

## ARTICLE

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## Cellular and Molecular Biology

# Immune profiling of gastric adenocarcinomas in EU and LATAM countries identifies global differences in immune subgroups and microbiome influence

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**BACKGROUND:** Gastric cancer (GC) patients from European (EU) and especially Latin American (LATAM) countries are underrepresented in previous large-scale multi-omic studies that have identified clinically relevant subgroups. The LEGACY study aimed to profile the molecular and immunological features of GCs from EU and LATAM countries.

**METHODS:** Tumor biopsies from 95 EU and 56 LATAM GCs were profiled with immunohistochemistry (CD3, CD8, FOXP3, PD-L1, MSI and HER2), Nanostring mRNA expression analyses, and microbiome sequencing.

**RESULTS:** Immune profiling identified four distinct immune clusters: a T cell dominant cluster with enriched activation pathways, a macrophage dominant cluster and an immune excluded microenvironment which were equally distributed among the countries. A fourth cluster of mostly Mexican patients consisted of excessive T cell numbers accompanied by enhanced cytokine signaling in absence of enhanced antigen presentation and cytotoxicity signatures and a strong association with *H. pylori* infection.

**DISCUSSION:** Both EU and LATAM countries have GCs with a T cell inflamed microenvironment that might benefit from checkpoint inhibition. We identified a highly inflamed GC subgroup that lacked antigen presentation and cytotoxicity associated with *H. pylori* CagA-positive strains, suggesting their contribution to tumor immune tolerance. Future studies are needed to unravel whether these cancers benefit from immunotherapy as well.

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## INTRODUCTION

Gastric cancer (GC) is a deadly disease leading to 659,853 annual deaths worldwide in 2022 [1]. The incidence of this disease varies across the world, with the highest age-standardized rates in Asia, followed by Latin America (LATAM), the Caribbean, Europe, and being lowest in Africa [2]. Geographic diversity in GC is not fully understood but is likely associated with differences in the prevalence of risk factors such as persistent *Helicobacter pylori* infection, genetic predisposition, and lifestyle-related factors [3]. Recent data also point to a link between the microbiota and GC, but the extent to which the microbiota may explain GC geographic differences is unclear [4, 5].

Advanced stage GC has a poor prognosis with a 5-year survival of <5% in case of metastatic disease as systemic therapies are only

limited effective [6]. The standard of care for this setting includes chemotherapy with a fluoropyrimidine-platin doublet and, in case of HER2 overexpression additional trastuzumab, which improves median survival from 11 to 16 months [7, 8]. Immune checkpoint inhibitors (ICI) are a recent addition to chemotherapy for HER2-negative and HER2-positive disease and greater improvements in case of PD-L1 positivity [9–12]. Although ICI improves median overall survival from 11.4 months to 14.1 months in the CheckMate 649 study, responses vary greatly between patients, likely as a result of differences in anti-tumor immune activity [10]. In previous studies we have observed that the tumor immunity depends on molecular subtype. GCs with microsatellite instability (MSI) or positivity for the Epstein Barr Virus (EBV) are highly T cell inflamed which was shown to be associated with durable

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responses to ICI. Moreover, not only the T cell infiltrates but also the immune signaling impacts the response to ICI [13].

Besides molecular subtypes, geographic location is associated with specific immune features. Different transcriptome studies have shown that tumors from Asian patients contain fewer CD8 T cell markers compared to cancers from non-Asian countries [14]. Furthermore, GCs of patients from so-called Western countries (Australia, North-America and Western-Europe) had higher CD4+ and CD8+ T cell scores compared to GCs of patients from Asian and Brazilian descents [15]. Geographic differences are also observed in responses to ICIs. For example, in lung cancer and other cancer types, patients from Asia benefit more from ICI compared to non-Asian populations, although this is not clear for GC [16]. Patients from Europe and particularly LATAM are underrepresented in global clinical studies, and it is not known how patients from these continents respond to ICI [10].

To unravel the molecular and immunological features of GC from EU and LATAM specifically, the LEGACY consortium profiled GCs from EU and LATAM countries in relation to the cancer genome, immune, microbiota, histopathological features, and epidemiology [17].

In the present study, we aimed to characterize the immune landscape of advanced GC from patients from EU and LATAM countries. This will not only improve our biological understanding of the disease but can also inspire the development of a global immune targeting strategy.

## METHODS

### Patient material

Patient material and patient characteristics, including disease outcomes were collected as part of an Ethical Review Board approved trial called LEGACy (NCT04015466) [17] and CEI/1412/19 from INCAN. More details on the ethical approvals are described in the Ethical Approvals section. As part of a sizeable standardized tissue sampling effort tumor biopsies and resection material were prospectively collected from 293 patients with primary, treatment-naïve advanced gastric adenocarcinoma (GC) including tumors of the gastro-esophageal junction (AEG II and AEG III according to Siewert and Stein) [18]. Patients were recruited between 2019 and 2022 in the participating hospitals from four hospitals in three EU countries (Spain, Portugal, and the Netherlands) and four hospitals from LATAM countries (Argentina, Mexico, Chile, and Paraguay). Data collection and handling of patient material has been standardized through a consensual lab handbook. Biopsies from the tumor and adjacent normal tissue are formalin-fixed and paraffin-embedded (FFPE) at each site and shipped to Ipatimup (Portugal) for pathological examination and immunohistochemistry, and then sent to VHI, Spain for DNA analysis and to Amsterdam UMC, Netherlands for mRNA analysis. Fresh frozen samples from biopsies from tumor-adjacent normal gastric mucosa were collected in parallel and centrally processed at Ipatimup (Portugal) for microbiota analysis.

### Pathological review

Histology was assessed by an expert pathologist on H&E stains, and tumors were classified according to both Lauren's classification and the 5th edition of the World Health Organization Classification of Tumors of the Digestive System. Tumor areas from all biopsies were annotated before further processing.

### Immunohistochemistry

FFPE samples were cut in 3 µm sections and stained with Ventana® BenchMark ULTRA (Roche) system together with the OptiView DAB IHC Detection Kit (#760-700, Roche) following standard protocol for the following proteins: PD-L1 (Anti-PDL1 Clone 22C3, Dako), CD3 (NCL-L-CD3-565 Clone LN10, Leica), CD8 (#790-4460 Clone SP57, Roche), FoxP3 (#12653 Clone D6O8R, Cell Signaling), MSH2 (#790-5093 Clone G219-1129, Roche), MSH6 (#790-5092 Clone SP93, Roche), MLH1 (#790-5091 Clone M1, Roche) and HER2 (#790-2991 Clone 4B5, Roche). For all antibodies antigen retrieval is performed with CC1 (EDTA) and hematoxylin is incubated for 8 min. For each slide to be stained, a positively staining control tissue was added. EBV status and HER2 status were determined using *in situ* hybridization for detecting HER2 amplification (Dual ISH DNA Probe Cocktail, 800-4422,

Roche) and Epstein-Barr Virus Early RNA (EBER probe, 800-2842, Roche) with the Ventana® system, together with the ultraView SISH DNP Detection Kit (#800-098, Roche) and ultraView Red ISH DIG Detection Kit (#800-505, Roche).

All samples were reviewed by two expert pathologists (FC and CMC) and the expression of mismatch repair proteins, HER2 and EBER was classified according to standard criteria [19, 20]. Positive lymphocytes for immune markers were counted using the positive cell detection script of the open-source software Qupath [21]. For CD3 and CD8 two hotspot areas of 0.30 mm<sup>2</sup> were selected. For FOXP3 counting, one hotspot area of 0.20 mm<sup>2</sup> was selected. Normal mucosa, gastritis, granulation tissue, and necrosis were avoided. The combined positive score (CPS) for PD-L1 was evaluated following the PD-L1 IHC 22C3 pharmDx Interpretation Manual for gastric cancer (Interpretation manual Dako). The number of positive mononuclear inflammatory cells (cytoplasmic or membranous staining) and positive tumor cells (presenting membranous staining) were recorded separately.

### Nanostring mRNA expression analyses

Annotated tumor areas were manually cut out of 10 µm FFPE slides using a scalpel. RNA was isolated from the FFPE tumor material using the Qiagen RNeasy FFPE kit (Qiagen, Germantown, MD). RNA quantity was measured by Qubit RNA IQ Assay on the Qubit 4 fluorometer (Thermo Fisher, US). The RNA quality was measured with an Agilent RNA 6000 Nano kit using Bioanalyzer instrument (Agilent Technologies, US). mRNA was analyzed using the NanoString nCounter® analysis system with the Nanostring PanCancer Immune Profiling panel (NanoString Technologies, Seattle, WA). Data was analyzed using the Nanostring nSolver software version 4.0. All samples used for the final analysis have passed quality control for quality control of imaging, binding density, positive linearity and limit of detection and the data has been normalized according to housekeeping genes. For advanced analysis, encompassing cell type and pathways scores as well as differential expression, the nCounter Advanced analysis 2.2 plugin was used and the accompanying nanostring celltype and pathway annotations were utilized.

### Microbiota analysis

DNA isolation from fresh frozen biopsies from tumor-adjacent normal mucosa was performed using the QIAamp DNA FFPE Tissue Kit (QIAGEN) according to manufacturer's instructions [4]. The 16S rRNA gene was amplified at the V5-V6 hypervariable region. The sequencing library was sequenced in an Illumina MiSeq platform (Illumina, San Diego, CA, USA), with a read length of 300 bp paired-end reads and an expected output of 100,000 reads per sample [22]. Reads were then quality filtered by imposing a maximum number of expected errors of 1.0 and trimmed at a fixed length. Filtered reads were dereplicated and amplicon sequence variants (ASVs) were clustered using the UNOISE algorithm [23]. Next, each biological sequence was taxonomically assigned using SINTAX algorithm [24] with the 16S RDP Classifier v16 training set as the reference database. Sequence data analysis was performed using usearch\_v8.1.11861\_i86linux64 and usearch11.0.667\_i86linux32 [25].

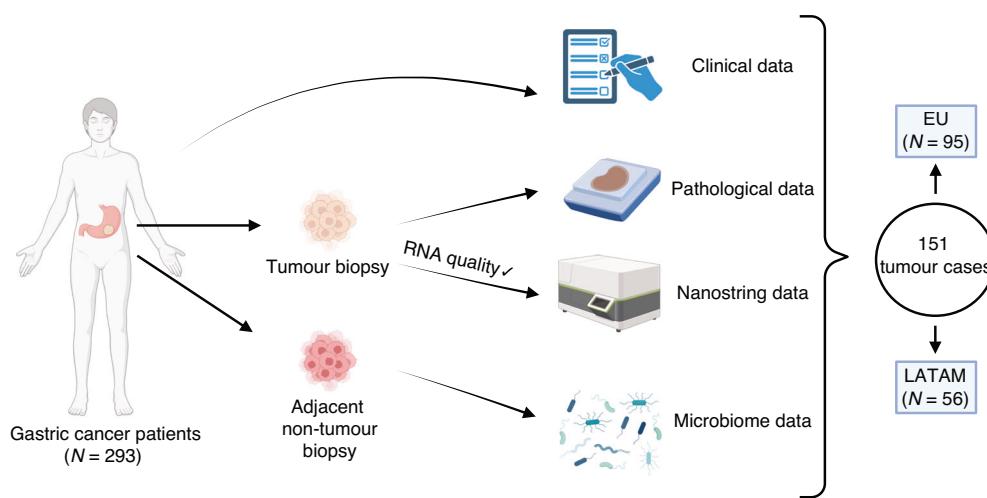
### Statistical analysis

IBM SPSS Statistics version 26.0 (IBM Corporation, Armonk, NY, USA), R4.4.0 and Graphpad prism were used for performing statistical analysis and making corresponding figures. To compare three groups, Kruskal-Wallis test with Dunn's post correction was used. To compare two groups, normality test was first run to determine distribution and Mann-Whitney U test was used. Statistical analysis of differential gene expression data, both at gene and pathway levels, was performed using nCounter Advanced Analysis Software 2.0 (NanoString Technologies). *p*-value was adjusted for multiple comparisons using the false discovery rate proposed by Benjamini and Hochberg [26].

## RESULTS

### Gastric cancers from LATAM are less often MSI and express less PD-L1

In this prospective study, we included tissue biopsies from 293 advanced stage GCs as well as 113 fresh-frozen biopsies from non-cancer adjacent tissue to analyze the microbiota. After shipment and extraction of slides for pathological and DNA analyses,



**Fig. 1** Study outline. EU Europe, LATAM Latin America.

238 samples were available for RNA extraction. Eighty-seven samples were excluded due to insufficient tumor material or low RNA quality leading to a total number of 151 samples with sufficient quantity and quality RNA. Of these, 63% ( $n = 95$ ) were from EU countries [Portugal ( $n = 17$ ), Spain ( $n = 37$ ), and The Netherlands ( $n = 41$ )], and 37% ( $n = 56$ ) were from LATAM countries [Argentina ( $n = 7$ ), Chile ( $n = 18$ ), Paraguay ( $n = 15$ ) and Mexico ( $n = 16$ ) (Fig. 1)].

The clinicopathological details per continent are listed in Table 1. According to Lauren's classification, the most common tumors were of the intestinal type (88/151, 58%) and 90 (59%) of the patients were male. In 96 out of 151 cases (64%), the tumors had spread to distant organs. Among the tumors, 18 (12%) were MSI and 6 (4%) were EBV-positive. Additionally, more than half of the tumors had a PD-L1 CPS  $\geq 5$  (90/151, 60%).

When comparing patients from EU and LATAM, we observed that EU patients had more antrum-distal located tumors (35% vs 16%,  $p = 0.046$ ), while tumors from patients of LATAM countries were mostly located at the fundus/body (50%). Furthermore, MSI was more often detected in the EU cohort (17% vs 4%,  $p = 0.028$ ) and also PD-L1 CPS  $\geq 5$  (65/95, 68%) was more often detected in EU tumors compared to LATAM tumors (25/56, 45%,  $p = 0.002$ ) (Table 1). Clinicopathological differences were also analyzed per country which showed that patients from Argentina and Mexico are significantly younger ( $p = 0.006$ ). A higher proportion of patients with distant metastases was also observed in patients from Spain, Chile and Mexico ( $p < 0.001$ ). Moreover, although no significant differences were observed in the proportion of MSI or EBV-positive patients between countries ( $p = 0.618$ ), patients from Chile and the Netherlands had the highest frequencies of PD-L1 CPS  $> 5$  (add percentage  $p < 0.001$ ) (Supplementary Table 1).

We next evaluated the immune infiltrate of advanced GCs using immunohistochemistry (IHC) with antibodies against CD3, CD8, and FoxP3. Overall, intratumoral CD3-positive cells varied in number from 37 to 20,083 counts per mm<sup>2</sup> (mean 3797), CD8-positive cells ranged from 17 to 23,563 counts per mm<sup>2</sup> (mean 2718), and FoxP3-positive cells ranged from 35 to 2820 counts per mm<sup>2</sup> (mean 556). As expected, MSI and EBV-positive tumors had more CD8+ T cells compared to MSS/EBV-negative tumors. Besides a trend towards less FOXP3-positive cells in LATAM cancers no differences in number of CD3+ or CD8+ cells were observed (Table 1, Supplementary Table 1).

#### Transcriptomic analysis identified distinct GC immune clusters

We next used Nanostring mRNA expression data to further characterize immune features of both cohorts. We first performed an unsupervised hierarchical clustering based on cell type scores

and identified two main GC immune clusters: cluster 1 ( $n = 125$  patients) and cluster 2 ( $n = 26$  patients) (Fig. 2A). Cluster 2 was characterized by higher scores for B cells, CD8 T cells, cytotoxic cells, dendritic cells, neutrophils, NK cells, T cells, and T regulatory cells (all  $p < 0.0001$ ; Supplementary Fig. 1A). Cluster 1 contained tumors with a more heterogeneous immune infiltration and could be subdivided by three subclusters: cluster 1A ( $n = 66$  patients), characterized by an enrichment of mast cells, B cells, and exhausted CD8 T cells; cluster 1B ( $n = 38$  patients), characterized by very low numbers of immune cells; and cluster 1C ( $n = 21$  patients), with an immune infiltrate dominated by macrophages and dendritic cells. Validation of these four immune scenarios with IHC data confirmed significantly higher CD8+ cell counts (adj  $p = 0.0245$ ) and lower FOXP3-positive cells in cluster 2 compared to cluster 1B (adj  $p = 0.0444$ , Fig. 2B).

We next looked at the difference in immune pathway expression between the clusters. Interestingly, while having generally lower immune cell scores in cluster 1A compared to cluster 2, cluster 1A was enriched for antigen presentation, cytotoxicity, and immune cell adhesion and migration compared to the other clusters (adj  $p < 0.05$ , Fig. 2C). Cluster 1B showed higher expression of hypoxia and low number of immune cells and cluster 1C was enriched for extracellular matrix remodeling (adj  $p < 0.05$ , Fig. 2C).

At last, we determined oncogenic pathway signaling for all four clusters and identified that highly inflamed cluster 2 was enriched for Hedgehog, JAK-STAT, MAPK, NF-κB, Notch, and Wnt signaling pathways (adj  $p < 0.05$ , Fig. 2C), and presented a downregulation of interferon, PI3K-Akt, and TGF-β networks (adj  $p < 0.05$ , Fig. 2C), in comparison with the other clusters. Cluster 1B had significantly lower scores for JAK-STAT, MAPK, interferon, and Wnt signaling pathways in comparison with the other subclusters in cluster 1 (adj  $p < 0.05$ , Fig. 2C). Finally, analysis of the inter-cluster variability in gene expression of targets for ICIs and new immunotherapies showed that patients belonging to cluster 2 presented higher expression of immune checkpoints, such as *PDCD1*, *CD274* (encoding PD-L1), *CTLA4*, *TNFRSF4* (encoding OX40), *TIGIT* and *HAVCR2* (encoding TIM3), compared to clusters 1A, 1B, and 1C (Fig. 2D, Supplementary Fig. 1B) likely indicative for the high number of T cells in this cluster. The clusters did not differ in MSI or HER2 status (Supplementary Table 2).

#### Gastric cancer immune profiles show geographic specificities

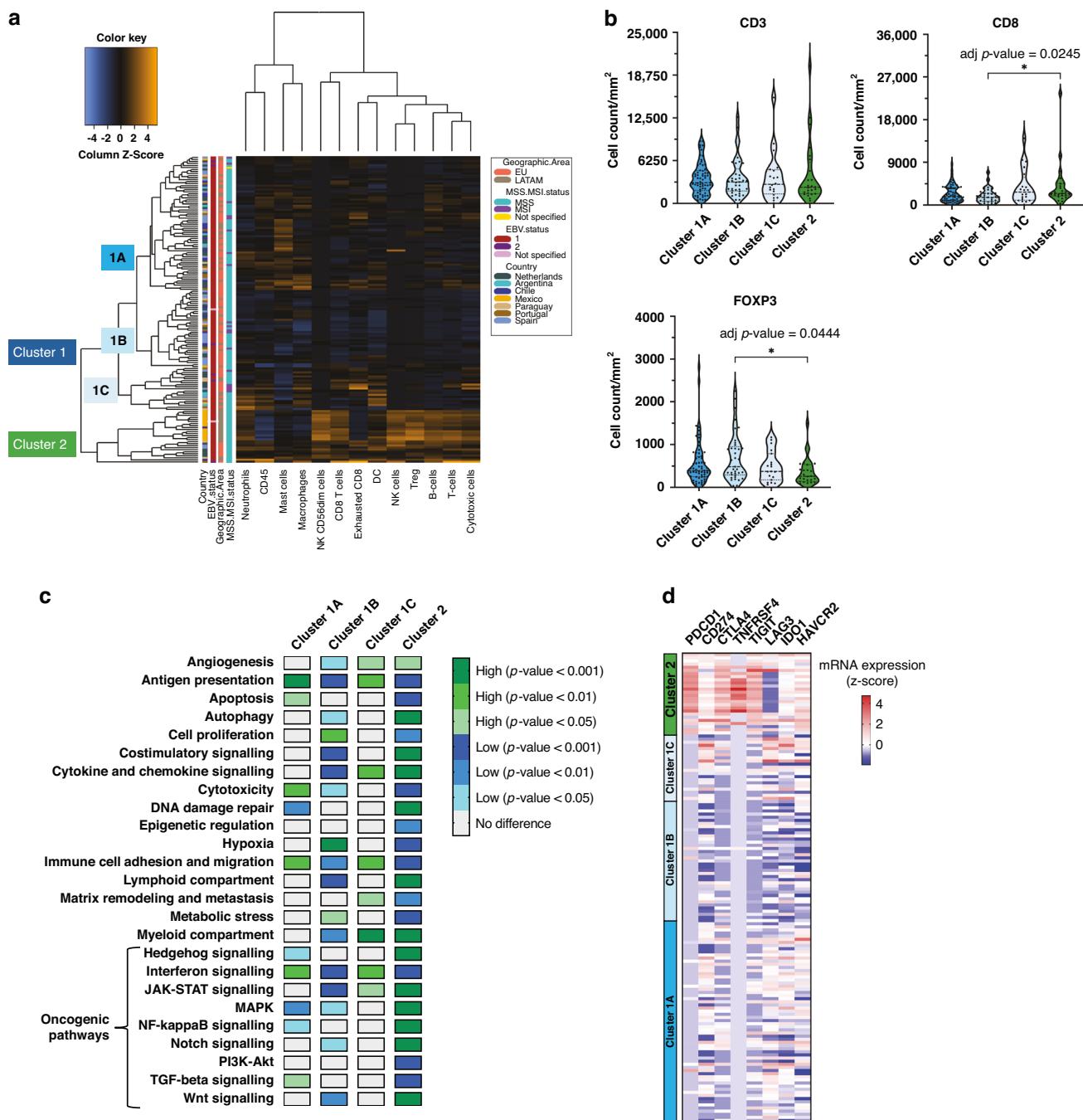
We next evaluated the geographic differences across the four immune clusters and observed that the distribution of the immune clusters between EU and LATAM GCs was significantly different ( $p = 0.001$ , Fig. 3A). Cancers from the EU were more often

**Table 1.** Clinicopathological characteristics of the study population.

<b>Characteristic</b>	<b>Total</b>		<b>EU</b>		<b>LATAM</b>		<b>p-value</b>
	<b>N</b>	<b>%</b>	<b>N</b>	<b>%</b>	<b>N</b>	<b>%</b>	
Patients enrolled	151	100	95	63	56	37	
Age (median, range, Y)	67	26–89	67	31–89	66	26–83	0.132
Gender							0.466
Male	90	60	54	57	36	64	
Female	61	40	41	43	20	36	
Race							<0.001
White Hispanic or Latino	70	46	18	20	52	95	
White not-Hispanic nor Latino	69	46	66	73	3	5	
Asian	1	1	1	1	0	0	
Black or African American	6	4	6	7	0	0	
Tumor Location							0.046
GE Junction/Cardia/Proximal	45	30	29	31	16	29	
Fundus/Body	60	40	32	34	28	50	
Antrum/Distal	42	28	33	35	9	16	
Lauren's classification							0.174
Intestinal	88	58	59	62	29	53	
Diffuse	51	34	27	28	24	44	
Mixed	10	7	8	8	2	4	
Medullary	1	1	1	1	0	0	
cTNM staging							<0.001
Primary tumor (T)							
1	2	1	2	2	0	0	
2	6	4	6	6	0	0	
3	47	31	41	43	6	11	
4	56	37	31	33	25	45	
x	40	26	15	16	25	45	
Regional lymph nodes (N)							<0.001
0	9	6	8	8	1	2	
1	25	17	20	21	5	9	
2	28	19	26	27	2	4	
3	25	17	15	16	10	18	
x	64	42	26	27	38	68	
Distant metastasis (M)							0.086
0	55	36	40	42	15	27	
1	96	64	55	58	41	73	
Molecular characterisation							0.028
MSI/EBV–	18	12	16	17	2	4	
MSS/EBV–	126	83	74	79	52	93	
MSS/EBV+	6	4	4	4	2	4	
HER2 status							0.467
Negative	136	90	83	90	53	95	
Positive	12	8	9	10	3	5	
CPS score							0.002
0–5%	52	34	22	23	30	54	
5–10%	14	9	11	12	3	5	
>10%	76	50	54	57	22	39	
IHC (mean, range)							
CD3	3797	37–20,083	4104	473–20,083	3289	37–9103	0.124
CD8	2718	17–23,563	2874	17–23,563	2453	107–8593	0.382
FOXP3	556	35–2820	616	35–2820	457	35–1440	0.056

P-values ≤0.05 were considered statistically significant (in bold).

CPS combined positive score, CD3 CD8 and FoxP3 given in counts per mm<sup>2</sup>, ns non-significant, EBV Epstein Barr Virus, MSI microsatellite instable, MSS microsatellite stable, HER2 Human Epidermal growth factor Receptor 2, IHC Immunohistochemistry, EU Europe, LATAM Latin America.



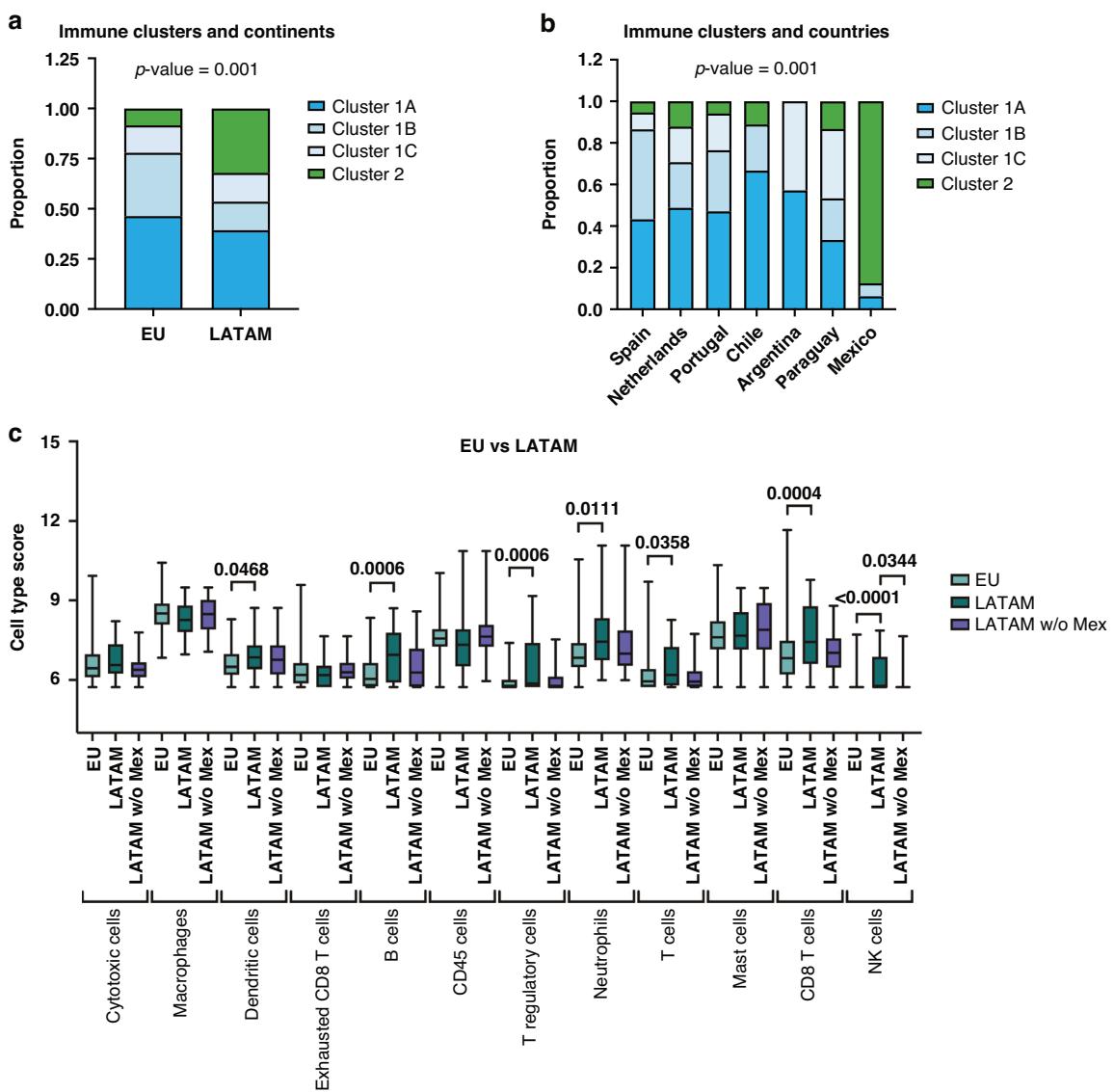
**Fig. 2 Transcriptomic analysis identified distinct GC immune clusters. A** Unsupervised hierarchical clustering heatmap based on transcriptional cell type scores identifying two main GC immune clusters: cluster 1 (subdivided into clusters 1A, 1B and 1C) and cluster 2. **B** IHC data validating the four immune scenarios detected by the transcriptomic analysis. Adj  $p < 0.05$  were considered as statistically significant. **C** Differential pathways expression across the four distinct immune clusters.  $P < 0.05$  were considered as statistically significant. **D** Heatmap showing the z-score mRNA expression of gene targets for ICIs and new immunotherapies: *PDCD1*, *CD274*, *CTLA4*, *TNFRSF4*, *LAG3*, *IDO1*, and *HAVCR2*. EU Europe, LATAM Latin America.

in the non-inflamed cluster 1B (32% vs. 14% in LATAM), while cluster 2 was overrepresented in LATAM (32% vs. 8% in EU). Within the EU-group of countries not many differences were observed except for an overrepresentation of cluster 1B in GCs from Spain (Fig. 3B). Within LATAM, more country specificity was observed. In particular, 88% of GCs from Mexico were represented in the highly inflamed cluster 2, while immune-poor cluster 1B did not contain any Argentinian GC patients (Fig. 3B).

In analogy of immune cluster associations, cancers from Mexico showed the highest number of dendritic cells ( $adj\ p = 0.0468$ ), B

cells ( $adj\ p = 0.0006$ ), T regulatory cells ( $adj\ p = 0.0006$ ), neutrophils ( $adj\ p = 0.0111$ ), CD8 T cells ( $adj\ p = 0.0004$ ) and NK-cells ( $adj\ p < 0.0001$ ) (Fig. 3C). Without tumors from Mexico, no differences in immune composition were observed between tumors from EU and LATAM, indicating that in both continents GC can have different levels of antitumor immunity.

Regarding the patients belonging to cluster 2, we observed that the lack of cytotoxicity and antigen presentation was mainly related to the Mexican population (Supplementary Fig. 2A). Although the Mexican patients presented high number of CD8-



**Fig. 3** Gastric cancer immune profiles show geographic specificities. **A** Distribution of the four immune cluster showed differences between EU and LATAM continents ( $p = 0.001$ ). **B** Distribution of the four immune clusters showed differences across countries ( $p = 0.001$ ). **C** Immune cell type abundance comparison between EU and LATAM GCs patients with and without Mexico. EU Europe, LATAM Latin America, w/o Mex without Mexican population.

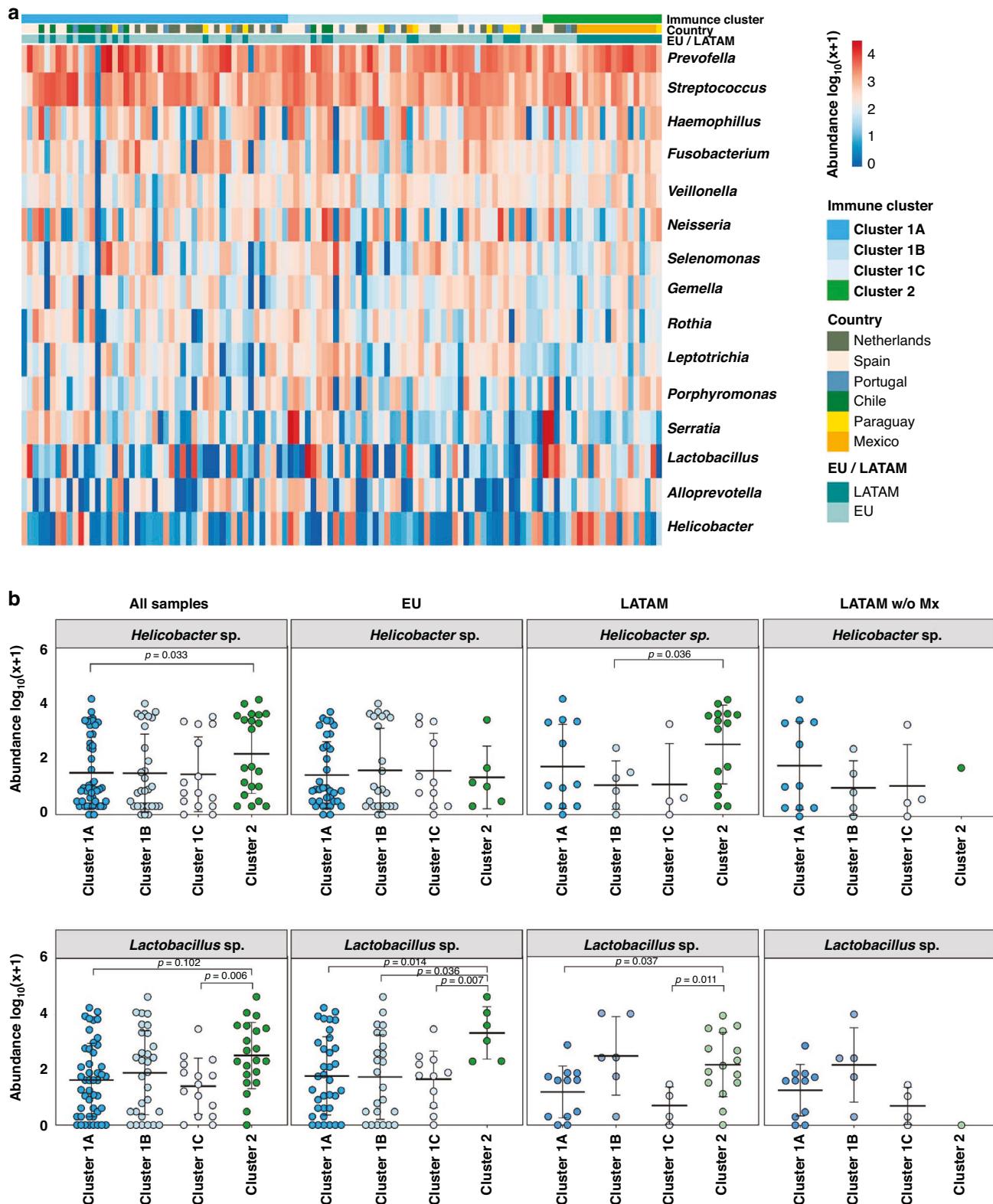
positive T cells, they also were the ones with the highest number of T regulatory cells, which may play a role in dampening the cytotoxic immune response (Supplementary Fig. 2B). Furthermore, these T cells also showed high expression of immunomodulatory genes such as *CTLA4*, *TNFRSF4*, *TIGIT* and *HAVCR2* (Supplementary Fig. 2C).

#### Helicobacter sp. and Lactobacillus are more abundant in GC immune cluster 2

As differences in the microbiome can provide an explanation for geographical immune differences, we next analyzed the microbiota in 113 (75%) of the 151 tumors from which fresh frozen tissue was available. The analyses showed that the most abundant bacteria found in the stomach of GC patients included the genera *Prevotella*, *Streptococcus*, *Haemophilus*, *Fusobacterium*, *Veillonella*, *Neisseria*, *Lactobacillus*, and *Helicobacter*, among others, without significant differences observed between EU and LATAM GCs (Supplementary Fig. 3). Overall, there was no significant clustering between the microbiota and specific immune clusters (Fig. 4A). However, *Helicobacter* sp. was

significantly more abundant in cluster 2 than in cluster 1A (Fig. 4B). The same accounted for *Lactobacillus* sp. which was significantly more abundant in cluster 2 compared to clusters 1A and 1C (Fig. 4B), with no additional statistically significant differences observed for the other genera (Supplementary Fig. 4). We next assessed the abundances of these taxa in each cluster by continent and identified that in LATAM GCs *Helicobacter* sp. was significantly more abundant in cluster 2 than in cluster 1B, but this difference was not observed in EU GCs (Fig. 4B). The prevalence of the virulence marker CagA was higher in LATAM (67%) than in EU (33%) *H. pylori* strains, but without statistical significance ( $p = 0.33$ ).

We next explored the relationships between the *H. pylori* CagA status and the immune characteristics of cluster 2. Patients infected with CagA-positive strains had increased (non-significant) number of T regulatory cells, and significantly decreased cytotoxicity, number of macrophages, and antigen presentation signature (Supplementary Fig. 5), suggesting that these strains contribute to tumor immune evasion. In EU GC patients *Lactobacillus* sp. was significantly more abundant in immune



**Fig. 4 Relationship between the microbiota and the immune profiling of gastric cancer patients. A** Heatmap showing a supervised clustering analysis of GCs based on the top 15 most abundant genera. **B** Abundance of *Helicobacter* sp. and *Lactobacillus* sp. between immune clusters in all cases, per EU and LATAM GCs, and in LATAM excluding Mexican GCs.

cluster 2 than in all other clusters, while in LATAM GCs this increased abundance was only observed in comparison with clusters 1A and 1C (Fig. 4B). When the analysis was performed by removing the samples from Mexico, the relationships between

*Helicobacter* sp. and *Lactobacillus* sp. cluster 2 were not maintained, suggesting that at least the association between *Helicobacter* sp. and a T cell inflamed microenvironment was Mexico specific.

## DISCUSSION

In this study of the LEGACY consortium, we had the unique opportunity to profile the immune microenvironment of advanced GCs from European and Latin American patients, with standardized methods to sample tumor and adjacent normal tissue from patients in seven different countries. We identified four distinct immune clusters with different levels of immune activation. While all countries had tumors with more and less abundant immune infiltrates, cancers from Mexico had an immune microenvironment with an exceptional immune composition that clustered separately from all other cancers. Microbiota analyses identified a strong association of these cancers with *Helicobacter* sp. infection. Additional immune pathway analyses identified that these highly immune inflamed cancers were limited in expression of pathways associated with antigen presentation and cytotoxicity, while high in expression of pathways associated with DNA repair, NF- $\kappa$ B, MAPK signaling, and autophagy. As *H. pylori* is known to induce DNA damage and activate MAPKs and transcription factors NF- $\kappa$ B and AP-1, high abundance of the bacterium in these CGs may support such inflamed immune profile [27, 28]. The lack of antigen presentation and cytotoxicity argues in favor of an anti-microbiome directed immune response instead of an anti-cancer directed immune response.

Besides the highly inflamed cluster 2, we identified three other clusters with a differential immune status that were found in every country. Cluster 1A, characterized by a moderate presence of T-, B- and mast cells; cluster 1B, presenting low number of immune cells; and cluster 1C, mainly dominated by macrophages and dendritic cells. Interestingly, both cluster 1A and 1C were enhanced for antigen presentation and showed higher expression of immune checkpoint related genes, such as CD274 (PD-L1), TIGIT, LAG3, IDO1 and HAVCR (TIM3), compared to cluster 1B. Thereby, these clusters likely contain tumors with a high likelihood responding to immune checkpoint inhibitors, while the opposite is true for the immune deserted cluster 1B. However, while cluster 1A has a moderate presence of T cells, which is well-known to respond to immunotherapy [29], cluster 1C is enriched in macrophages and overexpressed the matrix remodeling process. It has been shown that tumor-associated macrophages (TAMs) limit the efficacy of immunotherapy. TAMs may reduce CD8+ T cell motility and confine them to the stroma and may contribute to ECM remodeling and disruption of its stiffness, thus limiting immune cell infiltration into the tumor and decreasing the therapeutic impact of ICIs [30–32]. Targeting macrophages could potentially improve immunotherapy response in these tumors [33]. On the other hand, cluster 1B is enriched for hypoxia, which is an important factor in immune excluded phenotypes [34]. In fact, increased intratumoral hypoxia and decreased CD8+ T cells have been shown in anti-PD-1 resistant head and neck tumors [35]. Hypoxia modulators hold promise to improve cancer immunotherapy, with ongoing efforts to develop highly selective hypoxia inhibitors [36].

As GCs from cluster 1A, 1B and 1C could be found in all countries, we concluded that both EU and LATAM countries have GCs with an immune composition that predisposes to a benefit from immune checkpoint inhibitors. Although Mexican GC patients in the highly inflamed cluster 2 contained a high number of T cells, these cancers lacked antigen presentation and cytotoxicity which argues in favor of an anti-microbiome immune response instead of an antitumor immune response. It is unknown whether these GCs will equally respond to ICIs compared to patients with cluster 1A tumors.

A growing number of studies have addressed the role of *H. pylori* infection on the efficacy of ICI therapy. While in preclinical data and in cancer types other than GC, *H. pylori* has been associated with lower effectiveness of anti-PD-1 immunotherapy [37], in the context of GC there have been contrasting results. In a retrospective analysis of a USA cohort of 215 metastatic GC patients treated with ICIs,

those with a history of *H. pylori* infection (23%) had significantly shorter median progression-free survival (PFS) and overall survival (OS) [38]. In the largest retrospective study to date on the relationship between *H. pylori* and immunotherapy response, a positive relation was shown [39]. In a Chinese cohort of 636 MSS/EBV-negative GC patients who were treated with anti-PD-1/PD-L1 therapy, *H. pylori*-positive patients had significantly longer immune-related-PFS and -OS compared to *H. pylori*-negative [39]. Moreover, *H. pylori*-positive GCs had significantly higher densities of PD-L1+ and of non-exhausted CD8+ T cells in the TME, and shared molecular characteristics similar to those of immunotherapy-sensitive GC. These results are in line with our findings in Mexican GC patients presenting high-inflamed tumors.

We additionally found an association between high abundance of *Lactobacillus* sp. and immune cluster 2, which was common to EU and LATAM GCs [40]. While high relative abundance of *Lactobacillus* has been described in the stomach of GC patients in comparison to patients without GC, little is known about the immune profile associated to this genus [4, 5]. Interestingly, in a MSI-high colorectal cancer xenograft mouse model, infection with *Lactobacillus* synergized with anti-PD1 therapy by enhancing CD8+ T cells and reducing Foxp3+CD25+ Treg intratumoural cell infiltration [41]. Furthermore, in HER2-negative advanced gastric or GEJ adenocarcinoma patients, *Lactobacillus* was enriched in the gut microbiome of responders to anti-PD-1/PD-L1 therapy and was associated with better PFS [40].

Our study has several limitations, such as the lack of representation of certain areas from LATAM or EU, as well as limitations of the NanoString panel, which does not encompass all transcriptomic signaling pathways. Additionally, the quality of tissue samples in some cases was insufficient, preventing analysis in certain patients. On the other hand, the LEGACy project was designed to provide a comprehensive overview of the tumor characteristics in EU and LATAM patients, but did not incorporate functional assays. Nevertheless, altogether, this study from the LEGACy consortium showed that the immune microenvironment of both EU and LATAM countries are heterogeneous and that only a subgroup of GC has an inflamed immune infiltrate, likely requiring immunostimulatory drugs for reactivation. The fact that a subgroup of cancers, mainly composed by tumors from Mexico, are inflamed but not enriched for antigen presentation and cytotoxicity pathways, suggests an immune response against *H. pylori* rather than an active antitumor response. Further research is needed to determine whether both anti-microbiota and antitumor immune responses positively influence the efficacy of checkpoint inhibitors.

## DATA AVAILABILITY

The data presented in this article are available upon request to the corresponding author.

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## AUTHOR CONTRIBUTIONS

Conceptualization and design—All (TG-VS, MC-S, RF, CM-C, RB, JS-A, AC, EF-F, LL-S, AH-G, ER-G, CC, HB, CG, DC, BF, FE, JO, AR, GO, ER, JCR, GL, MG, FR-P, MD-G, MA, FL, JF, JC, RV, RP, REP, EJ-M, AM, RD, CF, FC, AC, SD, TF). Sample and data collection—All (TG-VS, MC-S, RF, CM-C, RB, JS-A, AC, EF-F, LL-S, AH-G, ER-G, CC, HB, CG, DC, BF, FE, JO, AR, GO, ER, JCR, GL, MG, FR-P, MD-G, MA, FL, JF, JC, RV, RP, REP, EJ-M, AM, RD, CF, FC, AC, SD, TF). Data curation and formal analyses — TG-VS, MC-S, RF, CF, SD, TF. Statistical analyses—TG-VS, MC-S, RF, JC. Supervision—SD, TF. Funding acquisition—AC, SD and TF. Writing—Original draft—TG-VS, MC-S, RF, CF, SD, TF. Writing—review and editing—All (TG-VS, MC-S, RF, CM-C, RB, JS-A, AC, EF-F, LL-S, AH-G, ER-G, CC, HB, CG, DC, BF, FE, JO, AR, GO, ER, JCR, GL, MG, FR-P, MD-G, MA, FL, JF, JC, RV, RP, REP, EJ-M, AM, RD, CF, FC, AC, SD, TF).

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## COMPETING INTERESTS

MA discloses consultancy, advisory roles, honoraria from Amgen, AstraZeneca, Beigene, Drangofly Therapeutics, Jazz Pharmaceuticals, BMS, Lilly, Novartis and MSD.

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## ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study has been conducted according to the principles of the Declaration of Helsinki (Fortaleza, Brazil, October 2013), following the Medical Research Involving Human Subjects Act and Good Clinical Practice standards. The study can be found under ClinicalTrials.gov Identifier: NCT04015466, and NCT03957031, July 11, 2019. The study protocol has been approved by the ethics committee of all patient-recruiting centres: the ethics committee of University Clinical Hospital of Valencia, Spain (reference number 2018/205), the institutional review board of VU University Medical Center Amsterdam (reference number 2019.355. NL 69480.02919), the ethics committee of Instituto de Previsión Social, Asuncion-Paraguay (reference number CA Nº11-020/19), the ethical research committee of Instituto Alexander Fleming, Buenos Aires Argentina (Resolution July 25th, 2019, for LEGACy study 1 and 2 and October 3rd, 2019 for LEGACy study 3); the ethical committee of Instituto Nacional de

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## ADDITIONAL INFORMATION

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