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Highly sensitive methods are required to detect mutations in histiocytoses

Histiocytoses are rare diseases involving any tissue or organ of adults or children, and with variable clinical presentation and prognosis.¹ They can be classified into five main groups.² Most histiocytoses in the L group [HL; this group includes Langerhans cell histiocytosis (LCH), Erdheim-Chester Disease (ECD), mixed histiocytosis, indeterminate cell histiocytosis, and extracutaneous juvenile xanthogranuloma with mutation of the MAPkinase pathway] have oncogenic mutations of *BRAF*,³⁻⁴ and the remaining cases often have mutations of other genes, also activating the MAPkinase cell signaling pathway.⁵⁻⁷

Treatment of histiocytoses with MAPkinase pathway inhibitors induces major tumor response.⁸⁻¹⁰ Vemurafenib (a selective *BRAF* inhibitor) has obtained orphan disease designation for treatment of LCH and ECD in Europe and has recently been approved by the FDA for the treatment of ECD with *BRAF* mutation. The detection of *BRAF* mutations is therefore a major issue for patients with HL such as ECD and LCH.

We previously reported that in some cases, one of the methods currently used for the detection of *BRAF* mutations in melanomas was responsible for false negative results, but that this problem can be corrected by using highly sensitive pico-droplet digital polymerase chain reaction (pddPCR).⁵ Indeed, pddPCR allows the detection of mutations with a variant allele frequency (VAF) as low as 0.01%.¹¹ However a low VAF in solid tumors or

leukemia usually corresponds to a subclone, and may not be relevant clinically.¹² We thus decided to investigate VAF and response to *BRAF* inhibitors in a large series of patients with histiocytosis.

All patients were included in the French Histiocytosis Registry approved by the Comité de Protection des Personnes Ile de France III (#2011-A00447-34). Selection criteria for the present study were: age at the time of diagnosis of at least 18 years, and histiocyte-infiltrated sample available for histology review and molecular analysis. Patients with histiocytoses in the C, R, M and H groups² were excluded (*Online Supplementary Figures S2 and S3*). Detection of somatic mutations was performed on DNA extracted from areas infiltrated with the highest percentage of histiocytes, using pyrosequencing or pddPCR as previously described.^{5,13} Both pyrosequencing and pddPCR are quantitative methods, however a pyrosequencing result is based on an average of two PCR, while each pddPCR is obtained from 4 to 5,000,000 PCR. Thus pddPCR is highly sensitive, and it provides absolute quantification when the sample is diluted. For this latter method, *BRAF* was considered as mutated when at least 3 droplets in the cluster were positive.¹¹ Cases without mutation were screened for other mutations of genes in the MAPkinase pathway by targeted NGS. Cases without any mutations were classified as either wild type (WT) for *BRAF*^{V600E} when at least 1,000 droplets were amplified, or as non-conclusive when the number of amplified droplets was lower. The sensitivity to targeted treatments was evaluated using the best metabolic response (MR) at 3 or 6 months. MR was

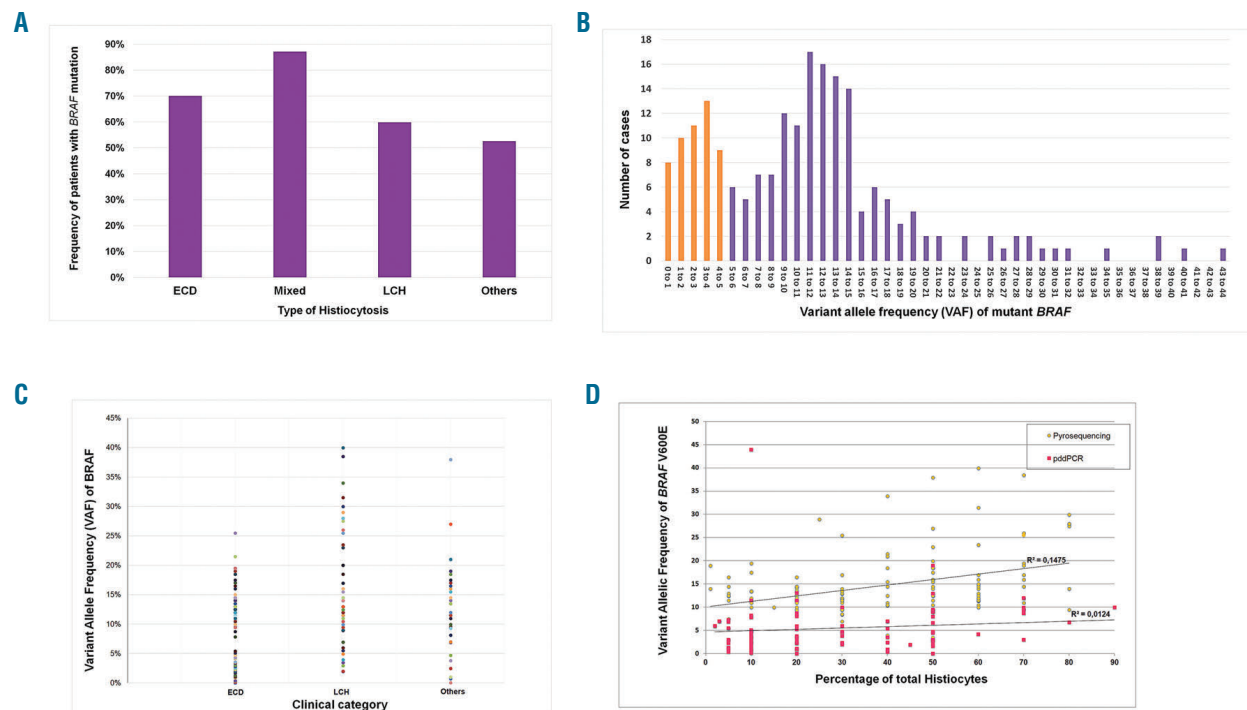


Figure 1. Variant allele frequencies of *BRAF* mutations in adult histiocytoses. (A) Frequencies of patients with *BRAF* mutations in the different types of histiocytoses. (B) Distribution of the histiocytoses according to their VAF. For instance, the numbers of cases with VAF 0 to 1%, 1 to 2% and 2 to 3% were 8, 10 and 11 respectively. (C) VAF values in the main types of histiocytoses. (D) Correlation of VAF with the percentage of histiocytes (i.e., all the histiocytes identified by histology among all cells present within the tissue). Whatever the method used, the correlation of VAF with the percentage of histiocytes was low: R2 was 0.15 and 0.01 in pyrosequencing and pddPCR respectively.

determined by [18F]fluorodeoxyglucose (FDG) positron emission tomography (PET) scan as previously described.⁸

We analyzed 577 tissue samples with histiocytosis infiltration, from 474 adult patients (flowchart, *Online Supplementary Figure S2*). Most (n=432) of the patients had HL, and the others were unclassified (*Online Supplementary Figure S3*). Among the 432 adult patients with HL, the median age at the time of diagnosis was 54.1 years (range 18.0 to 90.7 years), and the male/female ratio was 1.81 (270/150). The mutational status of 287 (66.4%) of the patients was identified (i.e., either *BRAF*^{V600E} mutation, another mutation in the MAPkinase pathway, or WT). In the 145 (33.6%) other cases, DNA obtained from infiltrated FFPE tissues could not be amplified (n=101), or no mutations were detected, but the amount or quality of DNA did not allow 1,000 amplicons to be obtained by pddPCR.

The frequency of mutations in the MAPkinase pathway in adults with HL was 70.4% (202/287). A *BRAF*^{V600E} mutation was detected in 177/287 (61.9%) patients. Another type of *BRAF* mutation or a mutation of another gene of the MAPkinase cell-signaling pathway were detected in 5/25 and 20/25 patients respectively. Among patients with HL, *BRAF*^{V600E} mutations were more frequent in mixed histiocytoses than in ECD and LCH (80.7%, 64.7%, and 57.0% respectively, $P < 0.05$, Chi² test) (Figure 1A).

Of the 577 samples, 135 were found by pyrosequencing to have a *BRAF*^{V600E} mutation. PddPCR analysis - which we had previously shown to have high sensitivity^{11,14} - was then run on 173 samples thought not to have the *BRAF*^{V600E} mutation. This detected mutations in 41 of them (23.6%) (*Online Supplementary Figure S4*). Thus, the use of a highly sensitive method is mandatory to reliably detect *BRAF*^{V600E} mutation in histiocytoses.

Median VAF was 11.0% (range 0.04 to 44.0%) in the 197 samples for which it was available. VAF in histiocytoses was thus obviously lower than the median VAF of 43.6% that we observed in melanomas over the same decade.¹⁴ Distribution of VAF in histiocytosis samples was bimodal (Figure 1B). Interestingly, VAF were lower than 5% and 2% in 49 (24.8%) and 16 (8.1%) of cases respectively. Most of the methods used to detect somatic mutations in FFPE samples of solid tumors, including NGS, do not routinely detect VAF as low as 5% or 2%, and are thus not appropriate to detect *BRAF*^{V600E} mutation in histiocytoses. This is an important message for non-specialized platforms, because of the risk of false negatives. We suspect that these methods can also fail to detect other mutations in such samples. Supporting this, in 54 samples of histiocytoses (children and adults) in which we detected mutations of *MAP2K1*, the median VAF was 7.5%, and 21/54 (38.9%) samples had a VAF <5% (J.F. Emile, MD, PhD, unpublished data, July 2018).

We then investigated the causes of the low VAF in histiocytoses. It was similar in ECD, LCH and unclassified histiocytoses (median 10.0%, 13.0% and 11.3% respectively) (Figure 1C). As VAF obviously depends on the respective amount of tumor and reactive cells within the analyzed tissues,¹⁴ we compared VAF with the evaluated percentage of histiocytes among all cell types (Figure 1D). Surprisingly, VAF was not correlated, which suggests that, at least in ECD, a variable and sometimes high proportion of histiocytes do not harbor the oncogenic mutation and are reactive stromal cells. This was confirmed by immunohistochemistry showing that the proportion of histiocytes stained with *BRAF*^{V600E}-specific antibody was very different in each biopsy (*Online Supplementary Figure*

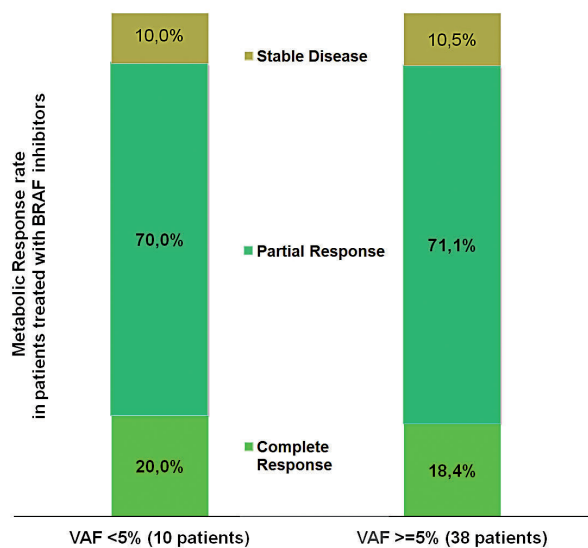


Figure 2. Best metabolic response to treatment with BRAF inhibitors at 3 or 6 months in patients, with either low (<5%) or high VAF.

S1). Alternatively, the histiocytes with *BRAF* mutation might be a subclone of the neoplasia.

Patients having ECD with *BRAF*^{V600E} mutation can benefit from treatment with BRAF inhibitors,⁸⁻¹⁰ and this treatment is now considered a standard of care in patients with life-threatening disease.^{1,15} The low VAF might be indicative of a subclone, and some oncologists suspect that patients with very low VAF will not respond to BRAF-targeted therapies. Among the 126 patients in our series with ECD or mixed histiocytosis and *BRAF*^{V600E} mutation, 48 were treated for at least 3 months with either vemurafenib or dabrafenib. We used the best metabolic response at 3 or 6 months of treatment to compare patients with low and high VAF (Figure 2). None of the patients had disease progression during treatment, and response rates were similar between patients with a VAF <5% and those with a higher VAF [90.0% (9/10) and 89.5% (34/38)] respectively. Thus, even in patients with low VAF the response rate to BRAF inhibitors was good. Furthermore there was no difference in the delay of response to targeted therapy. However, the first PET scan was performed at 3 months, and all but four patients were already responding to treatment at this time. The four patients whose best response occurred at 6 months had a VAF >5%.

In conclusion, we report that VAF is low in patients with histiocytosis, and is not related to percentage of histiocytes. We also show that low VAF does not impact on response to BRAF inhibitors. Therefore, highly sensitive methods are both necessary and appropriate to detect mutations in histiocytoses.

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