sup>7,8</sup> but not confirmed in others<sup>9</sup>, and have been considered as predictive for response to ibrutinib<sup>10</sup>. Other mutations have been described at a lower frequency (5-20%) in *ARID1A*, *CD79B*, *SPI1* or *TP53* genes<sup>11-14</sup>, the last two mutations being associated with poor survival but in single and limited series. Recently, we have also reported two groups of WM according to DNA methylation patterns, related to normal memory B-cells and plasma cells profiles, and respectively significantly associated to *CXCR4* mutations and del6q<sup>15</sup>.

Cytogenetic analyses combining chromosomal banding analysis (CBA) and fluorescent *in situ* hybridization (FISH) have been widely used in hematologic malignancies to evaluate and predict patient's prognosis. Both technics have limitations but are complementary. In B-cell lymphoproliferative disorders, such as chronic lymphocytic leukemia (CLL) and WM, one limitation of CBA was the relative difficulty in obtaining sufficient metaphases but this has been overcome by the introduction of modern cell stimulation protocols, allowing for robust CBA<sup>16,17</sup>. Importance of CBA has been emphasized by the association of karyotypic complexity with shorter treatment-free and OS in many hematologic malignancies and in particular CLL<sup>18,19</sup>. Recently, karyotypic complexity in CLL has been refined<sup>20</sup> demonstrating that complex karyotype (CK) comprises different subgroups with distinct prognosis, depending on the type of associated abnormalities, and that not all CK are of poor prognosis. Data regarding chromosomal abnormalities and karyotypic complexity are in contrast scarce in WM.

Immunochemotherapy (ICT), consisting in the association of an anti-CD20 monoclonal antibody and an alkylating agent, is part of the standard of care for WM patients. However, ICT use is still unsatisfactory, leading to non-complete responses and inevitable recurrence. Alternative treatments have been developed to obtain longer responses, consisting mainly in BTK inhibitors (BTKi) (ibrutinib, acalabrutinib, zanubrutinib) in monotherapy or in association with an anti-CD20 monoclonal antibody<sup>21,29,32</sup>. Although these latter regimens are efficient, data are lacking to choose one treatment or another according to a specific molecular or cytogenetic abnormality.

Recent advances in deciphering precise genomic landscape in WM have led to the proposition of a precision-guided treatment approach using *MYD88* and *CXCR4* mutational status<sup>11</sup>. While various studies have confirmed the relevance of this approach in WM patients receiving ibrutinib<sup>10,29-31</sup>, other studies have

shown more controversial results<sup>32,33</sup>, either regarding the impact of *CXCR4* mutations and/or in the specific context of ICT<sup>34</sup>. Finally, very limited data compiling both molecular and cytogenetic information are actually available and used in risk prognostication in WM.

The aim of this study was to evaluate clinical and biological characteristics of WM patients along with cytogenetic and molecular abnormalities, the potential association of CK with recurrent mutations identified in WM and their impact on outcome.

## **Patients and methods**

### ***Patients***

This retrospective study included 239 WM patients diagnosed from 1988 to 2020 and followed up in Pitié-Salpêtrière hospital (Paris, France). Diagnosis, treatment initiation and response criteria followed the WHO classification<sup>1</sup> and recommendations from the tenth International Workshop Waldenström's Macroglobulinemia (IWWM)<sup>21</sup>. All cases were selected based on the availability of chromosome banding analyses (CBA)/FISH and/or DNA material sufficient for evaluation of *MYD88* and *CXCR4* mutations. Written consent for bone marrow (BM) and biological analyses were obtained in accordance with the declaration of Helsinki and with ethical approval from national (CNIL 2212382) and local (CPP Ile-De-France 05/21/2014) ethics committees.

### ***Cytogenetic analyses***

CBA were successfully performed in 219 patients according to the usual techniques as previously described<sup>4</sup>, with 12-O-tetradecanoyl-phorbol-13-acetate (28 patients) until 2006 and CpG-oligonucleotides plus interleukin 2 stimulation (191 patients). All karyotypes (K) were described according to the International System for Human Cytogenetic Nomenclature (ISCN 2020). FISH was performed on interphase nuclei and metaphases, following standard procedures and using specific probes: *ATM* (11q22), *TP53* (17p13.1) (Metasystems), *BCL2* (18q21) (Zytovision), D12Z1 (12p11-q11), D13S319 (13q14), *LAMP1* (13q34) Metasystems, D6Z1 (6p11-q11)/SEC63 (6q21)/*MYB* (6q23) Metasystems, *FIP1L1/CHIC2/PDGFR4* (4q12) Deletion/Fusion Cytocell<sup>4</sup>.

To consider a karyotype normal, a minimum of 15 metaphases had to be examined. Single-cell abnormalities were taken into consideration only if verified by FISH analysis. A karyotype was defined as complex (CK) if  $\geq 3$  clonal aberrations were present in CBA, respectively. Highly CK (high-CK) and non-high-CK were respectively defined if  $\geq 5$  and 3 or 4 clonal aberrations were identified. CBA was performed at WM diagnosis or before the administration of any treatment in respectively 85/219 (39%) and in 99/219 (45%), with a median of 39 [1-92] months between diagnosis and karyotype in this latter situation.

### ***Mutation analyses***

Genomic DNA was extracted using the QiAmp DNA micro kit (Qiagen) from non-sorted bone marrow (BM) samples. Routine sequencing of *MYD88* L265P and *CXCR4* S338X mutations was performed by restriction fragment length polymorphism (RFLP) and allele-specific polymerase chain reaction (AS-PCR) for respectively 199 and 189 patients. Among them, 168 BM samples were analyzed by targeted sequencing, including three tumor controls pairs analyzed by whole-exome sequencing. Twenty-one recurrently mutated genes in WM or other lymphoproliferative B-cell disorders from our experience or in the literature were selected for targeted sequencing (see **Supplementary Tables S1** for genomic coordinates of targeted regions and for the list of genes) using TWIST custom capture kit (Bioscience, San Francisco, CA). Libraries were generated with addition of paired-end adaptors (NEXTflex, Bioo Scientific, Austin, TX) before paired-end sequencing (2 x 100 bp reads) using an Illumina Novaseq6000 flow cell and the onboard cluster method

(Illumina, San Diego, CA). Targeted sequencing was analyzed according to previously described algorithms with minor modifications<sup>22</sup>. Briefly, sequence reads were mapped to the reference genome GRCh38 using the Burrows–Wheeler Aligner (BWA) alignment tool. PCR duplicates were removed using Picard tools - Mark Duplicates (version 1.119). Local realignment around indels and base quality score recalibration were performed using GATK 3.2 (Genome Analysis Tool Kit). The number of reads containing single-nucleotide variations (SNV) and indels was enumerated using Varscan (v2.3.7). Functionally annotated variants were filtered according to the following criteria: synonymous variants and variants located outside coding regions were filtered; polymorphisms described in Kaviar, gnomAD and the 1000 Genomes Project were removed; variants with coverage < 30X and less than ten supporting reads and variants with an allelic fraction lower than 1% were filtered; the remaining variants, evaluated as candidate somatic mutations, were manually reviewed and tagged as oncogenic using different criteria based on information retrieved from the literature, sequence conservation and *in silico* prediction of effect. The mean read depth within the targeted regions was 2000X.

In total, both *MYD88* L265P and *CXCR4* S338X status were available for 189 samples, targeted NGS for 168 and both cytogenetic and targeted NGS analyses for 165.

Abnormalities of *TP53* were defined by the presence of del(17p) and/or *TP53* mutations.

### **Statistical analyses**

Main clinical and biological characteristics were collected **at diagnosis and treatment initiation**: age, hyperviscosity syndrome, lymphadenopathy, splenomegaly, hemoglobin level, platelet count, serum IgM monoclonal level,  $\beta$ 2-microglobulin (B2M), albumin, LDH. The International Prognostic Scoring System for WM (IPSSWM) was calculated according to previous published criteria<sup>2</sup>. Cytogenetic (FISH [del6q, trisomy 4, trisomy 12, del13q, del11q, del17p], chromosomal aberrations) and molecular abnormalities were analyzed as described above. Quantitative variables are presented as mean and standard deviation or median and range according to their distribution. Categorical variables are presented as numbers and related percentage. Primary and secondary endpoints were time to first treatment (TFT) for asymptomatic WM, and response to therapy, relapse rate, progression-free survival (PFS) and overall survival (OS) for the whole population. OS and PFS were calculated from the date of diagnosis/evaluation until the date of death from any cause or date of last follow up and date of progression, respectively. **Variables included in univariate analyses included: age, B2M, IPSSWM, cytogenetic abnormalities (del6q, tri12, tri4, tri18, del13q, del11q, del17p), CK and high-CK, mutations (*MYD88*, *CXCR4*, *CD79B*, *ARID1A*, *MLL2*, *TP53*, *SPI1*).** We excluded variables interesting less than 5 patients. Univariable Cox regression was applied to assess the prognostic significance of cytogenetic and molecular abnormalities, CK/high-CK and other prognostic factors on survival outcome. *P*-values were adjusted for age and multiplicity (Benjamini-Hochberg method). Multivariable Cox regression models were implemented to test the simultaneous effect of factors on outcomes, taking into account the relative effect of the remaining parameters. For the multivariable analysis, we considered only cases with available data for all the factors included in the model and variables that were significant ( $P \leq 0.05$ ) in univariate analyses. Biostatistic analyses were performed with the help of GenoSplice (Paris, France). Kaplan-Meier analysis was performed to construct survival curves and the log rank test used to determine differences between groups. The X2 or Fisher's exact test were used to compare data distribution in different subgroups. The significance level of  $p < 0.05$  was applied and statistical analyses were performed using the software SAS 9.3 (SAS Inc, Cary, NC) and R 3.0.2 (<http://www.R-project.org>).

## **Results**

### **Clinical characteristics**

Main clinical characteristics of the whole WM cohort are detailed in **Table 1**. The study population comprised 239 patients, including 63% of male. Median age at WM diagnosis was 65 years old (range, 28-88). WM was symptomatic at evaluation in 59% of patients. During the follow-up, 187/239 (78%) WM patients required first-line (1L) therapy. **The indications for 1L therapies are listed in Supplemental Table S2**. Those therapies consisted of chemotherapy (CT), immuno-CT (ICT), anti-CD20 monoclonal antibody alone, **or other type** in, respectively, 47/187 (25%), 125/187 (67%), 14/187 (7.5%) **and 1/187 (0.5%)** cases. ICT included dexamethasone-cyclophosphamide-rituximab (DRC), bendamustine-rituximab (BR) and fludarabine-rituximab based regimens in respectively 63/187 (34%), 36/187 (19%) and 23/187 (12%) (details regarding all the different types of treatment are provided in **Supplemental Table S3**). The median follow-up for the whole WM cohort was 6 years. Median PFS of patients receiving 1L therapy was 51 months and 5-year-OS was 91%. Forty-nine of 239 patients (20%) have died, **due to WM progression or transformation, therapy-related toxicity, other causes and of unknown origin in respectively 28 (57%), 12 (24%), 6 (12%) and 3 (7%) cases (Supplemental Table S4)**.

### **Cytogenetic and mutational abnormalities**

The distribution and frequency of gene alterations is represented in **Figure 1**. The most frequent mutations were identified in *MYD88* (93%), *CXCR4* (29%), *MLL2/KMT2D* (11%), *ARID1A* (8%), *TP53* (8%), *CD79A/B* (6%), *TBL1XR1* (4%), and *SPI1* (4%) (see **Supplemental Table S5** for details and list of mutations identified by targeted NGS). *MYD88* mutations other than the classical L265P (V217F, M232T and S243N) were found in 5 (2%) cases. Among the 7% *MYD88* wild-type (WT) cases, we observed mutations in other recurrently mutated genes such as *ARID1A*, *MLL2*, *CD79B* or *TNFAIP3*. *CXCR4* mutations were frameshift (FS) and nonsense (NS) in respectively 35 and 56% and more than half of them (55%) affected S338 amino-acid. *CXCR4* mutations affecting S338 amino-acid were mainly NS (23/27 (85%) cases) while NS mutations represented 5/21 (24%) cases of those affecting other amino-acids. Mutations identified in *CD79A/B*, *TBL1XR1*, *CARD11* (1%), *EZH2* (4%), *TNFAIP3* (3%), *NFKBIE* (2%) corresponded mainly to those previously described in other B-cell malignancies<sup>22-27</sup>. *SPI1* and *IKZF3* (3%) mutations were respectively hotspot Q226E and L162R<sup>13,28</sup>.

The median number of cytogenetic abnormalities per sample was two (0-22). No cytogenetic abnormality was detected by CBA in 87/191 (40%), and by both CBA and FISH in 55/166 (33%) evaluable cases. Cytogenetic abnormalities identified by CBA and/or FISH were as follows, in decreasing order of frequency: del6q (27%), tri4 (12%), tri18 (11%), del13q (11%), tri12 (8%), del17p (7%), tri3 (6%) and del11q (5%). *TP53* abnormalities (*TP53*abn) (either del17p and/or *TP53* mutation) were present in 15% of 165 evaluable patients.

CK was observed in 15% (n=31/219) of cases, comprising three, four and ≥ five chromosomal aberrations (high-CK) in respectively 7% (n=13), 3% (n=6) and 5% (n=12) of cases. Details of the 31 CK (either non-high-CK or high-CK) are provided in **Supplemental Table S6**. Among the 31 CK, 15 (48%) included at least one trisomy (one trisomy, n=6; two, n=6; three, n=2; four, n=1), while, among the 12 high-CK, 7 (58%) included at least one trisomy (one trisomy, n=4; two, n=2; three, n=1).

### **Correlation between cytogenetic and mutational alterations**

Significant associations between different genetic alterations are synthesized in **Supplemental Tables S7**. We did not observe specific mutations or cytogenetic abnormalities associated with *MYD88* WT status. *CXCR4* S338 mutations were significantly associated with CK ( $P=0.05$ ) and *TP53*abn ( $P=0.03$ ), while the



presence of *TP53*abn was associated with CK, either non-high-CK ( $P=0.02$ ) or high-CK ( $P=0.0005$ ). Del6q was associated with many other cytogenetic abnormalities (del13q, del11q, del17p, tri4) and non-high-CK/high-CK ( $P<0.0001$ ). Del6q and *CXCR4* mutations were not exclusive in our series, as 18/51 del6q cases detected by CBA and/or FISH and explored by targeted NGS also harbored *CXCR4* mutations (S338,  $n=10$ ; other amino-acid,  $n=8$ ). Tri4 and tri18 were significantly associated with each other ( $P=0.02$ ) as del17p and *TP53* mutations ( $P=0.03$ ).

Specific comparisons between non-high-CK and high-CK (**Supplemental Tables S8**) showed that this latter harbored significantly more frequent del6q (by CBA and/or FISH, 11/12 [92%] vs. 9/19 [47%],  $P=0.02$ ), del17p (5/12 [42%] vs. 1/19 [5%],  $P=0.02$ ) and *TP53*abn (6/12 [50%] vs. 2/15 [13%],  $P=0.03$ ) while no difference was observed in terms of specific gene mutation frequencies.

Of note, *TP53*abn were not equally distributed among CK subgroups as they were more frequently observed in CK without trisomies and more particularly in high-CK without trisomies. Only two *TP53*abn ( $n=2/14$ , 1 del17p, 1 *TP53* mutation) were identified in CK with trisomies (vs. 6/13 [45%] in CK without trisomies,  $P=0.07$ ). More precisely, the two *TP53*abn were identified in high-CK with trisomies ( $n=2/7$  vs. 4/5 in high-CK without trisomies,  $P=0.07$ ) while none was observed in non-high-CK with trisomies ( $n=0/7$  vs. 2/8 in non-high-CK without trisomies,  $P=0.15$ ).

#### **Correlation between genetic alterations and disease phenotype**

Significant associations between genetic alterations and disease phenotype are synthesized in **Supplementary Table S9**. When comparing the population carrying an abnormality to that without the same abnormality, lymphoplasmacytic BM infiltration was significantly increased in patients with *CXCR4* mutations (56% vs. 41%,  $P=0.02$ ), del6q (53% vs. 36%,  $P=0.001$ ), tri4 (58% vs. 35%,  $P=0.003$ ) and/or non-high-CK (55% vs. 35%,  $P=0.02$ )/high-CK (68% vs. 43%,  $P=0.003$ ); the presence of lymphadenopathy in those with *TP53*abn (44% vs. 21%,  $P=0.02$ ) and *SPI1* mutations (67% vs. 23%,  $P=0.03$ ). No significant correlation was observed between genetic alterations and IPSSWM.

In more detail, *CXCR4* mutations were also significantly associated with increased serum IgM levels (28 vs. 18 g/L,  $P=0.05$ ), symptomatic hyperviscosity at presentation (17% vs. 6%,  $P=0.04$ ; 53% of patients with symptomatic hyperviscosity at presentation harbored *CXCR4* mutations), and *CXCR4* mutated patients had more frequently platelet count  $< 100 \times 10^9/L$  (11/48 [23%] vs. 5/120 [4%],  $P=0.0002$ ). *TBL1XR1* mutations were associated with the lowest serum IgM levels (9.5 vs. 20 g/L,  $P=0.0007$ ). Del6q patients had lower hemoglobin level (101 vs. 120 g/L,  $P<0.001$ ) and tri4 lower hemoglobin (91 vs. 116 g/L,  $P=0.003$ ) and more frequently platelet count  $< 100 \times 10^9/L$  (9/27 [33%] vs. 19/183 [10%],  $P=0.001$ ) that may reflect in both cases the increased BM infiltration described above.

#### **Outcomes**

Among the 239 WM patients of our cohort, 179 (75%) were asymptomatic at diagnosis. The median time to first therapy (TFT) for asymptomatic WM at diagnosis was 43 months (range, 7-236). Only elevated B2M was associated with shorter TFT ( $P=0.02$ ). Cytogenetic and molecular abnormalities were not significantly associated with TFT; only a trend for shorter TFT was observed in tri12 and del6q patients (**Supplemental Table S10**).

Among the 187 (87%) symptomatic WM who received 1L therapy, response rates were distributed as followed: 6% ( $n=11$ ) complete response (CR), 11% ( $n=21$ ) very good partial response (VGPR), 49% ( $n=91$ ) PR, 24% ( $n=45$ ) stable disease (SD) and 10% ( $n=19$ ) progressive disease (PD). No significant correlation was

observed between cytogenetic/mutational abnormalities and response. One hundred and two (54%) patients further experienced relapse with a median time of 55 months (range, 3-255). Univariate analyses of clinical and biological variables associated with relapse, PFS and OS are represented in **Table 2** and **Supplemental Table S10**. Prognostic factors associated with shorter PFS included del6q ( $P=0.01$ ), *TP53*abn ( $P=0.002$ ) and high-CK ( $P=0.01$ ) (**Figure 2**). OS was pejoratively impacted by IPSSWM ( $P=0.002$ ), del6q ( $P=0.027$ ), tri4 ( $P=0.026$ ), *CXCR4* frameshift ( $P=0.047$ ), *SPI1* mutations ( $P=0.037$ ), *TP53*abn ( $P=0.002$ ) and high-CK ( $P=0.008$ ) (**Figure 2** and **Supplemental Figure S1**). In multivariate analyses, only *TP53*abn ( $P=0.03$ ) for PFS and IPSSWM ( $P=0.03$ ) and *TP53*abn ( $P=0.04$ ) for OS retained significant.

As the entire cohort of WM patients received two main different types of 1L therapies (CT and ICT), we compared PFS and OS of these two subgroups (respectively, 5-year PFS, 40 vs. 50% [ $P=0.02$ ]; 10-year OS, 76 vs. 78% [ $P=0.3$ ]; **Supplemental Figure S1**). The repartition of main cytogenetic and molecular abnormalities was similar in these two subgroups (**Supplemental Table S11**). We then specifically analyzed prognostic factors for PFS and OS in 1L ICT patients (**Figure 3** and **Supplemental Table S12**). Del6q, high-CK, *TP53* abnormalities negatively impacted PFS (**Figure 3**) while only IPSSWM and *TP53* abnormalities were significantly associated with shorter OS in univariate analysis in this specific population. In multivariate analyses, only *TP53*abn for PFS and IPSSWM and *TP53*abn for OS retained significant (**Supplemental Table S12**).

Regarding more specifically the outcomes of CK, the pejorative impact on PFS and OS was stronger for high-CK compared to non-high-CK. High-CK was one of the most impactful prognostic factors, being associated with one of the shortest median PFS of 20 months and a 5-year OS of 75%. CK with trisomies were associated with a trend to better PFS compared to CK without trisomies (**Supplemental Figure S2**).

Nine patients experienced transformed WM in the course of the disease. For the seven patients for whom cytogenetic and molecular screening were available, all harbored either high-CK ( $n=4/7$ , 57%, all these four including del6q) and/or *TP53* abnormalities ( $n=6/7$ , 87%) (see **Supplemental Table S13** for details regarding cytogenetic and molecular abnormalities of these samples).

## Discussion

Our comprehensive approach integrating CBA, FISH and targeted NGS analyses in a large cohort of WM patients offered the opportunity to study the prognostic impact of both molecular and cytogenetic abnormalities and, to our knowledge, for the first time the one of high-CK that has been recently emphasized in CLL<sup>20</sup>. In this series, we confirmed many of the already published WM biological features but also extended our knowledge of particular associations between different genomic characteristics and finally highlighted prognostic factors associated with those, which could be of importance in future 1L therapeutic strategies in WM patients.

Our cohort harbored main characteristics of WM real-life patients: median age of 65 years, 80% of kappa isotype, mean IgM level around 20 g/L, > 90% *MYD88* L265P, 30% *CXCR4* mutations, and respective 5-year and 10-year OS of 91% and 75%. IPSSWM strongly impacted OS (**Table 1** and **Supplemental Figure S1**) supporting the validity and reliability of our cohort. However, our study harbored notable limitations due in part to its retrospective design encompassing a long period of time, including patients with missing data and receiving diverse therapies. Since many patients have a smoldering disease not requiring therapy, the analysis of OS performed from the date of diagnosis date can be in part misleading. More, the absence of patients treated in 1L by BTKi that have actually no marketing authorization in France for 1L WM limited the possibility to infer which therapies between ICT and BTKi will more benefit for certain

cytogenetic/molecular abnormalities. Further prospective studies are thus clearly warranted to address this important question.

Chromosomal abnormalities have been little studied so far in WM and information about frequencies and characteristics of the most recurrent abnormalities is therefore of interest. In this respect, we confirmed our previous results regarding the occurrence of del6q (27%) and tri4 (12%) and their respective association with CK and tri18<sup>4</sup>. Frequency of del6q was slightly lower in our cohort than that historically reported in the literature (40-50%)<sup>35,36</sup> but was concordant with the one (28/93 [30%]) identified in symptomatic WM of a recent Spanish study<sup>37</sup>. Although del6q and *CXCR4* mutations have been suggested to be mutually exclusive<sup>38</sup>, we did not observe this exclusivity in our series. This difference could be due in part by the technics used for del6q identification (CBA and/or FISH vs. RQ-PCR). Del6q and tri4 cases had more aggressive presentation with increased BM involvement, lower hemoglobin and platelet counts, and shorter PFS and OS, confirming recent published data for del6q<sup>37</sup>. Del6q-associated poor prognosis may be in part due to its association with CK and more particularly with high-CK as nearly all these latter (11/12, 92%) harbored del6q and plead for its potential implication in chromosomal instability. Further studies will be necessary to confirm that del6q could represent a particular group of patients with potential specific methylation profile, association with *VH3* usage, CD38 expression and enrichment in plasmacytoid lymphocytes as previously suggested<sup>15</sup>. We also brought more information about del17p (7%)/*TP53*abn and CK frequencies, that are confirmed to be recurrent events in WM as previously described<sup>4,12,39</sup>. Other trisomies than tri4 such as tri18 and tri3 were recurrent representing respectively 11 and 6% of cases.

We provided more precise characterization of CK in WM, especially high-CK, which was positively associated in our cohort with the presence of del6q and *TP53*abn. As described in CLL<sup>20</sup>, not all CK were equivalent, as in particular (i) the pejorative impact on PFS and OS was stronger for high-CK compared to non-high-CK and (ii) CK with trisomies were associated with a lower frequency of *TP53*abn and a trend to better PFS compared to CK without trisomies. This latter point will need to be confirmed in largest cohorts of patients.

Regarding main somatic gene mutations, frequencies were relatively similar to those previously described for *CXCR4*, *ARID1A*, *CD79A/B*, *TP53* and *SPI1*<sup>7,11-14</sup>. No significantly relevant association with cytogenetics was observed for most gene mutations (**Supplemental Tables S5**), except for the ones described above for *TP53* and *CXCR4*. The number of mutated cases was too small for *EZH2*, *IKZF3*, *PRDM1*, *TNFAIP3*, *CARD11*, *ETV6* and *HIST1H1E* to draw reliable conclusions. *CXCR4* mutated patients represented around one third of the cohort and presented with increased BM infiltration, serum IgM levels and symptomatic hyperviscosity as previously described<sup>7</sup>. Somatic mutations in *ARID1A* were identified in 8% of patients, including NS and FS variants, but were not associated with specific clinical presentation.

Interestingly, various gene mutations were associated with outcome. We did observe a trend for shorter PFS for non-*MYD88* L265P cases but this was not confirmed if we integrated others (non-L265P) *MYD88* mutated cases in the analysis. Definitive conclusions are difficult to draw in this particular population regarding the small number of patients. The poor prognosis of *SPI1* mutations was confirmed as previously suggested<sup>13</sup>. *CXCR4* S338 and/or NS mutations did not affect outcomes in our cohort while *CXCR4* FS have a slight significant pejorative impact on OS (**Supplemental Figure S1**). These results are different from what has been described in WM patients treated with BTKi ibrutinib for whom the presence of *CXCR4* NS mutations impacted survival outcomes<sup>40,41</sup>. Further studies will be necessary to interrogate the hypothesis that BTKi and ICT may be beneficial specifically for *CXCR4* FS and NS respective populations. Interesting information is also provided in this WM cohort receiving 1L (I)CT regarding the pejorative role of *TP53*abn

for PFS and OS in uni- and multivariate analyses, emphasizing its **potential** predictive value for considering 1L targeted therapies in this specific population as described in CLL. **This pejorative impact on PFS and OS was confirmed in the group of patients who specifically received 1L ICT (n=125) in uni- and multivariate analyses (Figure 3 and Supplemental Table S12).** The negative impact of del6q and high-CK on PFS was also confirmed in this specific group of patients in univariate but not multivariate analysis (**Supplemental Table S12**).

Finally, as WM is frequently an asymptomatic disease at diagnosis, prognostic factors predicting evolution to symptomatic disease are of importance. Only B2M was significantly associated with shorter TFT in our cohort and we failed to demonstrate any significant association between cytogenetic/molecular abnormalities and TFT. Larger studies in asymptomatic WM may be necessary to fully explore these potential associations.

In conclusion, our work is one of the first to describe a cohort of WM patients treated by (I)CT with comprehensive analysis of both cytogenetic and molecular abnormalities, providing important information for prognosis prediction and therapy selection. In particular, a negative impact of del6q, *TP53*abn and high-CK has been demonstrated on both PFS and OS. **Prospective studies are warranted to confirm these prognostic factors, the potential role of 1L targeted therapies in high-risk WM and the use of both cytogenetic and molecular screening for guiding therapeutic strategy between BTKi and ICT in 1L WM patients.**

**Acknowledgements:** This study was supported by grants from INCA-DGOS-Inserm\_12560 (SiRIC CURAMUS is financially supported by the French National Cancer Institute, the French Ministry of Solidarity and Health and Inserm with financial support from ITMO Cancer AVIESAN), prix Jeunes Chercheurs FILO-Janssen 2019 (to DRW) and Force Hémato 2020 (to DRW).

**Contribution statement:** DK, FNK and DRW designed the research, analyzed data and wrote the manuscript. DK, CB, LS, JC, EC and DRW performed experiments. DK, NG, CBG, MB, CB, FD, EC, SS, VL, FNK and DRW recruited patients. All authors reviewed and approved the manuscript.

**Conflict-of-interest disclosure:** No relevant COI

**Data availability statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References

1. Swerdlow SH, Campo E, Pileri SA, et al. The 2016 revision of the World Health Organization classification of lymphoid neoplasms. *Blood*. 2016;127(20):2375-2390.
2. Morel P, Duhamel A, Gobbi P, et al. International prognostic scoring system for Waldenstrom macroglobulinemia. *Blood*. 2009;113(18):4163-4170.
3. Kastritis E, Morel P, Duhamel A, et al. A revised international prognostic score system for Waldenstrom's macroglobulinemia. *Leukemia*. 2019;33(11):2654-2661.
4. Nguyen-Khac F, Lambert J, Chapiro E, et al. Chromosomal aberrations and their prognostic value in a series of 174 untreated patients with Waldenstrom's macroglobulinemia. *Haematologica*. 2013;98(4):649-654.

5. Schop RF, Kuehl WM, Van Wier SA, et al. Waldenstrom macroglobulinemia neoplastic cells lack immunoglobulin heavy chain locus translocations but have frequent 6q deletions. *Blood*. 2002;100(8):2996-3001.
6. Terre C, Nguyen-Khac F, Barin C, et al. Trisomy 4, a new chromosomal abnormality in Waldenstrom's macroglobulinemia: a study of 39 cases. *Leukemia*. 2006;20(9):1634-1636.
7. Treon SP, Cao Y, Xu L, Yang G, Liu X, Hunter ZR. Somatic mutations in MYD88 and CXCR4 are determinants of clinical presentation and overall survival in Waldenstrom macroglobulinemia. *Blood*. 2014;123(18):2791-2796.
8. Poulain S, Roumier C, Decambren A, et al. MYD88 L265P mutation in Waldenstrom macroglobulinemia. *Blood*. 2013;121(22):4504-4511.
9. Abeykoon JP, Paludo J, King RL, et al. MYD88 mutation status does not impact overall survival in Waldenstrom macroglobulinemia. *Am J Hematol*. 2018;93(2):187-194.
10. Treon SP, Xu L, Hunter Z. MYD88 Mutations and Response to Ibrutinib in Waldenstrom's Macroglobulinemia. *N Engl J Med*. 2015;373(6):584-586.
11. Treon SP, Xu L, Guerrero ML, et al. Genomic Landscape of Waldenstrom Macroglobulinemia and Its Impact on Treatment Strategies. *J Clin Oncol*. 2020;38(11):1198-1208.
12. Poulain S, Roumier C, Bertrand E, et al. TP53 Mutation and Its Prognostic Significance in Waldenstrom's Macroglobulinemia. *Clin Cancer Res*. 2017;23(20):6325-6335.
13. Roos-Weil D, Decaudin C, Armand M, et al. A Recurrent Activating Missense Mutation in Waldenstrom Macroglobulinemia Affects the DNA Binding of the ETS Transcription Factor SPI1 and Enhances Proliferation. *Cancer Discov*. 2019;9(6):796-811.
14. Gustine JN, Tsakmaklis N, Demos MG, et al. TP53 mutations are associated with mutated MYD88 and CXCR4, and confer an adverse outcome in Waldenstrom macroglobulinaemia. *Br J Haematol*. 2019;184(2):242-245.
15. Roos-Weil D, Giacomelli B, Armand M, et al. Identification of 2 DNA methylation subtypes of Waldenstrom macroglobulinemia with plasma and memory B-cell features. *Blood*. 2020;136(5):585-595.
16. Haferlach C, Bacher U. Cytogenetic methods in chronic lymphocytic leukemia. *Methods Mol Biol*. 2011;730:119-130.
17. Nguyen-Khac F, Borie C, Callet-Bauchu E, Eclache V, Struski S. Cytogenetics in the management of chronic lymphocytic leukemia: an update by the Groupe francophone de cytogenetique hematologique (GFCH). *Ann Biol Clin (Paris)*. 2016;74(5):561-567.
18. Thompson PA, O'Brien SM, Wierda WG, et al. Complex karyotype is a stronger predictor than del(17p) for an inferior outcome in relapsed or refractory chronic lymphocytic leukemia patients treated with ibrutinib-based regimens. *Cancer*. 2015;121(20):3612-3621.
19. Baliakas P, Iskas M, Gardiner A, et al. Chromosomal translocations and karyotype complexity in chronic lymphocytic leukemia: a systematic reappraisal of classic cytogenetic data. *Am J Hematol*. 2014;89(3):249-255.
20. Baliakas P, Jeromin S, Iskas M, et al. Cytogenetic complexity in chronic lymphocytic leukemia: definitions, associations, and clinical impact. *Blood*. 2019;133(11):1205-1216.
21. Castillo JJ, Advani RH, Branagan AR, et al. Consensus treatment recommendations from the tenth International Workshop for Waldenstrom Macroglobulinaemia. *Lancet Haematol*. 2020;7(11):e827-e837.
22. Damm F, Mylonas E, Cosson A, et al. Acquired initiating mutations in early hematopoietic cells of CLL patients. *Cancer Discov*. 2014;4(9):1088-1101.

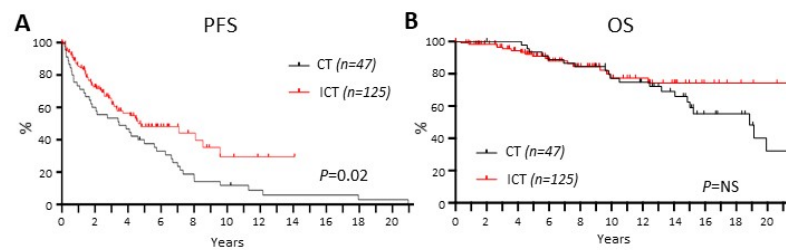
23. Lenz G, Davis RE, Ngo VN, et al. Oncogenic CARD11 mutations in human diffuse large B cell lymphoma. *Science*. 2008;319(5870):1676-1679.
24. Mansouri L, Sutton LA, Ljungstrom V, et al. Functional loss of IkappaBepsilon leads to NF-kappaB deregulation in aggressive chronic lymphocytic leukemia. *J Exp Med*. 2015;212(6):833-843.
25. Morin RD, Johnson NA, Severson TM, et al. Somatic mutations altering EZH2 (Tyr641) in follicular and diffuse large B-cell lymphomas of germinal-center origin. *Nat Genet*. 2010;42(2):181-185.
26. Davis RE, Ngo VN, Lenz G, et al. Chronic active B-cell-receptor signalling in diffuse large B-cell lymphoma. *Nature*. 2010;463(7277):88-92.
27. Gonzalez-Aguilar A, Idbaih A, Boisselier B, et al. Recurrent mutations of MYD88 and TBL1XR1 in primary central nervous system lymphomas. *Clin Cancer Res*. 2012;18(19):5203-5211.
28. Landau DA, Tausch E, Taylor-Weiner AN, et al. Mutations driving CLL and their evolution in progression and relapse. *Nature*. 2015;526(7574):525-530.
29. Treon SP, Tripsas CK, Meid K, et al. Ibrutinib in previously treated Waldenstrom's macroglobulinemia. *N Engl J Med*. 2015;372(15):1430-1440.
30. Treon SP, Meid K, Gustine J, et al. Long-Term Follow-Up of Ibrutinib Monotherapy in Symptomatic, Previously Treated Patients With Waldenstrom Macroglobulinemia. *J Clin Oncol*. 2021;39(6):565-575.
31. Dimopoulos MA, Trotman J, Tedeschi A, et al. Ibrutinib for patients with rituximab-refractory Waldenstrom's macroglobulinaemia (iNNOVATE): an open-label substudy of an international, multicentre, phase 3 trial. *Lancet Oncol*. 2017;18(2):241-250.
32. Dimopoulos MA, Tedeschi A, Trotman J, et al. Phase 3 Trial of Ibrutinib plus Rituximab in Waldenstrom's Macroglobulinemia. *N Engl J Med*. 2018;378(25):2399-2410.
33. Tomowiak C, Poulain S, Herbaux C, et al. Obinutuzumab and idelalisib in symptomatic patients with relapsed/refractory Waldenstrom macroglobulinemia. *Blood Adv*. 2021;5(9):2438-2446.
34. Laribi K, Poulain S, Willems L, et al. Bendamustine plus rituximab in newly-diagnosed Waldenstrom macroglobulinaemia patients. A study on behalf of the French Innovative Leukaemia Organization (FILO). *Br J Haematol*. 2019;186(1):146-149.
35. Ocio EM, Schop RF, Gonzalez B, et al. 6q deletion in Waldenstrom macroglobulinemia is associated with features of adverse prognosis. *Br J Haematol*. 2007;136(1):80-86.
36. Chang H, Qi C, Trieu Y, et al. Prognostic relevance of 6q deletion in Waldenstrom's macroglobulinemia: a multicenter study. *Clin Lymphoma Myeloma*. 2009;9(1):36-38.
37. Garcia-Sanz R, Dogliotti I, Zaccaria GM, et al. 6q deletion in Waldenstrom macroglobulinaemia negatively affects time to transformation and survival. *Br J Haematol*. 2021;192(5):843-852.
38. Guerrera ML, Tsakmaklis N, Xu L, et al. MYD88 mutated and wild-type Waldenstrom's Macroglobulinemia: characterization of chromosome 6q gene losses and their mutual exclusivity with mutations in CXCR4. *Haematologica*. 2018;103(9):e408-e411.
39. Wang Y, Gali VL, Xu-Monette ZY, et al. Molecular and genetic biomarkers implemented from next-generation sequencing provide treatment insights in clinical practice for Waldenstrom macroglobulinemia. *Neoplasia*. 2021;23(4):361-374.
40. Gustine JN, Xu L, Tsakmaklis N, et al. CXCR4 (S338X) clonality is an important determinant of ibrutinib outcomes in patients with Waldenstrom macroglobulinemia. *Blood Adv*. 2019;3(19):2800-2803.

41. Castillo JJ, Xu L, Gustine JN, et al. CXCR4 mutation subtypes impact response and survival outcomes in patients with Waldenström macroglobulinaemia treated with ibrutinib. *Br J Haematol.* 2019;187(3):356-363.

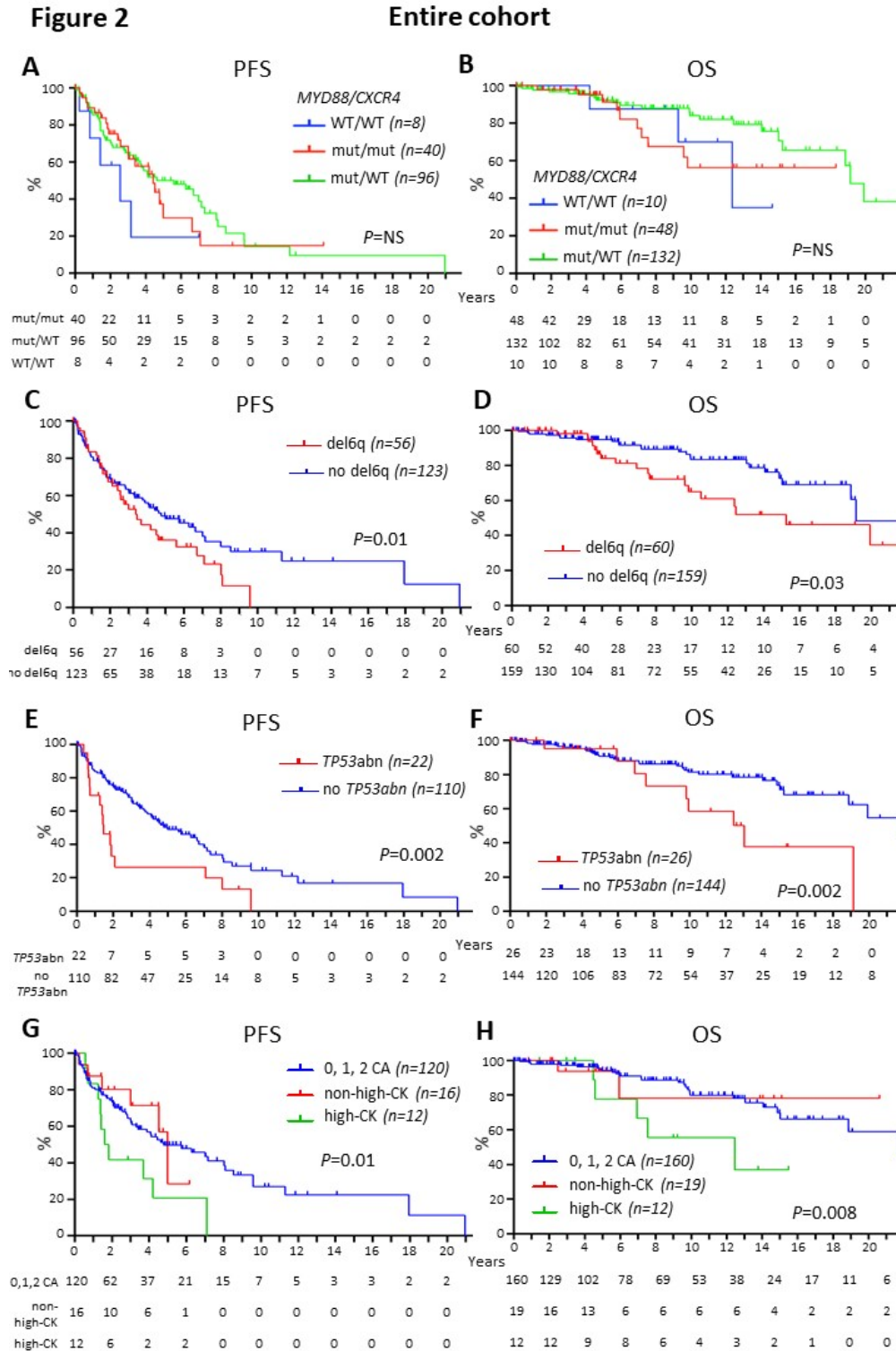
### Figures legends

**Figure 1.** Mutational and cytogenetic analyses of Waldenström macroglobulinemia (WM) samples by chromosome banding analysis (CBA), FISH and/or targeted sequencing. Each column represents a patient sample and each row a mutated gene (italic) or cytogenetic abnormality. The percentage of each mutated gene or cytogenetic abnormality in the whole cohort are indicated on the right of the grid. Complex karyotypes (CK) are represented at the top for highly CK (high-CK) and non-high-CK in respective dark blue and light blue. Colored box: presence; white box: absence; light grey box: not available.

**Supplemental Figure S1**

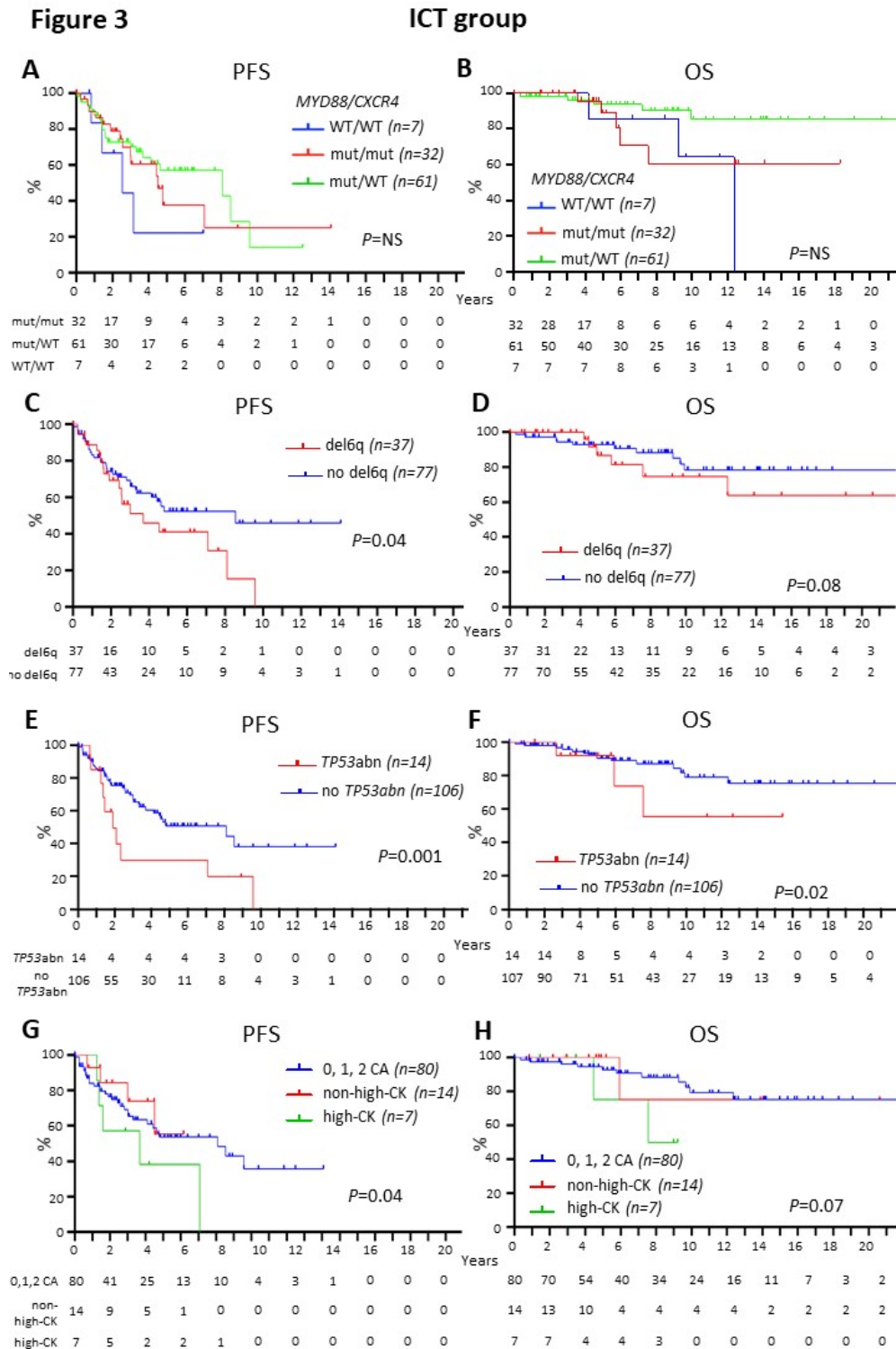


**Figure 2.** Respective progression free-survival (PFS) and overall survival (OS) for the following recurrent molecular/cytogenetic abnormalities in the entire cohort: *MYD88/CXCR4* status (A, B), del6q (C, D), *TP53*abn (E, F), non-high-CK and high-CK (I, J). Abbreviations: abn, abnormalities; CA, cytogenetic abnormalities; high-CK, highly complex karyotype; mut, mutated; WT, wild-type.





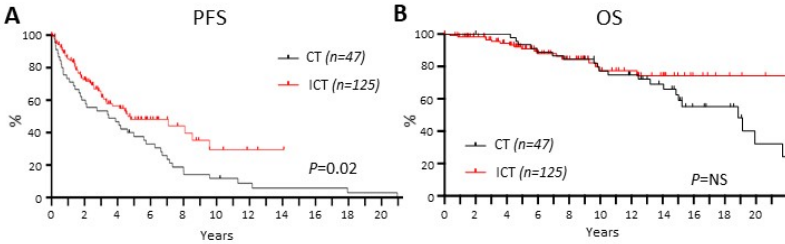
**Figure 3.** Respective progression free-survival (PFS) and overall survival (OS) for the following recurrent molecular/cytogenetic abnormalities in patients who received first-line immunochemotherapy (ICT): *MYD88/CXCR4* status (A, B), del6q (C, D), *TP53*abn (E, F), non-high-CK and high-CK (I, J). Abbreviations: abn, abnormalities; CA, cytogenetic abnormalities; high-CK, highly complex karyotype; mut, mutated; WT, wild-type.



**Supplemental Figures legends**

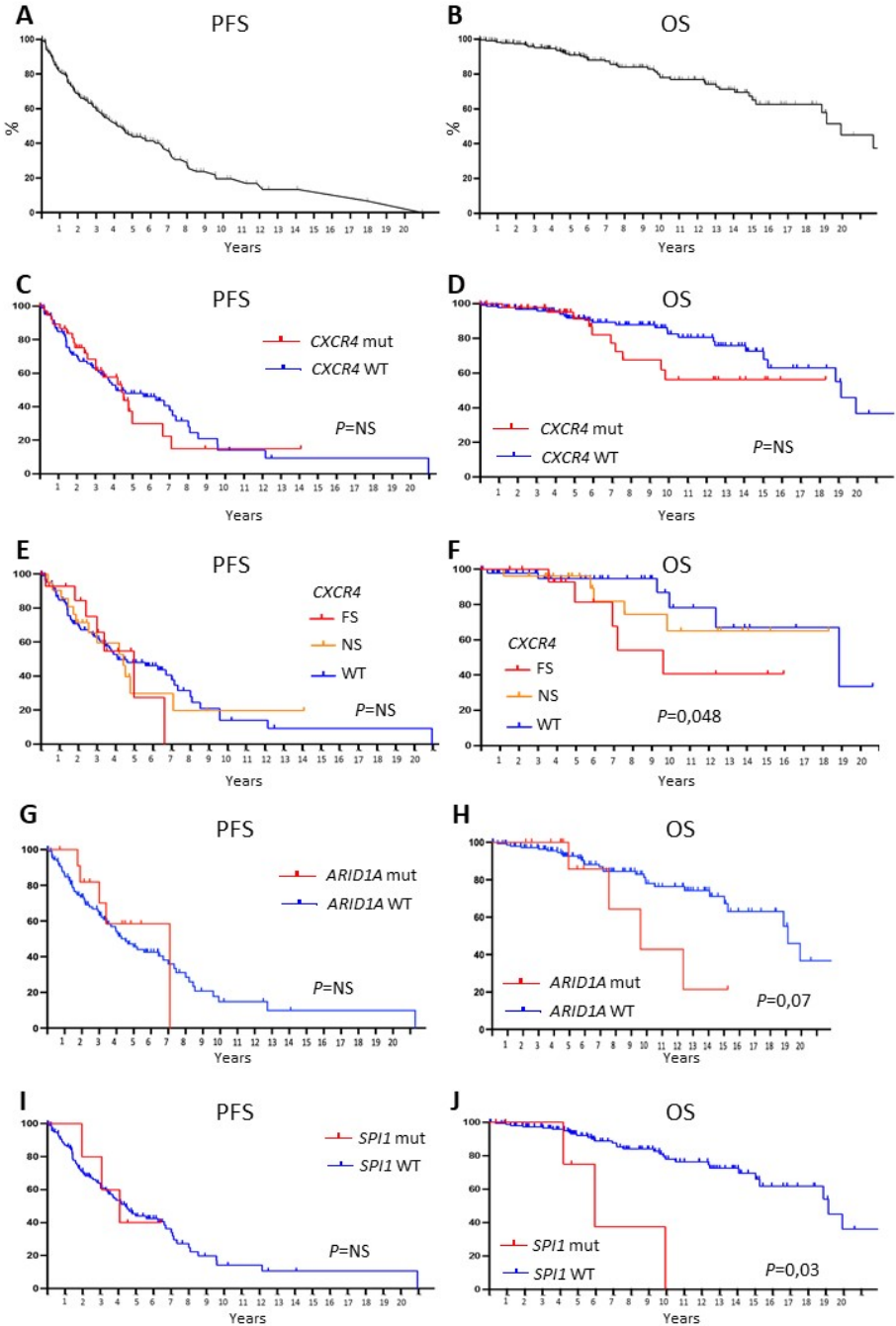
**Figure S1.** Progression free-survival (PFS) (A) and overall survival (OS) (B) of WM patients who received either 1L chemotherapy (CT, n=47) or immunochemotherapy (ICT, n=125).

**Supplemental Figure S1**

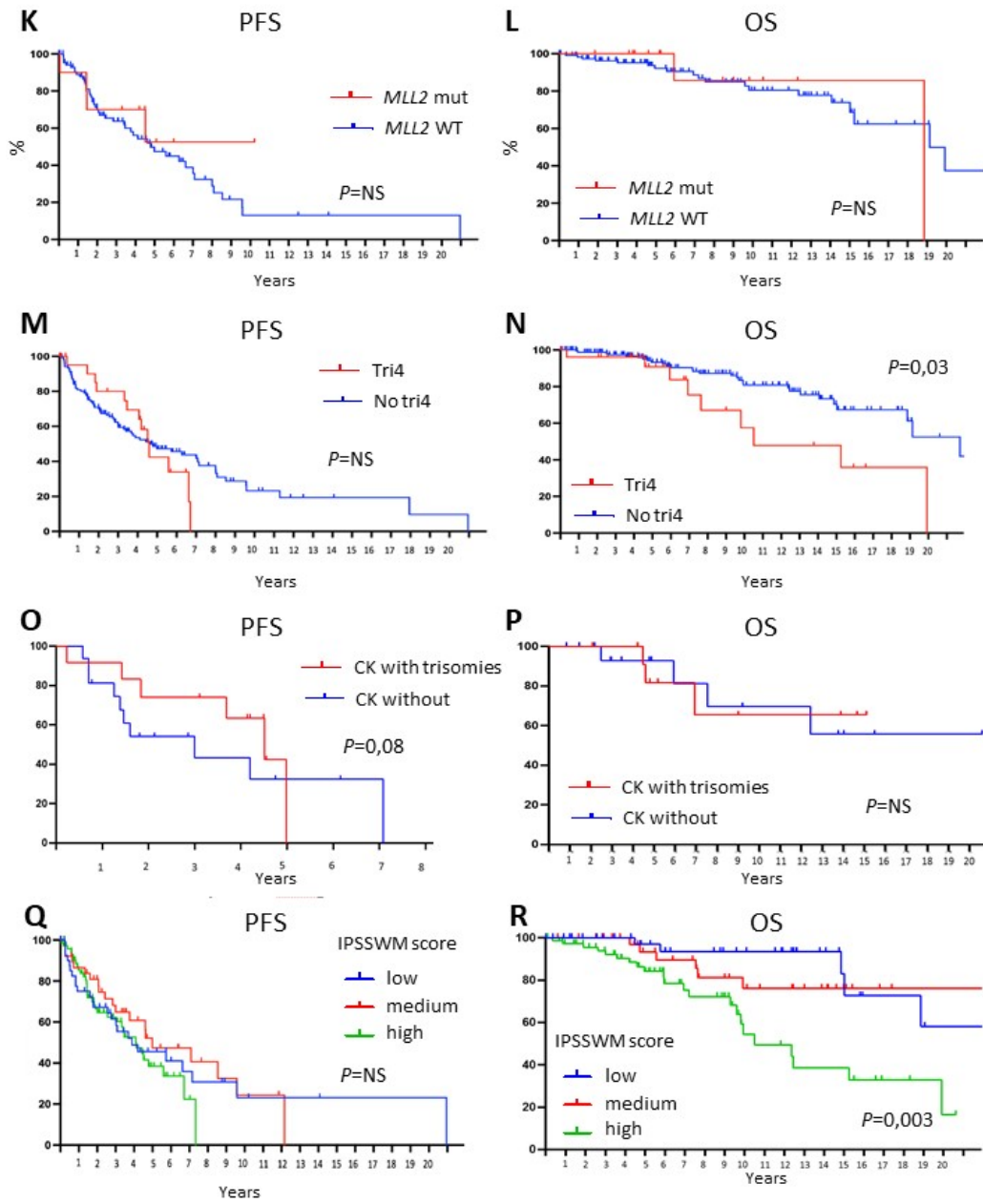


**Figure S2.** Progression free-survival (PFS) (A) and overall survival (OS) (B) of the whole WM cohort and respective PFS/OS for the following recurrent molecular/cytogenetic abnormalities: *CXCR4* mutated vs. WT (C, D), *CXCR4* WT vs. nonsense (NS) vs. frameshift (FS) mutations (E,F), *ARID1A* (G,H), *SPI1* (I,J), *MLL2* (K,L), tri4 (M,N), CK with/without trisomies (O,P) and IPSSWM (Q,R).

**Supplemental Figure S2**



Supplemental Figure S2



## Tables

<b>Table 1.</b> Main characteristics of the whole WM cohort		
	<b>n (%)</b>	
Total	239 (100)	
<b>Median age at WM diagnosis, years (range)</b>		65 (28-88)
<b>Sex, male</b>	155/239 (63)	
<b>Clinical and biological parameters at evaluation</b>		
Adenopathy $\geq$ 1,5 cm	57/230 (25)	
Splenomegaly	32/230 (14)	
Hemoglobin, mean in g/dL (range)		11.5 (4.2-16.3)
Hemoglobin < 11,5 g/dL	114/233 (49)	
Platelets, mean (G/L)		242 (26-630)
Platelets < 100 G/L, yes (%)	78/229 (34)	
IgM, mean in g/L (range)		18 (2-78)
Isotype, kappa	184/232 (80)	
Bone marrow infiltration, mean in % (range)		44 (10-100)
<b>Requiring first-line therapy</b>	187/239 (78)	
<b>IPSSWM</b>		
Low	43/156 (27)	
Intermediate	39/156 (25)	
High	74/156 (48)	
<b>Type of first-line therapies</b>		
Alkylating agents	47/187 (25)	
Immunochemotherapy (ICT)	125/187 (68)	
Anti-CD20 monotherapy	14/187 (7)	
Other	1/187 (1)	
<b>Cytogenetic abnormalities by CBA and/or FISH</b>		
del6q	60/219 (27)	
tri4	27/219 (12)	
del13q	25/219 (11)	
tri18	25/219 (11)	
tri12	17/219 (8)	
del17p	16/219 (7)	
del11q	11/219 (5)	
complex karyotype (CK)	31/219 (14)	
highly CK (high-CK)	12/219 (5)	
missing data	20/239 (8.5)	
<b>Mutations</b>		
<i>MYD88</i>	186/199 (93)	
L265P mutation	181/186 (97)	
Other <i>MYD88</i> mutations	5/186 (3)	
<i>CXCR4</i>	48/168 (29)	
S338	27 (55)	
Other	21 (45)	
<b>TP53 abnormalities (del17p/TP53 mutation)</b>	26/170 (15)	
Abbreviations: CBA, chromosome banding analysis; IPSS, international prognostic scoring system; WM, Waldenström macroglobulinemia		

	PFS						OS					
	Univariate (n=187)			Multivariate* (n=121)			Univariate (n=239)			Multivariate* (n=136)		
	HR	IC 95%	P	HR	IC 95%	P	HR	IC 95%	P	HR	IC 95%	P
<b>B2M</b>	-	-	NS	-	-	NS	-	-	NS	-	-	NS
<b>IPSSWM</b>	-	-	NS	-	-	NS	3.70	1.47-9.10	0.002	3.06	1.26-5.96	0.03
<b>Del6q</b>	2.24	1.17-4.29	0.01	-	-	NS	2.02	1.07-3.83	0.027	-	-	NS
<b>Tri4</b>	-	-	NS	-	-	NS	2.38	1.08-5.22	0.026	-	-	NS
<b>CK</b>	-	-	NS	-	-	NS	-	-	NS	-	-	NS
<b>High-CK</b>	3.29	1.23-8.79	0.01	-	-	NS	3.44	1.30-9.10	0.01	-	-	NS
<b>TP53 abn</b>	3.19	1.48-6.85	0.002	2.9	1.08-5.33	0.03	2.95	1.43-6.07	0.002	2.41	1.19-4.83	0.04
<b>CXCR4 FS mutations</b>	-	-	NS	-	-	NS	2.56	1.00-6.66	0.047	-	-	NS
<b>SPI1 mutations</b>	-	-	NS	-	-	NS	4.10	1.01-12.4	0.037	-	-	NS

\*For multivariable analyses, we considered only variables that were significant (P ≤ 0.05) in univariate analyses and cases with available data for all the factors included in the model.

Abbreviations : B2M, beta2microglobulin; CI, confidence interval; CK, complex karyotype; high-CK, highly CK; HR, hazard ratio; IPSSWM, international prognostic scoring system for Waldenström macroglobulinemia; NS, non significant; PFS, progression-free survival; OS, overall survival.



**Supplemental Table S1.** List of targeted genes and genomic coordinates

<b>Gene</b>	<b>RefSeq sequences (coding transcripts)</b>	<b>Chromosomal region</b>	<b>Targeted exons</b>
<i>CARD11</i>	NM_032415	7p22.2	exon 4-9
<i>CD79A</i>	NM_001783	19q13.2	exon 4-5
<i>CD79B</i>	NM_000626	17q23.3	exon 5-6
<i>MYD88</i>	NM_002468	3p22	all
<i>TP53</i>	NM_001126112	17p12	exon 2-11
<i>CXCR4</i>	NM_003467	2q21	all
<i>SPI1</i>	NM_003120	11p11.2	all
<i>TNFAIP3</i>	NM_001270508	6q23.3	all
<i>PRDM1</i>	NM_001198	6q21	all
<i>EZH2</i>	NM_004456	7q36.1	all
<i>MLL2</i>	NM_003482	12q13.12	all
<i>ARID1A</i>	NM_006015	1p36.11	all
<i>IKZF3</i>	NM_012481	17q12	exon 5
<i>NOTCH2</i>	NM_024408	1p12	exon 34
<i>KLF2</i>	NM_016270	19p13.11	all
<i>NFKBIE</i>	NM_004556	6p21.1	all
<i>HIST1H1E</i>	NM_005321	6p22.2	all
<i>CREBBP</i>	NM_004380	16p13.3	exon 23-27
<i>TBL1XR1</i>	NM_001321193	3q26.32	all
<i>ETV6</i>	NM_001987	12p13.2	all
<i>IRF4</i>	NM_002460	6p25.3	exon 2-3



**Supplemental Table S2.** Different indications of therapy

Type of indications	Number (%)
Symptoms related to BM involvement	119 (64)
Anemia	101 (54)
Thrombopenia	18 (10)
Bulky extramedullary disease	33 (18)
Symptomatic hyperviscosity	14 (7)
Bing-Neel syndrome	4 (2)
Other IgM related complications (cryoglobulinemia, amyloidosis, acquired vWF disease, neuropathy)	17 (9)
Total	187 (100)

**Supplemental Table S3.** Details regarding different types of first-line therapies

	<b>Number of patients</b>
<b>Chemotherapy</b>	<b>47</b>
Chlorambucil	34
Fludarabine	10
Cyclophosphamide	1
CHOP	1
Fludarabine-Cyclophosphamide	1
<b>Immunochemotherapy</b>	<b>125</b>
Dexamethasone-Rituximab-Cyclophosphamide (DRC)	61
Dexamethasone-Rituximab-Cyclophosphamide (DRC) + Bortezomib	2
Fludarabine-Rituximab (FR)	13
Fludarabine-Cyclophosphamide-Rituximab (FCR)	10
Bendamustine-Rituximab (BR)	36
Rituximab-Chlorambucil	1
Rituximab-miniCHOP	1
Bortezomib-Dexamethasone-Rituximab (BDR)	1
<b>Rituximab monotherapy</b>	<b>14</b>
<b>Other</b> (bortezomib/dexamethasone)	<b>1</b>

**Supplemental Table S4.** Causes of death (n=49)

Type of cause	Number (%)
WM progression	24 (49)
Transformed WM	4 (8)
Therapy-related toxicity	12 (24)
Other	6 (12)
Unknown	3 (7)
Total	49 (100)



Supplemental Table S6. Details of non-highly complex karyotypes (non-high CK) and high-CK.

Patient	Karyotype according to ISCN 2020
Non-high CK	1 46,XY,t(6;6)(q12;q2?6),del(11)(q14)[2]/46,XY,del(6)(q12),del(11)(q14)[2]/46,XY[16]
	2 46,X,-X,+4[2]/47,sl,+18[2]/46,XX[16]
	3 48,XY,+12,+18[2]/48,sl,+3,-12[1]/46,XY[17]
	4 46,XY,del(6)(q12)[1]/46,sl,-Y,+9[19]
	5 47,X,-X,+4,+18[11]/46,XX[9]
	6 49,XY,+4,+15,+18[11]/46,XY[9]
	7 48,XX,+3,+12[1]/48,XX,+12,+18[1]/46,XX[10]
	8 46,XY[19]/50,XY,del(6q),+4,+8,+10,+12 [1]
	9 45,X,-Y,del(6)(q12),del(7)(q22q3?5)[3]/46,XY[17]
	10 45,X,-Y,-6,add(15)(q?26),+mar[cp2]/46,XY[18]
	11 47,XY,del(9)(p12),t(18;21)(q23;q21),+19[cp15]/46,XY[5]
	12 94,XXYY,der(6)t(3;6)(q11;q11)x2,+18,+18[3]/92,XXYY[1]/46,XY[16]
	13 46,XX,del(6)(q1?4q24),?der(16)[1]/46,XX,add(11)(q11)[1]/46,XX[18]
	14 48,XX,+4,del(9)(q2?1q?31),+12[3]/48,sl,dup(17)(q12q2?5)[10]/46,XX[7]
	15 45,X,-X[2]/45,sl,der(11)t(8;11)(q?22;q?22)[13]/46,sl,+12[4]/47,sd1,+18[1]
	16 46,XY,del(6)(q?21q?24)[2]/46,idem,der(22)t(1;22)(q1?1;p1?3)[2]/46,XY,del(20)(q11)[6]/46,XY [10]
	17 46,XY,del(6)(q11)[13]/45,sl,-4,der(17)t(4;17)(p11;q11),der(22)t(4;22)(q12;q13)[3]/46,XY[4]
	18 47,XX,+3[2]/48,sl,+12[2]/46,XX,der(8)t(3;8)(q?12;p?12),t(14;19)(q1?1;p12)[13]/46,XX[3]
	19 46,XY,t(3;11)[3pter->3p10::11p1?4->11pter;11p1?4->11q2?5::3q21->3qter],del(6)(q?16q2?4)[13]/47,XY,+4[1]/46,XY[6]
High-CK	20 46,XX,der(1)t(1;11)(q?21;p1?2),der(11)t(1;11)(q?21;p1?2)t(11;18)(q22;q2?2),der(18)t(11;18)(q22;q2?2)[cp11]/46,XX[2]
	21 46,XY,?der(4)t(4;6;7),der(6)t(4;6)(?q;q22),del(6)(q24),der(7)t(4;7;?10),der(10)[13]/46,XX[7]
	22 46,XY,+4,del(6)(q21q2?4),i(8)(q10),-13,der(20)t(13;20)(q3?1;q13)[17]/46,XY[3]
	23 47,XY,t(1;9)(p34;p24),t(3;15)(p26;q21),+4,del(6)(q1?5q2?2),del(13)(q14q31)[cp2]/46,XY[18]
	24 44,X,-Y,add(2)(p2?4),ins(4;8)(q?;?q),del(6)(q16;q24),-8,der(12)del(12)(p11)del(12)(q11), der(13)t(12;13)(q12;q1?3),add(17)(p12),-20,+mar1[cp3]/44,idem,-11,add(12)(p13),+mar2[cp5]/ 43,idem,-11,add(18)(q2?1)[cp4]
	25 45,XY,del(6)(q1?3),add(12)(q2?4),-14,add(17)(p1?2),?der(18)[cp8]/ 45,XY,del(3)(p?21),add(5)(p1?4),del(6)(q1?3),-14,add(17)(p1?2)[cp3]/46,XY[9]
	26 46,XY,del(17)(p11)[10]/45,sl,del(6)(q2?1q2?3),-16[3]/46,sl,+mar[4]/46,XY,del(13)(q1?3q2?1)[2]/46,XY[1]
	27 46,XY,add(8)(q24),del(12)(p1?2)[4]/49,sl,+4,+7,+9,add(22)(q?12)[10]/46,XY[6]
	28 45,X,-X,der(3)t(3;6)(p11;p11)x2,-6,der(11)t(3;11)(?;q22)[2]/45,idem,t(1;15)(q4?3;q1?2)[4] /46,XX[14]
	29 45,Y,add(X)(q28),add(2)(p1?2),der(?2),der(6)t(2;6)(q11;q11),-10,der(11)t(11;10)(q22;q21)[4]/46,sl,-add(X), add(17)(q2?5),-21,+mar[1]/46,XY[15]
	30 46,XX,del(2)(p?16),del(6)(q2?2),-8,der(12),add(17)(p12),add(17)(p1?2),+mar[cp4]/46,XX[16]
	31 81-84,XXYY,-1,-1,der(3)t(3;3)(p26;q2?2)x2,der(6)t(6;7)(q11;q11)x2,-7,-7,-8,-9,-10,-11, der(12)t(1;12)(q1?2;q?11),-13,-14,-14,-15,-17,+3~4mar,+?r[cp3]/45,X,-Y[3]/46,XY[14]



**Supplemental Tables S8.** Cytogenetic and mutational characteristics of non-highly-complex karyotype (non-high-CK) and highly CK (high-CK). ns, non significant

CBA +/- FISH	Non-high-CK	High-CK	P value
<b>6q deletion</b>			
Yes	9/19 (47%)	11/12 (92%)	<b>0,0201 (*)</b>
No	10/19 (53%)	1/12 (8%)	
<b>11q deletion</b>			
Yes	3/19 (16%)	3/12 (25%)	0,65 (ns)
No	16/19 (84%)	9/12 (75%)	
<b>13q deletion</b>			
Yes	2/19 (10%)	6/12 (50%)	<b>0,0316 (*)</b>
No	17/19 (90%)	6/12 (50%)	
<b>17p deletion</b>			
Yes	1/19 (5%)	5/12 (42%)	<b>0,0217 (*)</b>
No	18/19 (95%)	7/12 (58%)	
<b>Trisomy 12</b>			
Yes	5/19 (26%)	1/12 (8%)	0,363 (ns)
No	14/19 (74%)	11/12 (92%)	
<b>Trisomy 4</b>			
Yes	5/19 (26%)	4/12 (33%)	0,7039 (ns)
No	14/19 (74%)	8/12 (67%)	
<b>Trisomy 18</b>			
Yes	6/19 (32%)	1/12 (8%)	0,2015 (ns)
No	13/19 (68%)	11/12 (92%)	
<b>Trisomy 3</b>			
Yes	3/19 (16%)	3/12 (25%)	0,6526 (ns)
No	16/19 (84%)	9/12 (75%)	

Mutations	Non-high-CK	High-CK	P value
<b>MYD88</b>			
Yes	17/18 (94%)	11/11 (100%)	> 0,9999 (ns)
No	1/18 (6%)	0/11 (0%)	
<b>CXCR4</b>			
Yes	8/18 (44%)	3/11 (27%)	0,4486 (ns)
No	10/18 (56%)	8/11 (73%)	
<b>ARID1A</b>			
Yes	2/16 (13%)	1/11 (9%)	> 0,9999 (ns)
No	14/16 (87%)	10/11 (91%)	
<b>TP53</b>			
Yes	1/16 (6%)	3/11 (27%)	0,2729 (ns)
No	15/16 (94%)	8/11 (73%)	
<b>MLL2</b>			
Yes	3/13 (23%)	1/8 (13%)	> 0,9999 (ns)
No	10/13 (77%)	7/8 (87%)	
<b>TBL1RX1</b>			
Yes	1/13 (8%)	0/8 (0%)	> 0,9999 (ns)
No	12/13 (92%)	8/8 (100%)	
<b>SPI1</b>			
Yes	1/16 (6%)	0/11 (0%)	> 0,9999 (ns)
No	15/16 (94%)	11/11 (100%)	
<b>CD79B</b>			
Yes	0/16 (0%)	1/11 (9%)	0,4074 (ns)
No	16/16 (100%)	10/11 (91%)	

**Supplemental Table S8.** Correlations between disease phenotype and mutational/cytogenetic abnormalities. Cells in yellow, orange, red correspond to respective  $P \leq 0.05$ ,  $P \leq 0.01$ ,  $P \leq 0.001$ . Correlations were non significant or non applicable/relevant in respective dark grey and black cells. NS, non significant.

Disease phenotype	Mutational/cytogenetic alterations												
	<i>MYD88</i>	<i>CXCR4</i>	<i>ARID1A</i>	<i>MLL2</i>	<i>CD79A/B</i>	<i>TBL1XR1</i>	<i>SPI1</i>	del6q	tri18	tri4	CK	high-CK	<i>TP53abn</i>
Lymphadenopathy	NS	NS	NS	NS	NS	NS	3,32E-02	NS	NS	NS	NS	NS	2,24E-02
Splenomegaly	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Serum IgM level	NS	4,90E-02	NS	NS	NS	7,50E-04	NS	NS	NS	NS	NS	NS	NS
BM infiltration	NS	1,60E-02	NS	NS	NS	NS	NS	1,00E-03	NS	8,03E-03	2,70E-03	3,04E-03	NS
Hemoglobin < 10,5 g/dL	NS	NS	NS	NS	NS	NS	NS	5,00E-05	NS	3,40E-03	7,30E-03	3,70E-02	NS
Platelet count < 100 G/L	NS	2,00E-04	NS	NS	NS	NS	NS	NS	NS	5,20E-03	NS	NS	NS
Hyperviscosity syndrome	NS	4,02E-02	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
IPSSWM score	NS	NS	NS	NS	NS	NA	NA	NS	NS	NS	NS	NS	NS

BM, bone marrow; CK, complex karyotype; high-CK, highly CK; NA, not applicable (too few cases)



**Supplemental Table S10.** Univariate analyses of variables associated with time to first treatment (TFT) (n=239) and relapse (n=101).

	Time to first treatment		
	HR	IC 95%	P
B2M	2.27	1.11-4.6	0.02
IPSSWM	-	-	NS
Del6q	2.01	0.90-2.57	0.08
Trisomy 12	1.98	0.91-2.42	0.07
CK	-	-	NS
High-CK	-	-	NS
TP53 abn	-	-	NS
CXCR4 mutations	-	-	NS

As only one variable was significant in univariate analysis, multivariate analysis was not performed.

Abbreviations : B2M, beta2microglobulin; CI, confidence interval; CK, complex karyotype; high-CK, highly CK; HR, hazard ratio; IPSSWM, international prognostic scoring system for Waldenström macroglobulinemia; NS, non significant

	Relapse		
	HR	IC 95%	P
B2M	-	-	NS
IPSSWM	-	-	NS
Del6q	2.02	1.09-3.73	0.02
Tri4	-	-	NS
CK	-	-	NS
High-CK	3.09	1.57-8.02	0.01
TP53 abn	3.52	1.49-7.87	0.002
CXCR4 FS mutations	-	-	NS
SPI1 mutations	-	-	NS

Abbreviations : B2M, beta2microglobulin; CI, confidence interval; CK, complex karyotype; high-CK, highly CK;

**Supplemental Table S11.** Repartition of cytogenetic and molecular abnormalities according to chemotherapy (CT, n=47) and immunochemotherapy (ICT, n=125) groups of treatment

Mutations	CT	ICT	P value
<b>MYD88</b>			
Yes	33/33 (100)	97/105 (92)	0,1
No	0/33 (0)	8/105 (8)	
<b>CXCR4</b>			
Yes	7/33 (21)	32/100 (32)	0,238
No	26/33 (79)	68/100 (68)	
<b>ARID1A</b>			
Yes	2/33 (6)	10/86 (12)	0,37
No	31/33 (94)	76/86 (88)	
<b>TP53</b>			
Yes	4/33 (12)	6/86 (7)	0,365
No	29/33 (88)	80/86 (93)	
<b>MLL2</b>			
Yes	1/23 (4)	8/69 (12)	0,31
No	22/23 (96)	61/69 (88)	
<b>TBL1RX1</b>			
Yes	1/23 (4)	2/69 (3)	0,74
No	22/23 (96)	67/69 (97)	
<b>SPI1</b>			
Yes	2/33 (6)	3/86 (3)	0,9
No	31/33 (93)	83/86 (97)	
<b>CD79B</b>			
Yes	2/33 (6)	5/86 (6)	0,96
No	31/33 (88)	81/86 (94)	
<b>TP53 abnormalities</b>			
Yes	6/46 (13)	14/122 (11)	0,78
No	40/46 (87)	108/122 (89)	

CBA +/- FISH	CT	ICT	P value
<b>6q deletion</b>			
Yes	17/44 (39)	37/114 (32)	0,1
No	27/44 (61)	77/114 (68)	
<b>13q deletion</b>			
Yes	9/44 (20)	14/113 (12)	0,2
No	35/44 (80)	99/113 (88)	
<b>17p deletion</b>			
Yes	4/43 (9)	9/114 (8)	0,78
No	39/43(91)	105/114 (92)	
<b>Trisomy 4</b>			
Yes	8/41 (19)	14/107 (13)	0,1
No	33/41 (81)	93/107 (87)	
<b>Trisomy 18</b>			
Yes	5/41 (12)	10/114 (9)	0,53
No	36/41 (88)	104/114 (91)	
<b>Complex karyotype</b>			
Yes	7/34 (20)	20/111 (18)	0,3
No	27/34 (80)	81/111 (82)	

**Supplemental Table S12.** Uni- and multivariate analyses of variables associated with PFS and OS in ICT group (n=125).

	PFS						OS					
	Univariate (n=125)			Multivariate* (n=91)			Univariate (n=125)			Multivariate* (n=88)		
	HR	IC 95%	P	HR	IC 95%	P	HR	IC 95%	P	HR	IC 95%	P
<b>B2M</b>	-	-	NS				-	-	NS			
<b>IPSSWM</b>	-	-	NS				3.11	1.15-5.10	0.002	2.74	1.09-4.44	0.02
<b>Del6q</b>	1.98	1.02-2.89	0.04	-	-	NS	-	-	NS			
<b>Tri4</b>	-	-	NS				-	-	NS			
<b>CK</b>	-	-	NS				-	-	NS			
<b>High-CK</b>	2.21	1.08-3.87	0.04	-	-	NS	-	-	NS			
<b>TP53 abn</b>	3.35	1.39-6.02	0.001	3.19	1.48-6.85	0.01	2.09	1.30-3.18	0.002	1.96	1.22-2.46	0.05
<b>CXCR4 FS mutations</b>	-	-	NS				-	-	NS			
<b>SPI1 mutations</b>	-	-	NS				-	-	NS			

\*For multivariable analyses, we considered only variables that were significant ( $P \leq 0.05$ ) in univariate analyses and cases with available data for all the factors included in the model.

Abbreviations : B2M, beta2microglobulin; CI, confidence interval; CK, complex karyotype; high-CK, highly CK; HR, hazard ratio; IPSSWM, international prognostic scoring system for Waldenström macroglobulinemia; NS, non significant; PFS, progression-free survival; OS, overall survival.

**Supplemental Table S13.** Cytogenetic and molecular data of WM samples from nine patients who experienced transformed WM.

Mutated genes	Number of karyotypic abnormalities	Karyotype
<i>MYD88, CXCR4, ARID1A, TP53, CD79B, EZH2</i>	15	44,X,-Y,add(2)(p2?4),ins(4;8)(q?;?q),del(6)(q16;q24),-8,der(12)del(12)(p11)del(12)(q11),der(13)t(12;13)(q12;q1?3),add(17)(p12),-20,+mar1[cp3]/44,idem,-11,add(12)(p13),+mar2[cp5]/ 43,idem,-11,add(18)(q2?1)[cp4]
<i>MYD88</i>	5	94,XXYY,der(6)t(3;6)(q11;q11)x2,+18,+18[3]/92,XXYY[1]/46,XY[16]
<i>MYD88, CXCR4, TP53</i>	2	49,XY,del(6)(q),+4,+8,+10,+12 [5]/46,XY[15]
<i>MYD88, CD79B, IKZF3</i>	2	45,X,-X,del(17)(p12)[19]
<i>MYD88, CXCR4, TP53, MLL2</i>	3	47,XY,del(9)(p12),t(18;21)(q23;q21),+19[15]/46,XY[5]
<i>MYD88, HIST1H1E</i>	22	81-84,XXYY,-1,-1,der(3)t(3;3)(p26;q2?2)x2,der(6)t(6;7)(q11;q11)x2,-7,-7,-8,-9,-10,-11,der(12)t(1;12)(q1?2;q?11),-13,-14,-14,-15,-17,+3~4mar,+?r[cp3]/45,X,-Y[3]/46,XY[14]
Not available	2	48,XY,+3,+18[2]/46,XY[18]
Not available	7	46,XX,del(2)(p?16),del(6)(q2?2),-8,der(12),add(17)(p12),add(17)(p1?2),+mar[cp4]/46,XX[16]
<i>MYD88</i>	5	46,XY,del(5)(q3?2),add(9)(p2?3)[3]/46,XY[17]