



Phase II and biomarker study of programmed cell death protein 1 inhibitor nivolumab and metronomic cyclophosphamide in paediatric relapsed/refractory solid tumours: Arm G of AcSé-ESMART, a trial of the European Innovative Therapies for Children With Cancer Consortium

Claudia Pasqualini, Jonathan Rubino, Caroline Brard, Lydie Cassard, Nicolas André, Windy Rondof, Jean-Yves Scoazec, Antonin Marchais, Souad Nebchi, Lisa Boselli, et al.

► To cite this version:

Claudia Pasqualini, Jonathan Rubino, Caroline Brard, Lydie Cassard, Nicolas André, et al.. Phase II and biomarker study of programmed cell death protein 1 inhibitor nivolumab and metronomic cyclophosphamide in paediatric relapsed/refractory solid tumours: Arm G of AcSé-ESMART, a trial of the European Innovative Therapies for Children With Cancer Consortium. *European Journal of Cancer*, 2021, 150, pp.53-62. 10.1016/j.ejca.2021.03.032 . hal-03625350

HAL Id: hal-03625350

<https://amu.hal.science/hal-03625350>

Submitted on 24 Apr 2023

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.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Phase II and bio-marker study of programmed cell death protein 1 inhibitor nivolumab and metronomic cyclophosphamide in pediatric relapsed/refractory solid tumors: Arm G of AcSé-ESMART, a trial of the European Innovative Therapies for Children with Cancer consortium.

Claudia Pasqualini^a, Jonathan Rubino^b, Caroline Brard^c, Lydie Cassard^d, Nicolas Andre^{e,f,g}, Windy Rondot^h, Jean-Yves Scoazecⁱ, Antonin Marchais^h, Souad Nebchi^c, Lisa Boselli^d, Jonathan Grivel^d, Isabelle Aerts^j, Estelle Thebaud^k, Xavier Paoletti^{c,*}, Véronique Minard-Colin^{a,h}, Gilles Vassal^b, Birgit Geoerger^{a,h}

^a Department of Pediatric and Adolescent Oncology, Gustave Roussy Cancer Campus, Université Paris-Saclay, Villejuif, France

^b Clinical Research Direction, Gustave Roussy Cancer Campus, Université Paris-Saclay, Villejuif, France

^c Biostatistics and Epidemiology Unit, Gustave Roussy Cancer Campus, INSERM U1018, CESP, Université Paris-Saclay, Villejuif, France

^d Laboratory of Immune-monitoring in Oncology, Gustave Roussy Cancer Campus, Université Paris-Saclay, Villejuif, France

^e Department of Pediatric Oncology, Hôpital de la Timone, AP-HM, Marseille, France

^f UMR Inserm 1068, CNRS UMR 7258, Aix Marseille Université U105, Marseille Cancer Research Center (CRCM), Marseille, France

^g Metronomics Global Health Initiative, Marseille, France

^h INSERM U1015, Gustave Roussy Cancer Campus, Université Paris-Saclay, Villejuif, France

ⁱ Department of Medical Biology and Pathology, of Translational Research and Biobank, AMMICA, Laboratory INSERM US23/CNRS UMS3655, Gustave Roussy Cancer Campus, Université Paris-Saclay, Villejuif, France

^j SIREDO Oncology Center (Care, Innovation and research for children and AYA with cancer), Institut Curie, PSL Research University, Paris, France

^k Department of Pediatric Oncology, Centre Hospitalier Universitaire, Nantes, France

* Current address: Institut Curie, INSERM U900 STAMPM, UVSQ, St Cloud, France

Corresponding author: Birgit Geoerger, MD, PhD, Gustave Roussy Cancer Campus, Department of Pediatric and Adolescent Oncology, INSERM U1015, 114 Rue Edouard Vaillant, 94805 Villejuif, France. Tel +33 (0)1 42 11 46 61, Fax: +33 (0)1 42 11 52 75.

Email: birgit.geoerger@gustaveroussy.fr

Running head: Nivolumab and metronomic cyclophosphamide in pediatric tumors

Key words: pediatric cancers, immune checkpoint inhibitor, tumor microenvironment, immune monitoring, phase 2 clinical trial

Conflict of interest

NA, VMC, GV and BG declared consultancy or advisory role to BMS. All other authors declared no potential conflicts of interest.

Abstract 250 words

Text 2490 words

Figures 3

Data sharing statement

Data available on request due to privacy/ethical restrictions.

Highlights:

- Nivolumab with metronomic cyclophosphamide had limited activity in pediatric tumors
- Low PD-L1 expression, T cell infiltration and mutational load explain the results
- The tumor microenvironment consisted mainly in pro-tumoral macrophages
- The combination was not able to efficiently modulate circulating T cell phenotypes

Abstract

Purpose: AcSé-ESMART is a European multicenter, proof-of-concept multi-arm phase I/II platform trial in pediatric patients with relapsed/refractory cancer. Arm G assessed the activity and safety of nivolumab in combination with metronomic cyclophosphamide +/- irradiation.

Experimental design: Following a phase II Simon two-stage design, nivolumab was administered intravenously at 3 mg/kg every 2 weeks of a 28-day cycle, oral cyclophosphamide at 25 mg/m² twice a day, 1 week on/1 week off. The primary endpoint was objective response rate. Irradiation/radioablation of primary tumor or metastasis could be administered as per physician's choice. Biomarker evaluation was performed by tumor immunohistochemistry, whole exome and RNA sequencing, and immunophenotyping of peripheral blood by flow cytometry.

Results: Thirteen patients were treated with a median age of 15 years (range: 5.5-19.4). Main histologies were high-grade glioma, neuroblastoma, and desmoplastic small round cell tumor (DSRCT). The safety profile was similar to those of single agent nivolumab albeit hematologic toxicity, mainly lymphocytopenia, was commonly reported with the addition of cyclophosphamide +/- irradiation. Two patients with DSRCT and ependymoma presented unconfirmed partial response and prolonged disease stabilization. Low mutational load with modest intratumor CD3+ T-cell infiltration and immunosuppressive tumor microenvironment were observed in the tumor samples. Under combined treatment, no positive modulation of circulating T-cells was displayed, while derived neutrophil-to-lymphocyte ratio increased.

Conclusions: Nivolumab in combination with cyclophosphamide was well tolerated but had limited activity in this pediatric setting. Metronomic cyclophosphamide did not modulate systemic immune response that could compensate limited T-cell infiltration and the immunosuppressive tumor microenvironment.

ClinicalTrials.gov Identifier: NCT2813135

INTRODUCTION

In spite of 80% of overall survival (OS) among children, adolescents and young adults diagnosed with cancers, 20% still die from recurrent or refractory disease (1). Widening the therapeutic approaches is of paramount importance and defining new compounds or combinations is the next step to improve pediatric patient's survival. Immunotherapy with immune checkpoint inhibitors acting through the programmed cell death protein 1 (PD-1) pathway has shown efficacy in some chemotherapy-resistant adult cancers (2–6). However, single-agent checkpoint inhibitors in children have demonstrated activity only in Hodgkin lymphoma, hypermutated tumors and few rare tumor types (7–11).

A synergistic effect of metronomic cyclophosphamide with T-related immunotherapies had been suggested (12) through its immunomodulatory properties characterized by T regulatory (Treg) depletion and Natural Killer (NK) cell modulation, although limited activity have been observed in sarcoma (13,14). Preclinical data and clinical trials in adults reported that irradiation is potentially capable of increasing the response to immune checkpoint inhibitors by inducing tumor-specific immunity (15,16).

Based on these data, we hypothesized that metronomic cyclophosphamide +/- irradiation of primary tumor or metastasis could enhance PD-1 inhibitor nivolumab activity in pediatric patients with relapsed/refractory malignancies. Potential biomarkers of response were studied using immunohistochemistry (IHC), bulk RNA sequencing (RNAseq), whole exome sequencing (WES) and peripheral white blood cell flow cytometry.

METHODS

Study and patients

AcSé-ESMART (Secured Access - European proof-of-concept therapeutic Stratification trial of Molecular Anomalies in Relapsed or refractory Tumors; NCT02813135/EUDRACT N°:2016-000133-40, Innovative Therapies for Children with Cancer (ITCC)-057) is an international, multi-center, open-label, proof-of-concept phase I/II platform trial, in which each arm is separately implemented (17).

Arm G consisted in a combination of nivolumab, metronomic cyclophosphamide and, according to physician's decision, irradiation of limited lesions. Patients less than 18 years at initial diagnosis with recurrent/refractory evaluable or measurable malignancy were eligible.

Molecular profiling of the recurrent/refractory tumor by RNAseq and WES and access to raw data and tumor material was required prior to inclusion. Programmed cell death 1 ligand 1 (PD-L1) expression or high tumor mutation burden were enrichment criteria albeit were not mandatory for inclusion. Patients required a Performance scale ≥ 70 , adequate hematological and organ function. Patients with active brain metastases, previous allogeneic transplantation, diagnosis of immunodeficiency, active autoimmune disease, receiving systemic steroid therapy within 7 days prior to study treatment, evidence of interstitial lung disease were excluded. All patients or legal representatives provided written informed consent. The trial complies with the Declaration of Helsinki, International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use, local laws and regulations.

Study treatment and evaluations

Nivolumab was administered intravenously every 2 weeks of a 28-day cycle (days 1 and 15) at 3 mg/kg/dose, cyclophosphamide was given orally at 25 mg/m² twice a day, 1 week

on/1week off. Irradiation, whenever appropriate, started at least 2 weeks after the first nivolumab injection.

Response assessment was performed according to Response Evaluation Criteria In Solid Tumors (RECIST) (version 1.1) (18), Response Assessment in Neuro-Oncology (RANO) (19) and International Neuroblastoma Response Criteria (INRC) (20) for solid tumors, glioma and neuroblastoma, respectively, every two cycles. Objective responses (OR), defined as complete (CR) or partial response (PR)), were to be confirmed 4-6 weeks after the first occurrence.

Adverse events were graded according to the National Cancer Institute Common Terminology Criteria for Adverse Events (CTCAE) 4.03.

Treatment continued until progressive disease (PD), unacceptable toxicity, patient or legal representative withdrawal of consent, or investigator's decision, for a maximum of 2 years.

Trial design

Based on previously reported data (7,8,10), only one dose level was explored in this phase II study. A Simon two-stage minimax design (21) was implemented to test whether the true response rate was lower than 10% with a 90% power if the objective response rate was higher than 30%, at the level of 10%. In stage 1, 12 evaluable patients were expected. If one response or less was seen, the arm was interrupted for lack of activity. Otherwise, stage 2 was initiated with 13 additional evaluable patients. The arm was declared positive if 6 or more objective responses were observed.

The response rate based on radiological response after 2 cycles, best response over the whole duration of treatment, progression-free survival (PFS) and OS rates calculated from the date of treatment initiation are reported. The PFS and OS curves have been estimated using the

Kaplan-Meier method. The 95% confidence intervals have been estimated using the Rothman method.

Tumor microenvironment and mutational load analysis

The evaluation of the density of tumor-infiltrating lymphocytes (TILs) was done by an experienced pathologist (JYS) in 10 consecutive fields in hematoxylin and eosin stained 4 μ m-thick formalin-fixed paraffin-embedded tissue sections of tumor material used for the prior molecular profiling analysis. Their density was expressed as a percentage of all tumor and/or stromal cells present and not as a percentage of the stromal surface as, as expected in most cases, no or very little stroma was present in the tumor tissue samples available.

The PD-L1 (clone E1L3N, Cell Signaling, Danvers, MA) and CD3 (clone 2GV6, Ventana) expression was analyzed using an automated stainer (Ventana Benchmark Ultra, Tucson, AZ). PD-L1 expression was defined as positive if displayed on more than 1% of tumor cells. CD3+ cell density was expressed as the mean of CD3 positive cells in at least 10 consecutive fields of 1 mm² in surface.

WES and RNAseq of the recurrent or refractory disease were performed in MOSCATO-01 and MAPPYACTS as previously described (22,23). Tumor immune infiltrates were estimated using the absolute version of the CIBERSORT algorithm (24). Somatic coding mutations were filtered according to their enrichment in the tumor samples compared to the paired normal samples using a Fisher test and p-value<0.001. Questionable somatic variants observed in less than 3 reads or with an allele frequency lower than 0.05%, or described in 1000 genomes and EXAC databases with a frequency higher than 0.05%, or non-exonic variants were excluded. Mutational load was calculated as the number of non-synonymous somatic variants divided by the total length of targeted regions by the Exome capture kits with a minimum coverage of 10x.

Host immune response profiling

Heparinized blood samples (5-8 mL) were collected at Day 1 and 15 to monitor circulating immune system populations by flow cytometry. Fresh whole blood phenotyping of white cells (lymphocytes, granulocytes, monocytes) and T-cells was performed using Numeration, T cell 3 and Treg 2 panels as previously described (25). For the main populations (lymphocytes, neutrophils, eosinophils, monocytes, NK cells) absolute counts are reported. For the subpopulation of T cells (CD4, CD8, Treg), their modulation is expressed as percentage to avoid the impact of the absolute count variation likely due to chemotherapy. Derived Neutrophil-to-Lymphocyte ratio (dNLR) was calculated as follows: $dNLR = \text{absolute neutrophil count} / (\text{white blood cell count} - \text{absolute neutrophil count})$ (26). For immune parameters, statistical analyses were performed using Prism 6 software (GraphPad, San Diego, CA). *P* values < 0.05 were considered significant. Groups were compared using Mann–Whitney U test.

RESULTS

Patient characteristics

Between August 2016 and July 2017, 13 patients were enrolled (Table 1). The median age at study entry was 15.9 years (range, 5.5-19.4), 10 (77%) were male. Histologies were high-grade glioma, neuroblastoma, desmoplastic small round cell tumor (DSRCT), 3 each, two alveolar rhabdomyosarcoma, one ependymoma and one melanoma. The median delay from diagnosis to study entry was 2.0 years (range, 0.6-14.4). Ten (77%) had metastatic disease. Patients had received a median of 3.5 lines of treatment (range, 1-5). All but one had had conventional chemotherapy, all 3 patients with neuroblastoma had high-dose chemotherapy; the patient with melanoma had received anti-CTLA4 immunotherapy. Radiation therapy and

surgery of the primary tumor had been performed in 9 (69%) and 11 (85%) patients, respectively.

Study treatment and toxicity

Overall, 39 cycles were administered in 13 patients (Table 1), with a median of 2 cycles (range, 1-8) per patient. Eight patients received irradiation (loco-regional, n=6; metastasis, n=2) at doses of 20 to 40 Gy; all 4 brain tumors had re-irradiation.

Seventy-two of 194 (37%) adverse events of any grade were possibly treatment-related (Table 2); all non-hematologic events except one G3 vomiting were mild or moderate (G1-2). Five patients experienced possibly immune-mediated diarrhea (G1, n=3; G2, n=2), all with favorable recovery.

Antitumor activity

No confirmed objective response was observed in the 12 evaluable patients (Table 1). One patient with melanoma discontinued due to clinical progression after the first cycle. Five patients experienced stable disease as best response. One patient with DSRCT experienced reduction of target lesions of -29% at cycle 4 and -39% at cycle 6. A reduction of -37% of target lesions was noted at cycle 4 for the patient with ependymoma, although PR was not confirmed at the next assessment. They were treated during 8 and 6 months, respectively. Three additional patients had SD at cycle 2 as best response and progressed at 3.0 to 3.6 months. Discontinuation was related to PD in all patients. Six-months PFS and OS rates were 7.7% [95% CI, 1.4; 33.3] and 46.2% [95% CI, 23.2; 70.9], respectively (Figure 1). The median PFS was 1.7 months [95% CI, 1.3; 3.4] and the median OS was 3.4 months [95% CI, 2.2; 13.5].

Biomarker analysis and treatment-related immune system modulation

Eleven out of 12 patients had available tumor material to perform IHC for tumor immune infiltrate (Table 1, Figure 2A-D). Low PD-L1 expression (1%) on tumor cells was observed in one neuroblastoma, all other samples were PD-L1 negative. TILs were low in 10 evaluable samples, 1% in 6 patients, 5% in 1 patient and 10% in 3 patients. The median density of CD3-positive cells was 35 cells/mm² (range, 0-300).

Tumor mutational load was low in all 12 samples ranging from 0.04 to 1.52 mutation/Mb with a median of 0.42 mutation/Mb (Table 1).

Bulk RNAseq analysis in 9 contributive relapsed samples confirmed a low T cell signature, compared to a predominant pro-tumoral macrophage infiltration (Figure 2E).

We further analyzed the circulating immune cell phenotypes to explore the peripheral immune modulation under treatment (Figure 3; Supplementary Table 1). Paired analyses between Day 1 and 15 showed a decrease in absolute lymphocyte count ($p=0.01$) without a significant relative change of CD4+ and CD8+ T cells ($p=0.2$ and $p=0.4$, respectively). Among CD4+ T cells, Treg percentage remained stable. The pre-treatment level of PD-1+/CD8+ T cells varied from 0% to 61% of all CD8+ T cells, with no association with achieved disease control defined as prolonged SD. Study treatment exposure did not significantly modulate the percentage of CD4+ and/or CD8+ T-cells expressing immune modulatory markers such as CD57, CD160, CD5, CD69, OX40, and LAG3. The absolute peripheral circulating monocyte count (CD14+CD16- cells) as well as transient (CD14+CD16+) or residual monocytes (CD14^{low}/CD16+) did not significantly vary ($p=0.17$). Conversely, the NK cell absolute count as well as low/neg NK cells (CD56^{low}-CD16+) decreased significantly between baseline and C1D15 ($p=0.01$ and $p=0.007$, respectively), while bright- (CD56^{high}CD16-), inter- (CD56^{high}CD16+) and dim- (CD56^{low}CD16+) NK cells remained globally stable. No significant modification was displayed for neutrophils nor eosinophils ($p=0.77$ and $p=0.47$,

respectively). Interestingly, dNLR was lower than 3 in all patients at baseline, but increased significantly for all of them at Day 15 ($p=0.007$).

DISCUSSION

This phase II study explored the hypothesis that metronomic cyclophosphamide, alone or with radiation therapy, may modulate the immune response and enhance the activity of PD-1 inhibition in relapsed or refractory pediatric malignancies.

In our cohort of heavily pretreated patients, no patient experienced objective tumor response, 5 had SD as best response, two of them prolonged and with transient partial tumor regression. Based on these data, the study did not proceed to the second stage as per protocol design. These results are in line with previous reported data in adults on the modest activity of the PD-1 inhibitor pembrolizumab with metronomic cyclophosphamide in advanced osteosarcomas (13,14) and not different to single agent activity (7–10). The direct and “abscopal” impact of irradiation on cancer immune surveillance has been suggested in preclinical and clinical studies, even though optimal doses and schedules have not been defined (27). Eight of our 13 patients received radiation therapy as per physician’s decision. Although it is important to underline that among the 3 patients with DSRCT the only patient who presented a prolonged SD had received concomitant irradiation, the study design does not allow drawing any conclusion on its efficacy.

The identification of potential biomarkers is critical to better select patients and monitor therapeutic effects. In adults, several biomarkers involving tumor features (tumor cells, TME), blood (circulating cells, chemokines, cytokines), and stool microbiota have been associated to the activity of immune checkpoint inhibitors (28,29).

Pre-existing T-cell anti-tumor immunity is an important prerequisite to the anti-PD-1/PD-L1 response (30). In our cohort, IHC and RNAseq analyses confirmed the low density of tumor-infiltrating T cells compared with adult cancers, thus at least partially explaining the results of this study (31,32). In a meta-analysis including 1475 adults treated with nivolumab, pembrolizumab or atezolizumab, response rates were significantly higher in PD-L1 positive tumors (34% vs 19.9%), considering percentages of positivity higher than 5% (33). While PD-L1 expression in tumors has been associated with improved clinical response to PD-1/PD-L1 inhibitors in some adult tumor types, in pediatric cancers this evidence is limited (7,8). In our cohort, PD-L1 expression was found to be positive only in one patient and at low level, in agreement with previously reported studies (7,34,35). Other reasons that contribute to this limited activity might be the overall low tumor mutational load, predictive of response to checkpoint inhibitors since responsible for a reduced anti-tumor T cell response (29,36). Finally, the presence of an immunosuppressive TME, mainly pro-tumoral macrophages, is likely to be crucial to interpret these disappointing results. Indeed, the impact of tumor-associated macrophages (TAMs) on cancer progression has been described, although the involved mechanisms have not been fully characterized yet (37,38).

To monitor treatment effects directly on the TME was found not reasonable given the challenge to perform sequential tumor biopsies in children. In adults, the assessment of the prognostic and predictive value of circulating immune biomarkers in patients treated with immune checkpoint inhibitors is currently used, being an attractive tool owing to the easy accessibility of blood samples and limited costs of the technique (26,39,40). In our cohort, the flow cytometry analysis of circulating immune cells showed the lack of a significant phenotype modulation in T cells, including Treg, previously described with metronomic chemotherapy (41,42). This could be explained by the early timing of the second sampling or

be related to the chemotherapy schedule. Moreover, the potential counterproductive impact of the combination with a chemotherapy likely responsible for increased hematologic toxicity compared to immune checkpoint inhibitor monotherapy cannot be excluded, and other drugs, doses and schedules could be investigated (43).

Finally, although dNLR was low in comparison to adult cut-offs at baseline (26), noteworthy dNLR significantly increased after 2 weeks of treatment in all our patients, and its increase is a known negative predictive factor of response in adult cohorts (26).

To conclude, options for a more efficient development of checkpoint inhibitors in pediatrics could be the combination with modalities capable of bringing tumor-reactive effector lymphocytes into the tumor, such as engineered proteins (i.e. monoclonal antibodies and T cell engaging agents), cellular products (i.e. CAR-T cells and T cell receptor-engineered T cells) or peptide intra-tumor injection while improving on the other hand the reduced T-cell recognition (44). In parallel, the exploration of new immunotherapies targeting the innate immunity, especially TAMs, appears to be a top priority.

FUNDINGS

Supported by grants from the Institut National de Cancer (INCa) within the AcSé program, Fondation ARC (AcSé-ESMART and SIGN'IT), the Association Imagine for Margo, the Fédération Enfants et Santé, the Société Française de lutte contre les Cancers et les leucémies de l'Enfant et l'adolescent (SFCE), Bristol-Myers Squibb (BMS), and Fondation BMS. BG is supported by the 'Parrainage médecin-chercheur' of Gustave Roussy.

ACKNOWLEDGMENTS

We are grateful to all the patients and families who contributed to this study, their treating teams, to the Gustave Roussy Clinical Research Department for sponsoring the trial and to BMS for providing nivolumab.

REFERENCES

1. Grabow D, Kaiser M, Hjorth L, Byrne J, Alessi D, Allodji RS, et al. The PanCareSurFup cohort of 83,333 five-year survivors of childhood cancer: a cohort from 12 European countries. *Eur J Epidemiol*. 2018 Mar;33(3):335–49.
2. Topalian SL, Drake CG, Pardoll DM. Targeting the PD-1/B7-H1(PD-L1) pathway to activate anti-tumor immunity. *Curr Opin Immunol*. 2012 Apr;24(2):207–12.
3. Larkin J, Chiarion-Sileni V, Gonzalez R, Grob JJ, Cowey CL, Lao CD, et al. Combined Nivolumab and Ipilimumab or Monotherapy in Untreated Melanoma. *N Engl J Med*. 2015 Jul 2;373(1):23–34.
4. Giroux Leprieur E, Dumenil C, Julie C, Giraud V, Dumoulin J, Labrune S, et al. Immunotherapy revolutionises non-small-cell lung cancer therapy: Results, perspectives and new challenges. *Eur J Cancer*. 2017;78:16–23.
5. George S, Rini BI, Hammers HJ. Emerging Role of Combination Immunotherapy in the First-line Treatment of Advanced Renal Cell Carcinoma: A Review. *JAMA Oncol*. 2018 Nov 21;
6. Brahmer JR, Drake CG, Wollner I, Powderly JD, Picus J, Sharfman WH, et al. Phase I study of single-agent anti-programmed death-1 (MDX-1106) in refractory solid tumors: safety, clinical activity, pharmacodynamics, and immunologic correlates. *J Clin Oncol*. 2010 Jul 1;28(19):3167–75.
7. Georger B, Kang HJ, Yalon-Oren M, Marshall LV, Vezina C, Pappo A, et al. Pembrolizumab in paediatric patients with advanced melanoma or a PD-L1-positive, advanced, relapsed, or refractory solid tumour or lymphoma (KEYNOTE-051): interim analysis of an open-label, single-arm, phase 1-2 trial. *Lancet Oncol*. 2020 Jan;21(1):121–33.
8. Georger B, Zwaan CM, Marshall LV, Michon J, Bourdeaut F, Casanova M, et al. Atezolizumab for children and young adults with previously treated solid tumours, non-Hodgkin lymphoma, and Hodgkin lymphoma (iMATRIX): a multicentre phase 1-2 study. *Lancet Oncol*. 2020 Jan;21(1):134–44.
9. Georger B, Bergeron C, Gore L, Sender L, Dunkel IJ, Herzog C, et al. Phase II study of ipilimumab in adolescents with unresectable stage III or IV malignant melanoma. *Eur J Cancer*. 2017;86:358–63.
10. Davis KL, Fox E, Merchant MS, Reid JM, Kudgus RA, Liu X, et al. Nivolumab in children and young adults with relapsed or refractory solid tumours or lymphoma (ADVL1412): a multicentre, open-label, single-arm, phase 1-2 trial. *Lancet Oncol*. 2020;21(4):541–50.
11. Pearson ADJ, Rossig C, Lesa G, Diede SJ, Weiner S, Anderson J, et al. ACCELERATE and European Medicines Agency Paediatric Strategy Forum for medicinal product development of checkpoint inhibitors for use in combination therapy in paediatric patients. *Eur J Cancer*. 2020;127:52–66.

12. Mkrtichyan M, Najjar YG, Raulfs EC, Abdalla MY, Samara R, Rotem-Yehudar R, et al. Anti-PD-1 synergizes with cyclophosphamide to induce potent anti-tumor vaccine effects through novel mechanisms. *Eur J Immunol*. 2011 Oct;41(10):2977–86.
13. Toulmonde M, Penel N, Adam J, Chevreau C, Blay J-Y, Le Cesne A, et al. Use of PD-1 Targeting, Macrophage Infiltration, and IDO Pathway Activation in Sarcomas: A Phase 2 Clinical Trial. *JAMA Oncol*. 2018 Jan 1;4(1):93–7.
14. Le Cesne A, Marec-Berard P, Blay J-Y, Gaspar N, Bertucci F, Penel N, et al. Programmed cell death 1 (PD-1) targeting in patients with advanced osteosarcomas: results from the PEMBROSARC study. *Eur J Cancer*. 2019 Sep;119:151–7.
15. Liu Y, Dong Y, Kong L, Shi F, Zhu H, Yu J. Abscopal effect of radiotherapy combined with immune checkpoint inhibitors. *J Hematol Oncol*. 2018 16;11(1):104.
16. Golden EB, Chhabra A, Chachoua A, Adams S, Donach M, Fenton-Kerimian M, et al. Local radiotherapy and granulocyte-macrophage colony-stimulating factor to generate abscopal responses in patients with metastatic solid tumours: a proof-of-principle trial. *Lancet Oncol*. 2015 Jul;16(7):795–803.
17. Georger B, Schleiermacher G, Pierron G, Lacroix L, Deloger M, Bessoltane N, et al. Abstract CT004: European pediatric precision medicine program in recurrent tumors: first results from MAPPYACTS molecular profiling trial towards AcSe-ESMART proof-of-concept study. *Cancer Res*. 2017 Jul 1;77(13 Supplement):CT004.
18. Schwartz LH, Seymour L, Litière S, Ford R, Gwyther S, Mandrekar S, et al. RECIST 1.1 - Standardisation and disease-specific adaptations: Perspectives from the RECIST Working Group. *Eur J Cancer*. 2016;62:138–45.
19. Wen PY, Chang SM, Van den Bent MJ, Vogelbaum MA, Macdonald DR, Lee EQ. Response Assessment in Neuro-Oncology Clinical Trials. *J Clin Oncol*. 2017 Jul 20;35(21):2439–49.
20. Park JR, Bagatell R, Cohn SL, Pearson AD, Villablanca JG, Berthold F, et al. Revisions to the International Neuroblastoma Response Criteria: A Consensus Statement From the National Cancer Institute Clinical Trials Planning Meeting. *J Clin Oncol*. 2017 Aug 1;35(22):2580–7.
21. Simon R. Optimal two-stage designs for phase II clinical trials. *Control Clin Trials*. 1989 Mar;10(1):1–10.
22. Harttrampf AC, Lacroix L, Deloger M, Deschamps F, Puget S, Auger N, et al. Molecular Screening for Cancer Treatment Optimization (MOSCATO-01) in Pediatric Patients: A Single-Institutional Prospective Molecular Stratification Trial. *Clin Cancer Res*. 2017 Oct 15;23(20):6101–12.
23. Berlanga P, Pierron G, Lacroix L, Adam de Beaumais T, Bernard V, Cotteret S, et al. Can pediatric and adolescent patients with recurrent tumors benefit from a precision medicine program? The European MAPPYACTS experience. *JCO*. 2019 May 20;37(15_suppl):10018–10018.

24. Newman AM, Liu CL, Green MR, Gentles AJ, Feng W, Xu Y, et al. Robust enumeration of cell subsets from tissue expression profiles. *Nat Methods*. 2015 May;12(5):453–7.
25. Pitoiset F, Cassard L, El Soufi K, Boselli L, Grivel J, Roux A, et al. Deep phenotyping of immune cell populations by optimized and standardized flow cytometry analyses. *Cytometry A*. 2018;93(8):793–802.
26. Mezquita L, Auclin E, Ferrara R, Charrier M, Remon J, Planchard D, et al. Association of the Lung Immune Prognostic Index With Immune Checkpoint Inhibitor Outcomes in Patients With Advanced Non-Small Cell Lung Cancer. *JAMA Oncol*. 2018 Mar 1;4(3):351–7.
27. Ngwa W, Irabor OC, Schoenfeld JD, Hesser J, Demaria S, Formenti SC. Using immunotherapy to boost the abscopal effect. *Nat Rev Cancer*. 2018;18(5):313–22.
28. Yuasa T, Masuda H, Yamamoto S, Numao N, Yonese J. Biomarkers to predict prognosis and response to checkpoint inhibitors. *Int J Clin Oncol*. 2017 Aug;22(4):629–34.
29. Rizvi H, Sanchez-Vega F, La K, Chatila W, Jonsson P, Halpenny D, et al. Molecular Determinants of Response to Anti–Programmed Cell Death (PD)-1 and Anti–Programmed Death-Ligand 1 (PD-L1) Blockade in Patients With Non–Small-Cell Lung Cancer Profiled With Targeted Next-Generation Sequencing. *Journal of Clinical Oncology*. 2018 Mar;36(7):633–41.
30. Hamid O, Schmidt H, Nissan A, Ridolfi L, Aamdal S, Hansson J, et al. A prospective phase II trial exploring the association between tumor microenvironment biomarkers and clinical activity of ipilimumab in advanced melanoma. *J Transl Med*. 2011 Nov 28;9:204.
31. Vakkila J, Jaffe R, Michelow M, Lotze MT. Pediatric cancers are infiltrated predominantly by macrophages and contain a paucity of dendritic cells: a major nosologic difference with adult tumors. *Clin Cancer Res*. 2006 Apr 1;12(7 Pt 1):2049–54.
32. Carbognin L, Pilotto S, Nortilli R, Brunelli M, Nottegar A, Sperduti I, et al. Predictive and Prognostic Role of Tumor-Infiltrating Lymphocytes for Early Breast Cancer According to Disease Subtypes: Sensitivity Analysis of Randomized Trials in Adjuvant and Neoadjuvant Setting. *Oncologist*. 2016 Mar;21(3):283–91.
33. Carbognin L, Pilotto S, Milella M, Vaccaro V, Brunelli M, Calì A, et al. Differential Activity of Nivolumab, Pembrolizumab and MPDL3280A according to the Tumor Expression of Programmed Death-Ligand-1 (PD-L1): Sensitivity Analysis of Trials in Melanoma, Lung and Genitourinary Cancers. *PLoS ONE*. 2015;10(6):e0130142.
34. Majzner RG, Simon JS, Grosso JF, Martinez D, Pawel BR, Santi M, et al. Assessment of programmed death-ligand 1 expression and tumor-associated immune cells in pediatric cancer tissues. *Cancer*. 2017 Oct 1;123(19):3807–15.
35. Aoki T, Hino M, Koh K, Kyushiki M, Kishimoto H, Arakawa Y, et al. Low Frequency of Programmed Death Ligand 1 Expression in Pediatric Cancers. *Pediatr Blood Cancer*. 2016;63(8):1461–4.

36. Marabelle A, Fakih M, Lopez J, Shah M, Shapira-Frommer R, Nakagawa K, et al. Association of tumour mutational burden with outcomes in patients with advanced solid tumours treated with pembrolizumab: prospective biomarker analysis of the multicohort, open-label, phase 2 KEYNOTE-158 study. *Lancet Oncol.* 2020;21(10):1353–65.
37. Komohara Y, Takeya M. CAFs and TAMs: maestros of the tumour microenvironment. *J Pathol.* 2017;241(3):313–5.
38. Chen Y, Song Y, Du W, Gong L, Chang H, Zou Z. Tumor-associated macrophages: an accomplice in solid tumor progression. *Journal of Biomedical Science.* 2019 Oct 20;26(1):78.
39. Prelaj A, Tay R, Ferrara R, Chaput N, Besse B, Califano R. Predictive biomarkers of response for immune checkpoint inhibitors in non-small-cell lung cancer. *Eur J Cancer.* 2019;106:144–59.
40. Charrier M, Mezquita L, Lueza B, Dupraz L, Planchard D, Remon J, et al. Circulating innate immune markers and outcomes in treatment-naïve advanced non-small cell lung cancer patients. *Eur J Cancer.* 2019;108:88–96.
41. Ghiringhelli F, Menard C, Puig PE, Ladoire S, Roux S, Martin F, et al. Metronomic cyclophosphamide regimen selectively depletes CD4+CD25+ regulatory T cells and restores T and NK effector functions in end stage cancer patients. *Cancer Immunol Immunother.* 2007 May;56(5):641–8.
42. Cerullo V, Diaconu I, Kangasniemi L, Rajecki M, Escutenaire S, Koski A, et al. Immunological effects of low-dose cyclophosphamide in cancer patients treated with oncolytic adenovirus. *Mol Ther.* 2011 Sep;19(9):1737–46.
43. Wu J, Waxman DJ. Immunogenic chemotherapy: Dose and schedule dependence and combination with immunotherapy. *Cancer Lett.* 2018 Apr 10;419:210–21.
44. Majzner RG, Heitzeneder S, Mackall CL. Harnessing the Immunotherapy Revolution for the Treatment of Childhood Cancers. *Cancer Cell.* 2017 Apr;31(4):476–85.

Table 1. Patients and tumor characteristics (n=13)

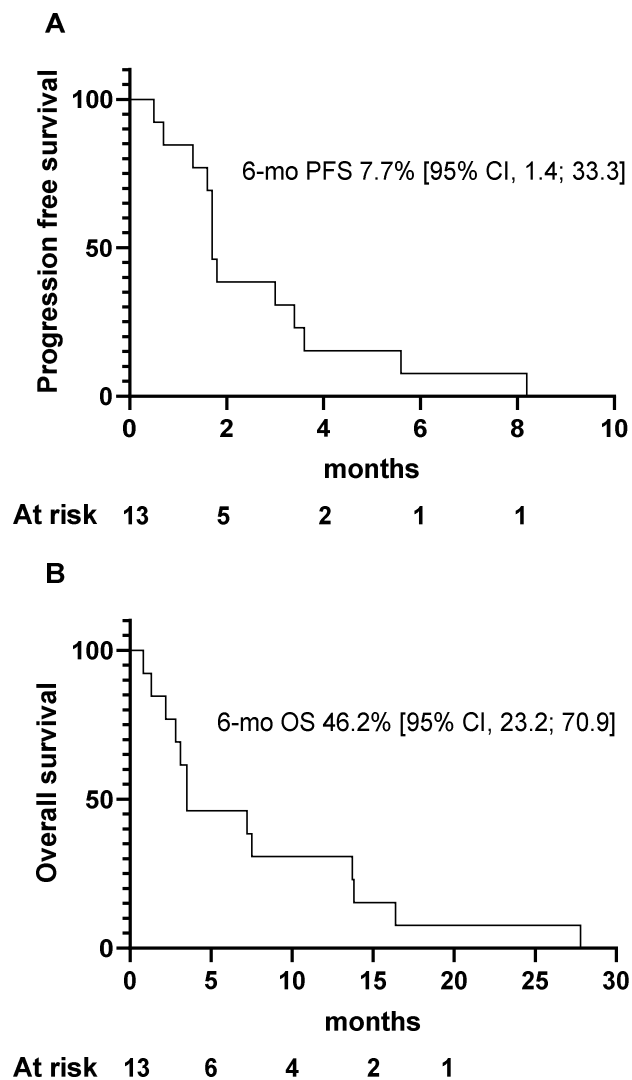
Patient	Diagnosis	Gender	Age (yrs)	Site of biopsy	PDL1	TILs	CD3 (cc/mm ²)	Mutational load (Mut/Mb)	RT	If RT Gy	N° cycles	Best response	Best response Cycle	PFS (mo)	OS (mo)
1	Neuroblastoma	M	5.8	M	1%	1%	90	NA	No		1	PD	1	0.5	0.8
2	Neuroblastoma	M	19.4	M	0%	NA	NA	1.52	No		2	PD*	2	1.6	13.7
3	Glioblastoma - midline (pineal, H3F3A)	M	15.9	M	NA	NA	NA	0.26	Brain	25	2	PD	2	1.7	7.5
4	Malignant glioma NOS	F	18.0	L	0%	1%	0	0.62	Brain	20	3	SD	2	3.0	13.7
5	DSRCT	M	17.9	L	0%	10%	120	0.22	LN	24	8	SD (uPR)	6	8.2	16.4
6	Melanoma	M	5.5	M LN	0%	1%	0	0.32	No		1	PD	1	0.7	1.3
7	Ependymoma	M	16.4	L	0%	5%	40	1.12	Brain	UKN	6	SD (uPR)	4	5.6	27.8
8	High grade glioma - thalamic ACVR1	F	7.2	L	0%	1%	0	0.04	Brain	25	4	SD	2	3.6	7.2
9	Rhabdomyosarcoma - alveolar	F	11.8	M	NA	NA	NA	0.36	Extremity	40	2	PD	2	1.7	2.7
10	Neuroblastoma	M	6.9	M LN	0%	10%	200	0.48	LN	25	2	PD	2	1.8	3.1
11	DSRCT	M	16.5	L	0%	1%	8	0.35	No		4	SD	2	3.4	3.4
12	Rhabdomyosarcoma - alveolar	M	14.3	M	0%	10%	300	0.55	Whole lung	25	2	PD	2	1.7	3.5
13	DSRCT	M	17.3	M	0%	1%	30	0.70	No		2	PD	2	1.3	2.2

DSRCT: desmoplastic small round cell tumor; NOS: not otherwise specified; M: male; F: female; M: metastasis; L: loco-regional; M LN: lymph node metastasis; NA: not available; PD-L1: Programmed death-ligand 1; TILs: tumor infiltrating lymphocytes; SD: stable disease; uPR: unconfirmed partial response; PFS: progression free survival; OS: overall survival. *Patient had mIBG positive disease only.

Table 2. All grades treatment-related adverse events (n=72) in 13 patients receiving 39 treatment cycles during the whole treatment duration

AE term (CTCAE v4.0)	G1	G2	G3	G4
Blood and lymphatic system disorders				
Anemia	1	8	4	0
Gastrointestinal disorders				
Abdominal pain	1	0	0	0
Nausea	0	1	0	0
Vomiting	3	1	2	0
Oral mucositis	0	1	0	0
Diarrhea	3	2	0	0
General disorders				
Fatigue	4	1	0	0
Investigations				
Cholesterol high	1	0	0	0
Lymphocyte count decreased	0	11	7	2
Neutrophil count decreased	1	1	3	1
Platelet count decreased	0	0	0	1
White blood cell decreased	2	1	1	1
Metabolism and nutrition disorders				
Anorexia	1	0	0	0
Hyperglycemia	0	1	0	0
Hyponatremia	1	0	0	0
Respiratory, thoracic and mediastinal disorder				
Cough	1	0	0	0
Dyspnea	1	0	0	0
Nervous system disorders				
Paresthesia	1	0	0	0
Skin and subcutaneous tissue disorders				
Skin pain	1	0	0	0
Total	22	28	17	5

Figure 1. Kaplan-Meier curves of Progression-free (PFS) (A) and overall survival (OS) (B) in the population of all treated patients (n = 13)



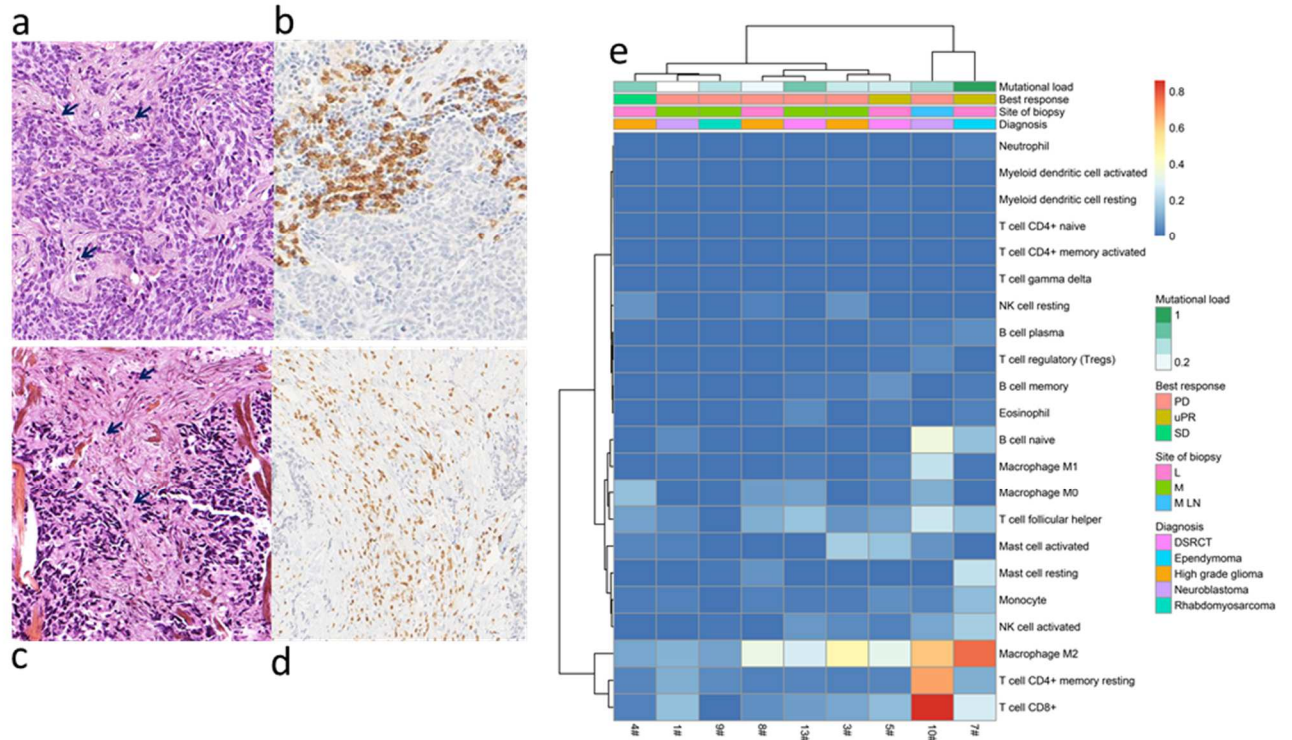


Figure 2. Tumor microenvironment features. Tumor microenvironment features. A-D) Representative sections of one case of DSRCT (a and b), and one case of alveolar rhabdomyosarcoma (c and d); hematoxylin-eosin-saffron (HES) staining (a and c) and CD3 immunostaining (b and d). In the case of the DSRCT, TILs are scattered in the stroma (a, arrows) and small aggregates of CD3+ T cells (b) are detected at the interface between stroma and tumor cells; no CD3+ cell is present within the tumor. In the case of alveolar rhabdomyosarcoma, TILs (c, arrows) and CD3+ T cells (d) are scattered in the stroma at distance from tumor cells. Original magnifications: a) x280; b) x220; c) x240; d) x180. E) Heatmap of RNA expression of immune cell subtypes (rows) by CIBERSORT abs., according to diagnosis, site of biopsy, best response and mutational load (n=9, patients in columns). DSRCT, desmoplastic small round cell tumor; L, loco-regional primary tumor; M, metastasis; M LN, lymph node metastasis; uPR, unconfirmed partial response; SD: stable disease; PD: progressive disease.

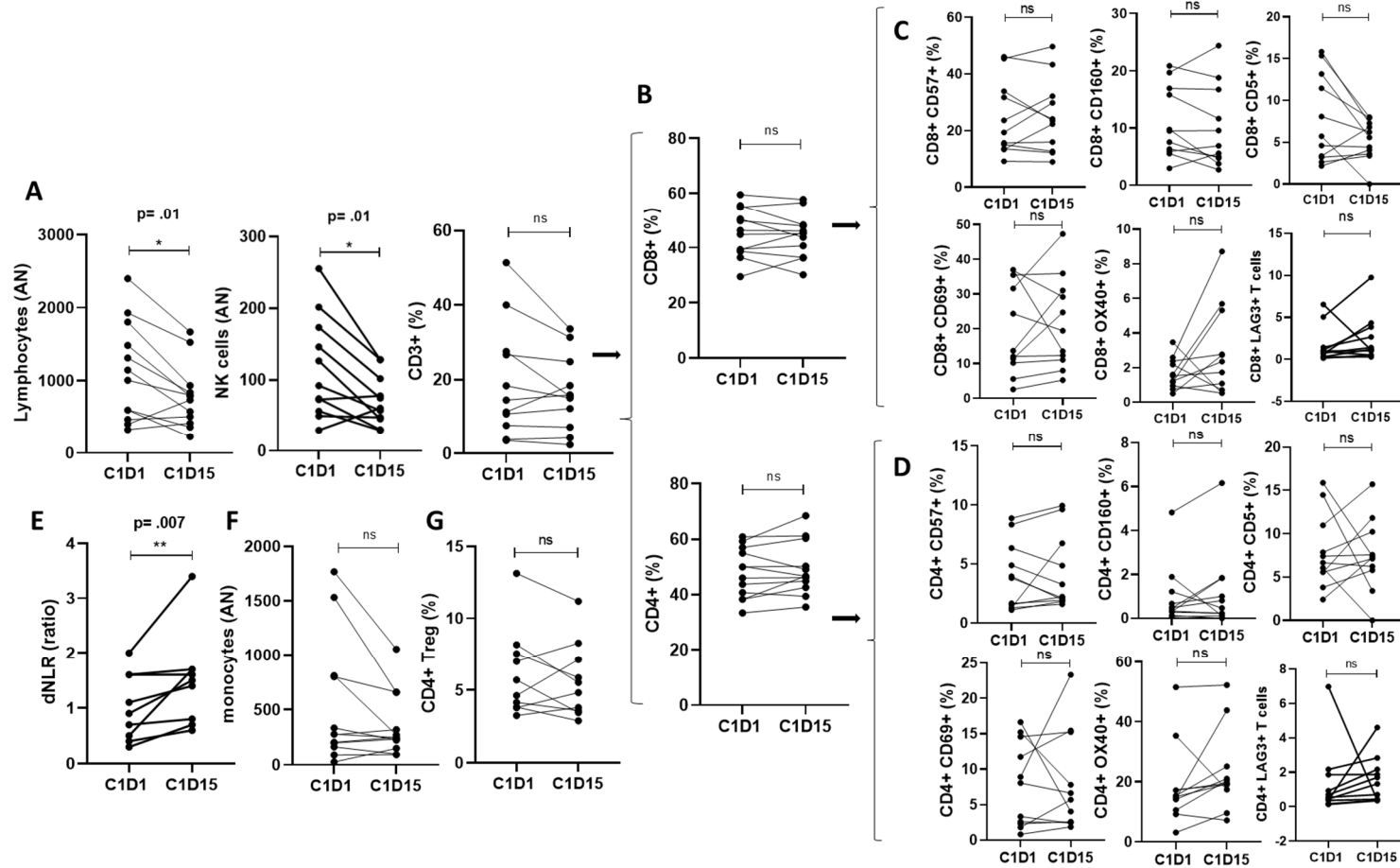


Figure 3. Modulation of circulating immune populations by flow cytometry, comparison of paired samples between C1D1 and C1D15. A) A decrease of the absolute number (AN) of lymphocytes and Natural Killer (NK) cells is displayed during treatment, while the percentage (%) of CD3+ cells is stable, $n = 10$; B) Relative number of CD4+ and CD8+ cells among CD3+ cells does not vary over time, $n = 8$; C-D) The expression of immune modulation markers such as CD57, CD69, CD160, CD5, and OX40 on CD8+ (C) and CD4+ cells (D) is not significantly modified by the treatment, $n = 10$; E) Derived Neutrophil-to-Lymphocyte ratio (dNLR) significantly increases during treatment, $n = 8$; F-G) The AN of

monocytes (F, n=8) and the percentage of regulatory T cells (Treg) among CD4+ T cells (G, n=10) do not significantly vary over time, respectively.