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Review

The immune landscape of neuroblastoma: Challenges and opportunities for novel therapeutic strategies in pediatric oncology

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Abstract Immunotherapy holds great promise for the treatment of pediatric cancers. In neuroblastoma, the recent implementation of anti-GD2 antibody Dinutuximab into the standard of care has improved patient outcomes substantially. However, 5-year survival rates are still below 50% in patients with high-risk neuroblastoma, which has sparked investigations into novel immunotherapeutic approaches. T cell-engaging therapies such as immune checkpoint blockade, antibody-mediated therapy and adoptive T cell therapy have proven remarkably successful in a range of adult cancers but still meet challenges in pediatric oncology. In neuroblastoma, their limited success may be due to several factors. Neuroblastoma displays low immunogenicity due to its low mutational load and lack of MHC-I expression. Tumour infiltration by T and NK cells is especially low in high-risk neuroblastoma and is prognostic for survival. Only a small fraction of tumour-infiltrating lymphocytes shows tumour reactivity. Moreover, neuroblastoma tumours employ a variety of immune evasion strategies, including expression of immune checkpoint molecules, induction of immunosuppressive myeloid and stromal cells, as well as secretion of immunoregulatory mediators, which reduce infiltration and reactivity of immune cells. Overcoming these challenges will be key to the successful implementation of novel immunotherapeutic interventions. Combining different immunotherapies, as well as personalised strategies, may be promising approaches. We will discuss the composition, function and prognostic value of tumour-infiltrating lymphocytes (TIL) in neuroblastoma, reflect on challenges for immunotherapy, including a lack of TIL reactivity and tumour immune evasion strategies, and highlight opportunities for immunotherapy and future

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perspectives with regard to state-of-the-art developments in the tumour immunology space.
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1. Introduction

Immunotherapy has recently led to a leap in survival rates in a variety of adult cancers [1]. State of the art immune interventions include immune checkpoint inhibition (ICI), antibody-mediated therapy and adoptive T cell therapy. Although immunotherapy may also hold great promise for pediatric oncology, it is still in the early stages of development for pediatric solid cancers. The increased survival of patients with high-risk neuroblastoma following the implementation of anti-GD2 therapy into standard care exemplifies the potential of immunotherapy in pediatric oncology [2].

Neuroblastoma is one of the most common extracranial solid tumours in children, arising from neural crest progenitor cells in the sympathetic nervous system. It presents with tumour masses in the adrenal glands and/or sympathetic ganglia. The prognosis of neuroblastoma depends heavily on the disease stage [3,4]. Patients are stratified into risk groups based on molecular factors and disease presentation, including patient age, tumour histology, localised versus metastatic disease, and genomic alterations, among which *MYCN* amplification is an important driver of poor prognosis [4,5]. Whereas patients with low-risk (LR) disease have a favourable prognosis with >90% survival, the 5-year survival rate of patients with high-risk (HR) disease is still below 50% [3]. The current standard of care for patients with HR-neuroblastoma consists of an intense treatment protocol with induction chemotherapy, surgical tumour resection, consolidation with single or tandem high dose chemotherapy followed by autologous stem cell transplantation, radiotherapy and immunotherapy with the anti-GD2 antibody Dinutuximab (which is currently combined with isotretinoin and in some regions with GM-CSF, but not anymore with IL-2) [6]. Dinutuximab-dependent cytotoxicity is thought to be mainly mediated by neutrophils and natural killer (NK) cells [7,8]. The introduction of immunotherapy into the standard treatment regimen has significantly improved survival rates [6,9–13]. However, the current prognosis with less than 50% survival in patients with HR-neuroblastoma remains dismal, nonetheless, with disease relapses being an important factor.

The encouraging results of Dinutuximab, but still unsatisfactory prognosis, have sparked investigations into novel immunotherapeutic approaches, which may provide immunological memory against the tumour to prevent disease relapses. Immune interventions that have demonstrated great success in a range of adult cancers, such as ICI and adoptive T cell therapy, however, meet challenges in pediatric oncology, resulting in limited effectivity [2,14]. First, pediatric solid cancers in general (and neuroblastoma in specific) have low immunogenicity, which can be attributed to a low mutational burden and consequently low neoepitope expression, as well as low expression of MHC-I [15–17]. This low immunogenicity results in a lack of tumour infiltration by lymphocytes and a suboptimal antitumour reactivity of the few tumour-infiltrating lymphocytes (TIL) present. Furthermore, tumour immune evasion strategies that are active both in the tumour microenvironment (TME) and systemically can additionally hamper lymphocyte infiltration and activity [18]. These factors, taken together, impede effective engagement of cytotoxic killer cells such as NK cells and cytotoxic T lymphocytes (CTL) during immunotherapy [1,2]. Successful implementation of novel immunotherapeutic interventions in pediatric oncology will, therefore, likely require a different or more extensive approach than in adults.

To provide a perspective for the development of novel immunotherapeutic strategies in neuroblastoma, we will 1) discuss the composition, function and prognostic value of TIL in neuroblastoma, 2) reflect on challenges for immunotherapy, including a lack of TIL reactivity and tumour immune evasion strategies, and 3) highlight opportunities for immunotherapy and future perspectives with regard to state-of-the-art developments in the tumour immunology space.

2. Tumour-infiltrating lymphocytes in neuroblastoma

2.1. TIL composition in human neuroblastoma

Although neuroblastoma has been considered to be an immunologically 'cold' tumour [19,20], multiple studies have demonstrated the presence of TIL, including T cells and NK cells, in human neuroblastoma tumours (Table 1 and Fig. 1) [21–42]. Also, invariant natural killer T cells (iNKT), NKT cells and γδ T cells have been identified [34–36,43], whereas B cells are rare and mostly undetectable [21,22,41]. The number and composition of TIL vary significantly between individual patients and tumour samples, with TIL detected in 28%–100% of tumours by immunohistochemistry (IHC) [24–27]. $CD3^+$ T cells make up ~5% of total cells in the tumour microenvironment (TME) [22,23], consist of both $CD4^+$ and $CD8^+$ T cells, and are more frequently detected in septa than tumour nests [28–30].

Table 1

TIL presence and distribution in human neuroblastoma. Disc = discovery cohort, FC = flow cytometry, ganglioNBL = ganglioneuroblastoma, HR = high-risk, IF = immunofluorescence, IHC = immunohistochemistry, IR = intermediate risk, LR = low-risk, MYCN-NA = MYCN non amplified, NBL = neuroblastoma, NHR = non high-risk, NK cells = natural killer cells, (i)NKT cells = (invariant) natural killer T cells, Pts = patients, (RT-q)PCR = (reverse transcriptase-quantitative) Polymerase Chain Reaction, seq = sequencing, TCR = T cell receptor, TIL = tumour infiltrating lymphocytes, Val = validation cohort, γδ T = gammadelta T cells.

Ref	Patients/samples/ material	Stage	Method	Lymphocytes	T cells		Other lymphocytes	
					CD3	CD4, CD8 and Tregs	NK, NKT and γδ T cells	B cells
[21]	9/9. Primary tumour	4	FC of ficoll-isolated cell fraction after digestion		10–80% (mean 50%) of total	CD4/CD8 ratio 0.5–5	NK: 1–30%	<2%
[22]	26/26. Primary tumour	3, 4	FC of total single-cell suspension after digestion		5% of viable cells			
[23]	8/8. Primary tumour versus blood	1, 2, 3, 4	FC of total single-cell suspension after digestion		0.4–17.8% (mean 4.5%) in TIL	CD4/CD8 ratio: TIL 0.3–1.7 (mean 0.8) versus PBL 0.2–2.7 (mean 1.5)		
[35]	24/30. Primary tumour	Unknown	FC of *ex vivo* expanded TIL		Present	CD4 and CD8 present	NKT present. γδ T present.	
[24]	53/53. Primary tumour	1, 2, 3, 4	IHC	In 28% of pts				
[25]	23/23. Primary tumour	N/A	IHC	In 96% of pts				
[22]	26/26. Primary tumour	3, 4	IHC CD3, CD4 and CD8	Organised lymphoid tissue and B-cell follicles at edges of tumour nests	CD3, including CD4 and CD8: 88% of lymphocytes in peritumoural stroma	CD4 and CD8 minimal/ undetectable in nests	NK rare/ undetectable	rare/ undetectable
[33]	15/15. Primary tumour	LR, IR, HR	IHC CD45 and CD4	Present		CD4 present		
[27]	111 untreated and 8 treated. Primary tumour	1, 2, 3, 4/ LR, MR, HR	IHC H&E	In 83% of NBL and 89% of ganglioNBL				
[29]	3 HLA*A201 patients. NY-ESO-1+ tumours from metastatic relapse	4	IHC		Present in nests and septa			
[26]	21/21. Primary tumour	N/A	IHC CD3		in 100% of samples			
[30]	84/84. Primary tumour	1, 2, 3, 4	IHC CD3, CD4 and CD8		~1.5x more frequent in septa than nests	CD4 and CD8 ~2x more frequent in septa than nests		
[31]	55/55. Primary tumour and metastasis	HR, NHR	IHC CD8			CD8 present in ~50–100% of HR and NHR tumours		
[28]	36/36. Resection tumour		IHC CD8			CD8 present in septa, nests and perivascular		
[38]	80/80	1, 2, 3, 4, 4S	IHC CD8			CD8 present		
[36]	129/129 MYCN-NA. Primary tumour	4	IF				NKT present	
[40]	8/8. Primary tumour versus blood	2, 3, 4	PCR of TCR		Polyclonal TCR, diverse Vα and Vβ. Vβ2 clonality in tumours.			
[43]	98/98. Primary tumour	4	RT-qPCR Vα24-Jα18, Flow cytometry				iNKT in 53% of samples	

(*continued on next page*)

Table 1 (*continued*)

Ref	Patients/samples/ material	Stage	Method	Lymphocytes	T cells		Other lymphocytes	
					CD3	CD4, CD8 and Tregs	NK, NKT and γδ T cells	B cells
[34]	107/107. Primary tumour	1, 2, 3, 4, 4S	RT-qPCR Vα24-Jα18				iNKT in 64% of samples	
[41]	2 patients (1 paired primary and resection, 1 resection)		10 × single-cell RNA seq		~2% in primary, 10–40% of cells in resection		NK: Undetectable in primary, ~0–20% in resection	Undetectable in primary, ~5% of resection
[33]	TARGET (n = 148). Primary tumour	1, 2, 3, 4	Deconvolution of bulk RNA seq with CIBERSORT	Present	Present	CD4 and CD8 present	NK present	Present
[39]	498 primary NBL. Primary tumour	4	Deconvolution of bulk RNA seq with CIBERSORT. Immune signature from [243]			CD8 present. Tregs present.	NK present	
[38]	TARGET (n = 150). Val (n = 190). Primary tumour	3, 4, 4S	Deconvolution of bulk RNA seq with CIBERSORT, TCR seq		Present. Some TCR clonality in *MYCN*-NA	CD4 and CD8 present	NK present. γδ T present.	Present
[37]	TARGET (n = 149). Val (n = 498), (n = 649), (n = 88). Primary tumour.	1, 2, 3, 4, 4S	Deconvolution of bulk RNA seq with xCell		Present	CD4 and CD8 present	NKT present	
[42]	TARGET (n = 160) and Val (n = 498). Primary tumour	1, 2, 3, 4, 4S	Deconvolution of bulk RNA seq with CIBERSORT		Present	CD4 and CD8 present	NK present	Present

Compared to blood, $CD8^+$ T cells are preferentially present over $CD4^+$ T cells in the TME, with reported CD4/CD8 ratios ranging from 0.3 to 5 [21,23,29]. Functionally, TIL are able to produce IL-4, IL-5, IL-8,

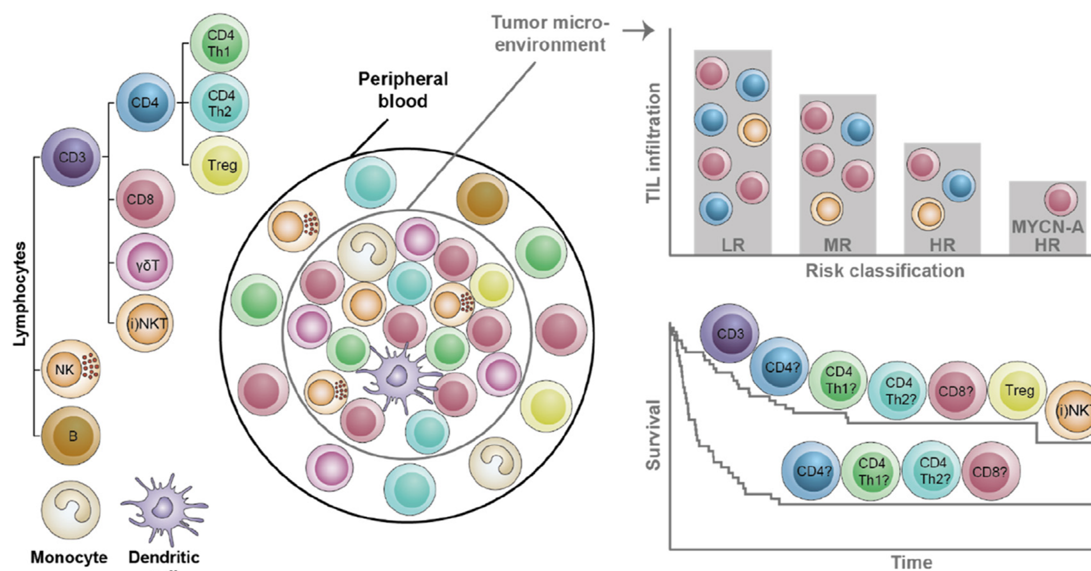

Fig. 1. **TIL composition and prognostic value.** T cells ($CD8^+$ T cells more than $CD4^+$ Th1, Th2 and Treg cells), NK cells, (i)NKT cells and a small number of B cells have been described in neuroblastoma tumours. High-risk (HR) tumours have less TIL infiltration than low-risk (LR) and medium risk (MR) tumours, with MYCN-A tumours having the lowest TIL infiltration. High infiltration of total $CD3^+$ T cells, Tregs and (i)NKT cells has been associated with improved survival, while the prognostic value of $CD4^+$ T cells, $CD4^+$ T helper subsets and $CD8^+$ T cells remains to be elucidated.

IL-10, interferon (IFN)-γ and TNFα mRNA in response to *ex vivo* stimulation with IL-2, which suggests a mixed population of both Th1 and Th2 cells [21]. The presence of Th17 cells in neuroblastoma has not been studied yet. NK cells were also variably detected, ranging from rare presence to constituting up to ~30% of TIL [21,22]. Since only two studies so far have compared *ex vivo* TIL characteristics to peripheral blood lymphocytes (PBL) from matched blood, one of which focused on the T cell receptor (TCR) repertoire, it is still unknown in which respect neuroblastoma-infiltrating lymphocytes have undergone functional specialisation and/or differentiation compared to their counterparts in blood.

Due to the limited availability of fresh neuroblastoma tumour material and the practical challenges of in-depth immune analyses, most studies describe a limited number of patients. Recent publications have resorted to computational methods to shed light on the immune composition of neuroblastoma and identified traces and signatures of immune infiltration by deconvolution of bulk RNA sequencing data of tumour samples [33,37–39]. At least 50% of cell components in the TME were predicted to consist of immune cells, half of which myeloid and half lymphoid [37]. The myeloid compartment was predicted to mainly consist of dendritic cells (DC), next to a small fraction of macrophages. The lymphoid compartment was dominated by $CD4^+$ T helper cells, next to B cells and a small fraction of $CD8^+$ cytotoxic T cells [37]. This contrasts with the $CD8^+$ dominance proposed by IHC-based studies, which may be due to differences in definitions and sensitivity of the methods. NK cells, NKT cells and γδ T cells were predicted to be present as well [33,37–39]. Of note, not only in primary but also in relapsed tumours, infiltration of $CD3^+$ T cells has been demonstrated [29].

Recently, the first single-cell RNA sequencing study of neuroblastoma showed a remarkable increase of T cell infiltration after chemotherapy in a paired patient sample – one taken at diagnosis and one in resection material after neo-adjuvant chemotherapy – indicating that chemotherapy-induced immunogenic cell death may attract lymphocytes to the tumour. The amount of lymphocyte infiltration after chemotherapy differed substantially between tumours of different patients [41].

The discrepancies between IHC-based and computational studies highlight the need for more standardised, high-quality and in-depth immunophenotyping in neuroblastoma. Future studies using techniques with single-cell resolution, comparing TIL and patient-matched PBL, will be essential to gain more insight into TIL composition, functional specialisation and changes over time upon therapy or disease progression.

2.2. Prognostic value of TIL profile

2.2.1. Prognostic value of TIL abundance

Although it is still largely unclear whether differences in immune cell infiltration are due to tumour characteristics, medication effects, or other factors, the extent and type of TIL infiltration has been associated with prognosis (Fig. 1) [24,25]. Martin & Beckwith, 50 years ago, demonstrated a stepwise decrease of lymphocyte infiltration with increasing tumour stage and a higher 2-year survival in patients with infiltrates than without infiltrates (Survival: 64% in TIL^{high} versus 11% TIL^{low}) [24]. Lauder & Aherne reported a direct correlation between survival time and intensity of lymphocytic infiltration in the primary tumour ($r_s = 0.69$, $p < 0.001$) [25]. These findings are now supported by more recent studies, showing reduced $CD3^+$, $CD4^+$ and $CD8^+$ T cell infiltration in high-risk, and especially in stage 4 tumours, as well as higher survival rates in patients with higher lymphocyte, $CD3^+$ and $CD4^+$ T cell infiltration (Table 2) [28,30,32,33,39,44]. Stratification of patients by $CD3^+$ TIL density demonstrated a significantly higher disease-free survival (DFS), overall survival (OS) and event-free survival (EFS) in patients with a higher TIL density [30,32]. Although Martin & Beckwith did not find a prognostic value of TIL infiltration for survival rates within the group of stage 3/4 tumours (OS: 17% in TIL^{high} versus 11% in TIL^{low}) [24], two other studies did observe a survival benefit of TIL infiltration in stage 4 neuroblastoma [39,44]. Not only the amount but also the localisation and organisation of T cells in the TME has prognostic value. Neuroblastoma patients with favourable outcomes were characterised by a more structured T cell infiltrate, which was gradually lost in tumours with a poor prognosis. While proliferating T cells were localised in close proximity to tumour cells in stage 4S tumours, they were placed distant from tumour cells in stage 4 tumours. Moreover, stage 4S tumours were characterised by a higher number of proliferating $Ki67^+CD3^+$ T cells than stage 4 tumours [30]. The role of immune surveillance in the spontaneous regression of 4S tumours, however, remains to be elucidated [45].

Overall, these results suggest a strong relation between TIL density and both tumour stage and patient survival. One may speculate that the association between TIL infiltration and tumour stage is related to the differentiation grade of the tumour, since it is an important determinant of tumour risk stage, and may influence immunogenicity [46]. For example, the notoriously low MHC-I expression of neuroblastoma [16], rather than being the result of active downregulation, may reflect the pre-MHC-I expressing, undifferentiated state of the neural crest [47]. Moreover, *in vitro* differentiation of neuroblastoma cell lines and *ex vivo* tumours was associated with increased immunogenicity, e.g. upregulated MHC-I expression, and

Table 2
Prognostic significance of TIL presence and composition in human neuroblastoma. » = positively associated with, DC = dendritic cell, disc = discovery cohort, expr = expression, EFS = event-free survival, fav = favourable, FC = flow cytometry, GFEA = Gene functional enrichment analysis, HR = high-risk, IHC = immunohistochemistry, IR = intermediate risk, LR = low-risk, mono = monocytes, MYCN-(N)A = MYCN-(non) amplified, MØ = macrophage, NBL = neuroblastoma, NHR = non-high-risk, OS = overall survival, Pts = patients, (RT-q)PCR = (reverse transcriptase-quantitative) Polymerase Chain Reaction, seq = sequencing, Th = T helper, TIL = tumour infiltrating lymphocytes, unfav = unfavourable, val = validation cohort, WGCNA = Weighted Gene Coexpression Network Analysis.

Ref	Patients/ samples	Stage	Method	Tumour stage					Risk	Survival analysis		*MYCN*
				1	2	3	4	4S	HR versus IR/LR	T cells	Other lymphocytes (γδ T, NK, (i)NKT and B)	
[23]	8/8. Primary tumour versus blood	1, 2, 3, 4	FC: % $CD3^+$ of total single-cell suspension after digestion	2.4 −17.8% (mean 6.7; n = 4) $CD3^+$	0.4% (n = 1) $CD3^+$	1.4 −7.1% (mean 4.3; n = 2) $CD3^+$	0.6% (n = 1) $CD3^+$					
[24]	53/53. Primary tumour	1, 2, 3, 4	IHC: % of patients with TIL infiltration	100% (5/5)	75% (3/4)	23% (3/13)	11% (3/28)			2-year OS: 64% in TIL^+ versus 11% in TIL^-. Within stage 3/4: 17% in TIL^+ versus 11% in TIL^-.		
[28]	36/36. Resection tumour	1, 2, 3, 4	IHC CD8: % of patients with $CD8^+$ infiltration	100% (9/9 pts) high $CD8^+$ in nests and stroma	94% (15/16 pts) high $CD8^+$ in nests and 63% (10/16 pts) high $CD8^+$ in stroma	0% (0/6 pts) high $CD8^+$ in nests and 17% (1/6 pts) high $CD8^+$ in stroma	0% (0/4 pts) high $CD8^+$ in nests and 0% (0/4 pts) high $CD8^+$ in stroma					
[34]	107/107. Primary tumour	1, 2, 3, 4, 4S	RT-qPCR: Vα24-Jα18	72.7% (32/44) Vα24-Jα18	66.7% (16/24) Vα24-Jα18	75% (6/8) Vα24-Jα18	44% (11/25) Vα24-Jα18	66.7% (4/6) Vα24-Jα18	Lowest levels in HR		iNKT: higher OS in pts with iNKT	
[30]	84/84. Primary tumour	1, 2, 3, 4	IHC CD3, CD4 and CD8				CD3, CD4 and CD8 lowest in stage 4			Higher OS in $CD3^{hi}$ and $CD4^{hi}$. CD8: no difference. Higher OS in $CD25^{hi}$ and $FOXP3^{hi}$.		No clear association
[25]	23/23. Primary tumour	N/A	IHC							TIL score correlates with OS months ($r_s = 0.69$; $p < 0.001$)		
[32]	77/77. Primary tumour	1, 2, 3, 4, 4S	IHC CD3, CD4 and CD8							Higher OS in $CD3^{hi}$ and $CD4^{hi}$. CD8: no difference		
[31]	55/55. Primary tumour and metastasis	HR, NHR	IHC CD8 and PD-1						HR: Higher $CD8^+$ and more PD-1 on $CD8^+$			

Table 2 (*continued*)

Ref	Patients/ samples	Stage	Method	Tumour stage					Risk	Survival analysis		*MYCN*
				1	2	3	4	4S	HR versus IR/LR	T cells	Other lymphocytes (γδ T, NK, (i)NKT and B)	
[33]	15/15. Primary tumour	LR, IR, HR	IHC CD45 and CD4						HR: Lower CD45 and CD4			Low CD4 infiltration in *MYCN*-A
[38]	80/80. Primary tumour	1, 2, 3, 4, 4S	IHC CD8									*MYCN*-A: lower $CD8^+$ than *MYCN*-A, also within HR
[44]	41/41. Primary tumour	4	RT-qPCR CD45 and FOXP3							Higher OS and EFS in $CD45^{hi}$and $FOXP3^{hi}$ tumours		
[36]	129/129 MYCN-NA. Primary tumour	4	Microarray							5-year EFS not associated with CD3Z, CD4, CD8A, GNLY, IFNG, TBX21, CD40LG, FOXP3, IL13, IL15, IL17	5-year EFS associated with CD1D andNKT	
[43]	98/98. Primary tumour	4	RT-qPCR Vα24-Jα18									$MYCN^{hi}$/ $CCL2^{lo}$ expression predicted absence of iNKT
[33]	TARGET cohort (n = 148). Primary tumour	1, 2, 3, 4	Deconvolution of bulk RNA seq with CIBERSORT							CD4: Higher OS in $CD4^{hi}$, also within *MYCN*-NA. Th2 (IL-4) but not Th1 (TNFα and IFNγ) » fav prognosis. CD8: no difference		Less $CD45^+$, B, $CD8^+$, $CD4^+$, NK, MØ, mono and DC in *MYCN*-A than *MYCN*-NA
[39]	498 primary NBL. Primary tumour	4	Deconvolution of bulk RNA seq with CIBERSORT. Immune signature from [243]							Higher OS in T $cell^{hi}$ and $cytotoxic^{hi}$ within stage 4		*MYCN*-A: less T cells and less cytotoxic signature, also within stage 4 tumours
[38]	TARGET cohort (n = 150). Validation cohort (n = 190). Primary tumour	3, 4, 4S	Deconvolution of bulk RNA seq with CIBERSORT, TCR seq, IHC.							CD4 and CD8 » fav outcome in *MYCN*-NA with high versus low *MYCN* expr	NK, γδ T and B » fav outcome in *MYCN*-NA with high versus low *MYCN* expr	*MYCN*-A: lower immune scores than *MYCN*-NA, especially cytotoxicity, NK and $CD8^+$ T, within HR

(*continued on next page*)

Table 2 (*continued*)

Ref	Patients/ samples	Stage	Method	Tumour stage					Risk	Survival analysis		*MYCN*
				1	2	3	4	4S	HR versus IR/LR	T cells	Other lymphocytes (γδ T, NK, (i)NKT and B)	
[37]	TARGET (n = 149). Val (n = 498), (n = 649), (n = 88). Primary tumour	1, 2, 3, 4, 4S	Deconvolution of bulk RNA seq with xCell							CD4 » unfav prognosis and OS. High Th1/ Th2 ratio » OS and EFS. CD8 » fav prognosis and OS	NKT » fav prognosis and OS	Less immune cells in *MYCN*-A. Higher Th1 and Th2 signatures in *MYCN*-A.
[244]	Disc (n = 105) and Val (n = 101). Primary tumour	1, 2, 3, 4 (disc) and N/A (val)	WGCNA, GFEA									Immune gene module associated with *MYCN*-A
[42]	TARGET (n = 160) and Val (n = 498). Primary tumor	1, 2, 3, 4, 4S	Deconvolution of bulk RNA seq with CIBERSORT							Risk score of 9 immune genes (SOCS1, MARCO, KLRK1, IRF7, UNC93B1, IGHV3–20, IGKV1–16, AMH, SECTM1) predicts OS		

enabled more efficient elimination of tumour cells by CTL and NK cells [48]. In line with this reasoning, tumoural MHC-I expression was an important predictor for survival [32]. Thus, different tumour aspects, such as differentiation grade and MHC-I expression, may influence TIL infiltration.

2.2.2. *Prognostic value of lymphocyte subsets*

While TIL density had a clear predictive value for survival, studies into the prognostic value of TIL subsets yielded conflicting results. On the one hand, two studies reported a beneficial prognostic role for CD8$^+$ T cells [31,37], with higher CD8$^+$ abundance in HR- compared to LR-neuroblastoma [31], and a higher predicted NKT and CD8$^+$ abundance correlating with a favourable prognosis and long-term survival, while CD4$^+$ abundance correlated with an unfavourable prognosis [37].

On the other hand, a prevalence of CD4$^+$ over CD8$^+$ T cells was associated with a better prognosis [30,32,33]. Patients with a high CD4$^+$ T cell density had longer OS, DFS, and EFS, while CD8$^+$ T cell abundance was not prognostic [30,32,33]. While the former studies emphasise a role for cytotoxic cells in the TME, the latter results suggest that CD4$^+$ T cell infiltration may be crucial for the creation of an effective immune response against the tumour.

Reports on CD4$^+$ T helper subsets are conflicting as well. One could perhaps expect a primary role for Th1 dominated CD4 responses to create help for CD8$^+$ CTL-mediated tumour killing, which is supported by higher Th1/Th2 ratios correlating with better long-term OS and EFS [37], and a higher OS in HR-neuroblastoma patients with a high cytotoxic signature [38,39]. However, others reported that a Th2 oriented CD4$^+$ T cell response (defined by IL-4 transcript levels) but not a Th1 oriented response (TNFα and IFNγ levels) was associated with a favourable prognosis [33]. Interestingly, the favourable effect of a Th2 oriented response would be in line with novel insights that B cell infiltration and activation in adult solid cancers yield an important survival benefit [49–51]. The prognostic differences of T cell subsets in neuroblastoma may have resulted from the different techniques, definitions and relatively low sample numbers used. Future studies will have to confirm whether these TIL subsets have a clear prognostic value and role in tumour elimination.

Regulatory T cells (Tregs), often identified by high expression of CD25 and their signature transcription factor FOXP3, play a crucial role in the TME of various tumours and have more often been associated with poor than good survival [52]. This negative effect on survival has been mainly attributed to their immunoregulatory function. In 84 patients with neuroblastoma, a high density of CD25$^+$ T cells in the nests and FOXP3$^+$ T cells in the septa was associated with better survival [30]. High FOXP3 gene expression in tumour biopsies at diagnosis also predicted a better EFS and OS [44]. Of

note, high expression of CD25 and expression of FOXP3 are not only indicators of Tregs but also of conventional T cell activation (FOXP3 at lower levels than in Tregs). Although Tregs can suppress TIL anti-tumour activity, which would imply a negative effect on survival, it seems that high FOXP3 expression may be a proxy for high T cell infiltration, which is rather, as discussed earlier, beneficial for prognosis.

Not only conventional T cells but also other (immune) cell subsets have been associated with tumour stage. The CD1d-restricted iNKT subset, characterised by expression of Vα24-Jα18, was more abundant in LR- than HR-neuroblastoma and predictive of better OS [34,36]. A combined predictive score, including immune and non-immune cells in the TME, was a potent predictor of OS and EFS, which indicates that not only immune components, but rather the interrelation or interaction between immune and non-immune cells within the TME determines the prognosis of neuroblastoma [37]. Also, others have constructed immune risk scores with predictive value for OS [42].

In conclusion, the prognostic relevance of $CD8^+$ and $CD4^+$ T cell infiltration, as well as Th polarisation, is still unclear. Future studies will have to point out whether a Th1 driven cytotoxic CTL response or a Th2 driven B cell response, or rather a combination of both, is required for the successful elimination of neuroblastoma tumours.

2.2.3. Relation with MYCN amplification status

Since *MYCN* amplification is an important driver in neuroblastoma and indicative of poor prognosis in low stage tumours [5], several studies have investigated its relation with TIL infiltration and composition. Four computational studies compared the immune composition of *MYCN* amplified (*MYCN*-A) and non-amplified (*MYCN*-NA) tumours by RNA deconvolution in multiple cohorts [33,37–39]. They revealed a strong inverse correlation between *MYCN* amplification and leukocyte infiltration, demonstrating less infiltration of *MYCN*-A tumours by $CD8^+$ and $CD4^+$ T cells, NK cells, NKT cells, B cells, macrophages, and monocytes (Fig. 1) [33,37–39]. Remarkably, one of the studies reported higher $CD4^+$ Th1 and Th2 signatures in *MYCN*-A tumours compared to *MYCN*-NA tumours, which may have resulted from distinct immune definitions used in the different deconvolution methods [37]. While one study did not find an association between TIL infiltration and *MYCN* status [30], the overall computational predictions were confirmed in two IHC-based studies, showing lower $CD4^+$ and $CD8^+$ T cell infiltration in *MYCN*-A tumours [33,38]. *MYCN* overexpression on RNA level in conjunction with low CCL2 expression also predicted the absence of iNKT cells [43]. Lastly, *MYCN*-A tumours had significantly lower cytotoxic TIL signatures and NK signatures compared to *MYCN*-NA tumours, indicating that not only the number of cells but also their cytotoxic activity may be lower [38,39].

Since *MYCN* amplification status and tumour stage are closely related, this raises the question whether the correlation with TIL infiltration is driven by *MYCN* amplification or tumour stage. Importantly, even within the group of HR-neuroblastoma, T cell and cytotoxic cell signatures, as well as $CD8^+$ infiltration, were lower in *MYCN*-A than *MYCN*-NA tumours [38,39], suggesting that low TIL infiltration is at least partly related to *MYCN* amplification. Overall, these results suggest that *MYCN*-A tumours have a reduced infiltration and activity of TIL compared to *MYCN*-NA tumours, independent of tumour stage.

Not only *MYCN* amplification but also *MYCN* overactivation may affect immune profiles. Within patients with *MYCN*-NA tumours, those with *MYCN* activation signatures had lower immune signatures and worse survival than those without *MYCN* activation. Strikingly, within the subgroup of *MYCN*-NA patients with high *MYCN* activation, those with elevated tumoural activated NK cells, $CD8^+$ T cells, and cytolytic signatures showed improved outcome compared to patients with lower immune signatures [38]. These findings suggest that activated infiltrating cytotoxic immune cells can 'rescue' patient outcomes within this specific subgroup of *MYCN*-NA HR-neuroblastoma.

Possible explanations for reduced TIL infiltration in *MYCN*-A tumours could be reduced immunogenicity or reduced lymphocyte attraction and activation. Tumour mutational load is an important determinant of tumour immunogenicity, as illustrated by higher TIL infiltration and cytotoxicity in tumours with a higher mutational load [53]. Neuroblastoma tumours typically have a low mutational burden, and therefore, low immunogenicity [15,54,55]. One study reported increased T cell signatures in HR-neuroblastoma with a high compared to low mutation load, which was dependent on *MYCN* status [39]. *MYCN*-A HR-neuroblastoma tumours had significantly less nonsynonymous mutations than *MYCN*-NA tumours [38,39]. However, other studies on neuroblastoma did not find a clear correlation between tumour mutational load and immune signatures, or mutational load and *MYCN* amplification [38,56]. If *MYCN* amplified tumours indeed have lower mutational load, this could partly explain their lower immunogenicity and low TIL infiltration.

Reduced immune cell attraction/activation in *MYCN*-A tumours could also explain reduced TIL infiltration. Layer *et al.* assessed the gene expression of chemotactic and immune-activating mediators in *MYCN*-A and *MYCN*-NA tumours. *MYCN*-A neuroblastoma showed reduced IFN pathway activity and lower expression of cytokine and chemokine genes [39]. However, it is difficult to dissect cause and consequence: while reduced IFN and chemokine expression could hamper T cell infiltration and activation, a reduced presence of TIL in these tissues could also account for lower cytokine and chemokine expression. A causal role

of *MYCN* was suggested by *MYCN* depletion in neuroblastoma cell lines, which enhanced IFN pathway activity, promoted expression of Th1 recruiting chemokines CXCL9 and CXCL10 and increased T cell infiltration [39]. Moreover, downregulation of *MYCN* in a neuroblastoma cell line enhanced expression of activating NK ligands MICA, ULBPs and PVR, resulting in increased NK cell cytolytic activity, while *MYCN* overexpression effectuated the opposite, which corroborated findings in human neuroblastoma tumours [57]. In addition, *MYCN*-A tumours repressed CCL2 expression, an important chemoattractant for lymphocytes [43,58]. Thus, *MYCN* amplification may directly impact the immunogenicity of neuroblastoma tumours and alter their chemokine profile.

Most studies, taken together, suggest that *MYCN*-A neuroblastoma may be less immunogenic to T cell immune surveillance on multiple levels. It would be interesting to investigate in an experimental model whether conditional knockdown of *MYCN* would increase TIL infiltration into tumours *in vivo*, to assess a causal relationship between *MYCN* expression and TIL infiltration. To our knowledge, such a study has not been performed yet.

2.3. Lessons from experimental models

Although fundamental differences in the human and murine immune system should be taken into account when translating results from experimental models to the human situation, several experimental studies with murine models have studied the effector cells involved in neuroblastoma anti-tumour immunity. In a murine A/J model of C1300 neuroblastoma treated intratumourally with activated DC, depletion of $CD4^+$ T cells or NK cells caused early outgrowth of tumours, whereas $CD8^+$ T cell depletion resulted in later tumour outgrowth similar to undepleted controls [59]. This suggests that $CD4^+$ T cells play an important role in DC-mediated anti-tumour immunity, which replicates the association between $CD4^+$ T cell infiltration and survival rates in human neuroblastoma.

In syngeneic C57Bl/6 mice injected with a transplantable TH-*MYCN* cell line endogenously expressing GD2 and lacking MHC-I, tumours in immunocompetent mice contained $CD4^+$ and $CD8^+$ T cells, macrophages and DC. However, the presence of adaptive immunity had limited influence on tumour growth, illustrating the low immunogenicity of neuroblastoma and/or low tumour reactivity of TIL. In contrast, depletion of NK cells resulted in enhanced tumour outgrowth, demonstrating their importance in the anti-neuroblastoma immune response in MHC-I negative tumours [60].

The tumour burden also impacts anti-tumour immunity. In A/J mice bearing subcutaneous NXS2 neuroblastoma, a smaller tumour burden at treatment start was associated with increased infiltration of NK and $CD8^+$ T cells and increased OS [61]. Similarly, in the transgenic TH-*MYCN* mouse model, small ‘early’ tumours had more T cell infiltration and IFNγ expression, while large ‘late’ tumours had more macrophages, DC, and myeloid-derived suppressor cells (MDSC). During cancer progression, the increased infiltration by myeloid cells may contribute to an immunosuppressive environment limiting lymphoid infiltration [62,63]. This suggests that early detection and treatment may be key to exploit the functionality of cytotoxic cells with immunotherapy in an early phase.

3. Challenges and opportunities for immunotherapy

3.1. Tumour reactivity of TIL

While TIL are present in neuroblastoma, the biggest challenge for immunotherapy so far is to generate effective tumour reactivity, which may depend on T cell-intrinsic factors, as well as tumour immunogenicity and immunomodulatory factors in the TME. The latter will be discussed in the next sections. The persistence of neuroblastoma tumours despite T cell infiltration may suggest that these T cells are not effectively recognising and/or killing neuroblastoma tumour cells. Also, the lack of survival differences between patients with HR-neuroblastoma with and without TIL infiltrates in some studies suggests that TIL may be present, but not tumour-specific or not functional [24]. Although the gathered data so far are not conclusive, some indications suggest that TIL can become activated and recognise autologous tumour cells, however, only at low levels (Fig. 2).

3.1.1. Clonality

Reduced clonality of the TCR repertoire is an indication of the antigen-driven expansion of specific T cell clones. A reduced TCR repertoire in TIL compared to PBL (which could be due to disproportional expansion of tumour reactive clones) could therefore hint towards tumour reactivity. Overall, the tumour-infiltrating T cell pool in untreated neuroblastoma was described as polyclonal, with a diverse Vα and Vβ repertoire [21,38,40]. In a small number of patients, increased clonality was observed in TIL compared to PBL, suggesting that in some patients, TIL expansion based on antigen specificity may occur. Since these studies were performed in untreated patients, they do not reflect possible induced tumour reactivity in response to treatment.

3.1.2. Activation

Not only clonality but also the expression of activation markers can indicate tumour reactivity. Although the levels of activation marker CD25 were similar to PBL in one study [64], another study reported higher levels of

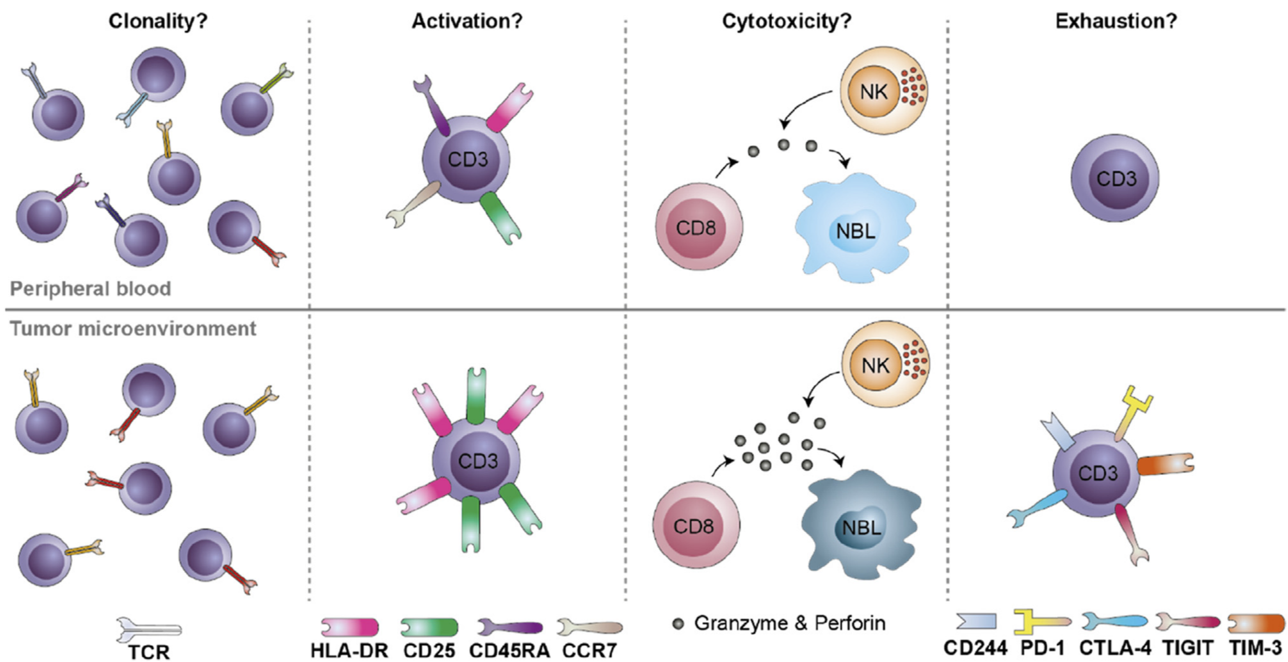

Fig. 2. **Tumour reactivity of TIL in neuroblastoma.** Some indications of tumour reactivity have been described in a small fraction of TIL, including reduced clonality of the T cell receptor repertoire, increased expression of activation markers HLA-DR and CD25, reduced expression of naive T cell markers CD45RA and CCR7, suggesting conversion to a memory state, increased cytotoxicity towards neuroblastoma cells and increased expression of immune checkpoints, which may or may not be associated with an exhausted state.

CD25 in TIL [23]. Others reported that both $CD4^+$ and $CD8^+$ TIL in neuroblastoma tumours partly expressed CD25 and/or HLA-DR, suggesting an activated state in a fraction of these cells [21]. A small number of T cells in the TME expressed Ki67, indicating active proliferation [23]. In the same detailed IHC-based study, also a redistribution of the CD3 component of the TCR toward the area of contact with the tumour cell was revealed. The authors suggested that the 'pattern of CD3 distribution, reflecting TCR aggregation [...] and the detection of the proliferation marker Ki67 [...] strongly indicate that tumour recognition takes place in situ' [23]. In line with a more activated state, cells with an effector memory phenotype ($CD45RA^-CCR7^-$) were more frequent in TIL than PBL, and the fraction of naive cells ($CD45RA^+CCR7^+$) was lower in TIL than PBL [23]. Although a predominance of effector memory cells might suggest differentiation upon recognition of a cognate antigen, it is also in line with current insights in the phenotype of human tissue-resident T cells, which is skewed towards the effector memory state in most, even steady-state tissues, precluding the requirement of antigen specificity [65].

Thus, the activation and memory states of TIL may suggest that, at best, a small fraction of T cells actively recognise tumour cells, implying that most are bystander cells. The suggested activation state of TIL could also be reproduced by stimulation of patient PBL with autologous tumour cells in short-term cultures, which increased the proportion of effector memory T cells, upregulated CD25 expression, stimulated the expression of the Th1 cytokines IFNγ and TNFα, and reduced the expression of TGFβ [23]. At least some T cell clones in the peripheral pool, therefore, seem capable of recognising autologous neuroblastoma, which may be indirect evidence that also tumour-infiltrating T cells could contain tumour reactive cells.

3.1.3. Cytotoxicity

As discussed in the previous sections, the presence of a high cytotoxic signature is beneficial for survival in HR-neuroblastoma patients, which underlines the importance of cytotoxic activity over the mere presence of TIL [38,39]. For mounting an effective anti-tumour response, T and NK cells need to be equipped with cytotoxic molecules such as perforin and granzymes to lyse tumour cells. The majority of $CD8^+$ T cells in peritumoural stroma expressed perforin [22]. Granzyme B was also detected in TIL, although at low frequency [29]. In patients with HR-neuroblastoma, high gene expression of perforin in biopsies at diagnosis predicted a better EFS and OS, whereas the expression of granzyme B was not prognostic [44]. *In vitro*, TIL showed enhanced cytotoxicity towards neuroblastoma lines compared to PBL [64]. Although this may suggest a degree of neuroblastoma specificity in TIL, it may also be explained by current insights that both tissue- and tumour-resident lymphocytes generally have an enhanced cytotoxic response [65]. Cytotoxicity of TIL against neuroblastoma cell lines was markedly reduced

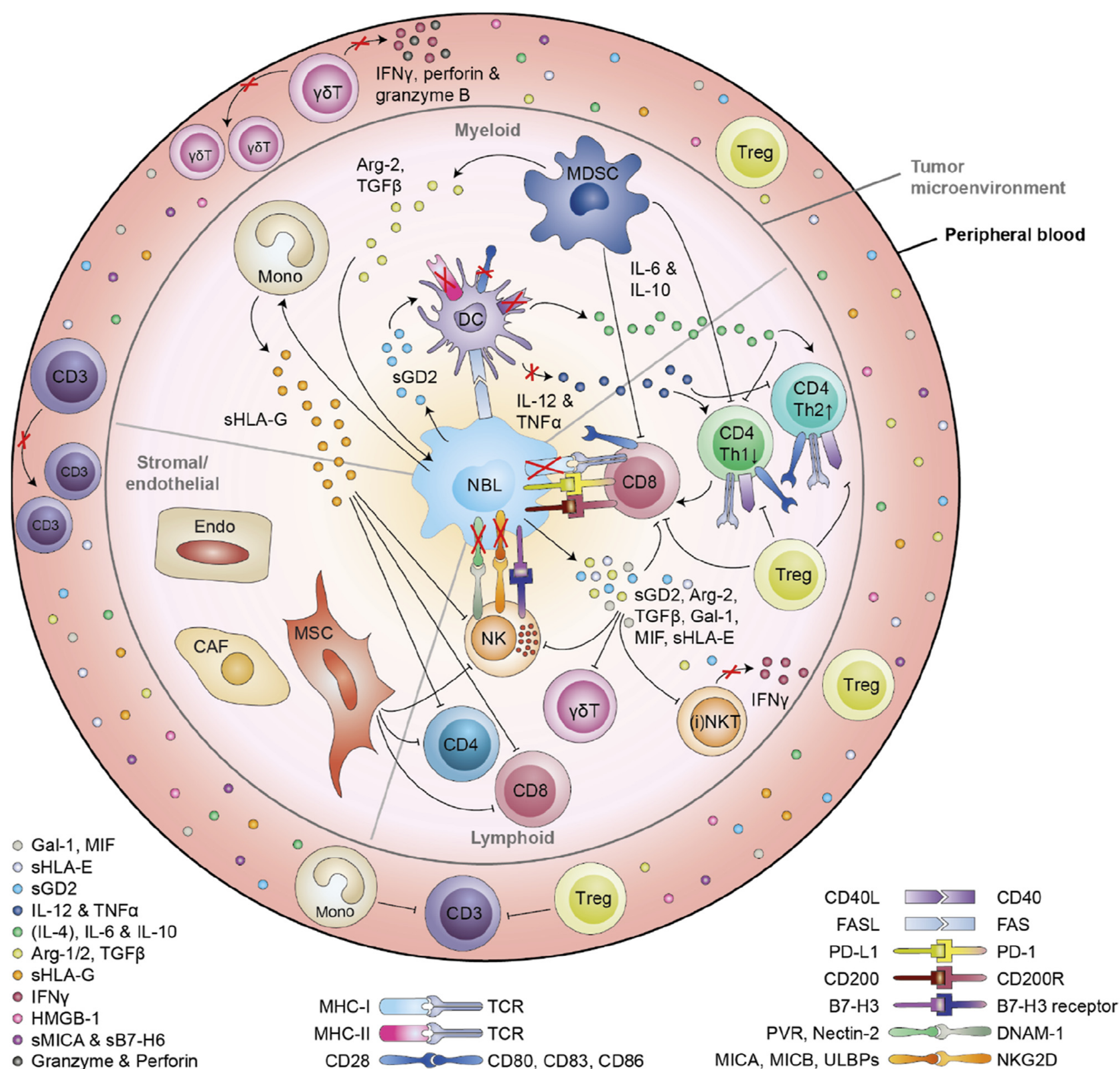

Fig. 3. **Immune evasion strategies employed by neuroblastoma.** Immune evasion strategies inhibiting T cell responses include downregulation of MHC-I, and expression of immune checkpoints PD-L1 and CD200. NK cell responses are inhibited by downregulation of ligands for the NK-activating receptors DNAM-1 and NKG2D and increased expression of B7−H3. Neuroblastoma secretes a variety of immunosuppressive molecules, including Gal-1, MIF, sGD2, sHLA-E, TGFβ, sMICA, sB7-H6 and arginase-2, which can impede TIL function. DC function is impaired by sGD2, which leads to decreased expression of MHC-II molecules (antigen presentation), decreased CD28 ligands and CD40 (co-stimulation), reduced Th1-related IL-12 and TNFα production, and increased IL-6 and regulatory IL-10 production. In response to neuroblastoma-derived factors, monocytes produce sHLA-G, which inhibits NK cells and T cells. Also Tregs, MDSC and MSC in the TME can suppress NK cells and T cells. Lastly, immunosuppressive molecules from the TME can reach the circulation and impair the proliferation and cytotoxicity of peripheral T cells and NK cells, while also inducing immunosuppressive monocytes and Tregs, thereby further aggravating lymphocyte dysfunction.

by depletion of $CD56^{+}$ cells from TIL, which recapitulates results in mice [60] and highlights the role of NK cells in anti-neuroblastoma immunity [64]. Since cell lines are derived from allogeneic material, this may not represent the anti-tumour response in an autologous setting. Coculture of autologous PBL with neuroblastoma reduced tumor growth by ~50% compared to controls, which was similar to the reduction by

allogeneic PBL [66]. *Ex vivo* expanded blood-derived CD8^{+} CTL from patients stimulated with IFNγ-treated neuroblastoma cells, specifically lysed autologous neuroblastoma cells, but not HLA-mismatched neuroblastoma or other autologous cells, suggesting tumour-specificity [67]. *Ex vivo* expanded TIL from neuroblastoma tumours, however, were largely non-reactive to autologous tumour cells, although they did retain the capacity to migrate towards neuroblastoma cell lines [35].

Although TIL may not show sufficient cytotoxic activity *in vivo*, with the right stimulation, they might be trained or unleashed to become reactive to the autologous tumour, which highlights the potential of immunotherapy.

3.1.4. Exhaustion

Another explanation for the 'ineffective' presence of TIL in neuroblastoma could be exhaustion, defined as a state of the reduced capacity of cytokine production and usually identified by the combination of typical markers [68]. In neuroblastoma, an upregulation of immune exhaustion genes was found in RNA sequencing data of tumour biopsies. Five out of seven chosen exhaustion markers (CD244, HAVCR2, CTLA4, TIGIT, PDCD1) were significantly higher in tumours with high cytotoxic signatures, possibly indicating that chronic stimulation of T cells with their cognate antigens may have led to an exhausted state [38]. It should be noted, however, that the state of exhaustion and its identification is still subject to discussion in the immunology space [69]. The here mentioned immune checkpoint molecules, which will be further discussed in the next section, do not necessarily indicate exhaustion, but at least point toward the increased activity of immunomodulatory pathways in tumours with a high cytotoxic signature. Moreover, TIL produce a variety of cytokines upon *ex vivo* stimulation with IL-2, which counters the notion of an exhausted state [21]. The relevance of T cell exhaustion in neuroblastoma is, therefore, still debatable.

In conclusion, several studies suggest that, at best, a small fraction of TIL in neuroblastoma may be tumour reactive, although the evidence is not conclusive. The defective anti-tumour response of TIL in neuroblastoma may not only be due to TIL-intrinsic lack of activation but may also result from external immunosuppression by the TME, including immune evasion strategies employed by the tumour.

3.2. Tumour immune evasion strategies

The presence of TIL in neuroblastoma and their possible tumour reactivity support the concept that patients can mount immune responses to neuroblastoma but that these are somehow rendered ineffective. Neuroblastoma tumours employ several strategies to escape killing by cytotoxic lymphocytes. Among these are the low expression of MHC-I, expression of immune checkpoint molecules, the induction of immunoregulatory myeloid cells and secretion of immunosuppressive mediators (Fig. 3).

3.2.1. Tumour immunogenicity

Neuroblastoma tumours are lowly immunogenic due to their low mutational burden, which is associated with a low generation of neo-antigens [15,54,55]. Tumour-associated antigens, which could be recognised by patrolling T cells, are therefore scarce, although some neuroblastoma-associated immunogenic antigens have been identified [17]. Also, the antigen-presenting machinery, consisting of MHC-I molecules, with which somatic cells constitutively present their intracellular antigens, is not functional in neuroblastoma [16,70,71]. These features render neuroblastoma cells virtually invisible to patrolling CD8^{+} T cells.

Tumoural MHC-I expression in neuroblastoma impacts the immune response. MHC-I expression on tumour cells correlated directly with the density of tumour-infiltrating CD3^{+} T cells, the latter being an important prognostic factor for survival [30]. Apart from CD3 infiltration, high tumoural MHC-I expression was associated with a significantly better OS than low MHC-I expression, and stage 3 and 4 tumours had significantly lower MHC-I expression than stage 1, 2 and 4S tumours [30,32]. The combined presence of MHC-I and/or TIL was even more predictive for survival: all patients with MHC-I^{high}CD3^{high} tumours were alive after >10 years of follow-up, while survival of patients with MHC-I^{low}CD3^{low} tumours was only ~40% [32]. Of note, tumour stage, influencing both MHC-I and CD3 status, likely contributed to this effect since patients were not stratified by tumour stage.

MHC-I expression also depends on *MYCN* amplification status. *MYCN*-A tumours had lower MHC-I expression than *MYCN*-NA tumours, and induction of *MYCN* expression in a *MYCN*-NA neuroblastoma cell line resulted in suppression of MHC-I [38]. Low immunogenicity of *MYCN*-A tumours, as discussed in previous sections, may therefore be a direct result of MHC-I suppression.

The relevance of MHC-I expression was also demonstrated experimentally. Both *in vitro* and *in vivo*, treatment of neuroblastoma models with IFNγ led to increased MHC-I expression and subsequently enhanced killing by CTL [72]. Moreover, a pilot clinical trial among 5 HR-neuroblastoma patients treated with intravenous IFNγ for 5 days resulted in increased MHC-I expression and augmented T cell trafficking in tumours in 2 out of 5 patients. In the other 3 patients, MHC-I was not upregulated, and only very few CD3^{+} T cells were observed [72]. These studies highlight the potential direct *in vitro* and *in vivo* effects of increased MHC-I expression on tumour immunogenicity.

In conclusion, MHC-I and neo-antigen expression are important determinants of tumour immunogenicity and thus T cell infiltration, which affects patient prognosis. MHC-I upregulation should, therefore, be considered as a therapeutic target that may be exploited in combination with additional immunotherapeutic strategies to overcome immune resistance [47,70].

3.2.2. Escaping NK cells

Due to their low MHC-I expression, neuroblastoma cells may not be susceptible to recognition by CTL, but should be rendered vulnerable to NK cells. *In vitro*, NK cells were indeed capable of killing neuroblastoma cells, although pre-activation of isolated NK cells was required in some settings [73,74]. However, in patients, additional escape mechanisms that modulate the balance between activating and inhibitory signals on NK cells seem to protect neuroblastoma from NK-mediated killing (reviewed in Refs. [75]). For example, neuroblastoma tumours have a low expression of ligands (PVR, nectin-2, MICA, MICB and ULBPs) for NK cell-activating receptors DNAM-1 and NKG2D [76,77]. *MYCN* expression can also modulate susceptibility of neuroblastoma to NK-mediated killing: upregulation of *MYCN* in an inducible cell line led to downregulation of NK-activating ligands, resulting in reduced NK-mediated lysis of the tumour cells [57]. However, as demonstrated in multiple studies, NK cell balance can be restored by the anti-GD2 antibody Dinutuximab, which potently induces NK cell cytotoxicity to neuroblastoma [7,9,12,78,79].

3.2.3. Immune checkpoint molecules

Next to low tumour immunogenicity, the reactivity of TIL towards neuroblastoma may be heavily modulated by the presence of immune checkpoints (IC) in the TME, the importance of which is underlined by the recent breakthroughs achieved by ICI in adult cancers [1].

In pediatric solid cancers, high expression of IC in the TME was associated with poor prognosis [80]. PD-L1 is a potent inhibitor of T cell responses by binding to its receptor PD-1 on effector T cells. Blockade of PD-1/PD-L1 interaction has demonstrated remarkable therapeutic efficacy in various adult cancers by restoring T cell reactivity [81]. Assessment of PD-L1 expression in neuroblastoma has so far yielded conflicting results. IHC-based studies reported variable PD-L1 expression, in 14%, 19%, 35% and >70% of neuroblastoma tumours [27,31,82,83]. High PD-L1 expression was associated with inferior survival and an increased risk of recurrence [27,32,82,83], which was in line with stage 3/4 tumours having higher PD-L1 expression than stage 1, 2 and 4S tumors [32]. Even within HR and stage 4 patients, high PD-L1 expression was associated with inferior survival [27]. While patients with PD-L1^{high}CD3^{low} tumours had the worst prognosis, patients with PD-L1^{low}CD3^{high} tumours had the best OS [32]. Other studies, however, reported opposite results with lower PD-L1 expression in HR tumours [83,84], or similar PD-L1 expression between HR and non-HR tumours [31]. Reduced PD-L1 expression was also reported in *MYCN*-A tumours [39,83]. Thus, while PD-1 and PD-L1 are expressed in neuroblastoma, their prognostic significance remains uncertain.

Several studies point towards the involvement of the PD-1/PD-L1 axis in TIL infiltration in neuroblastoma. While PD-L1 expression did not correlate with CD45$^+$ leukocyte or CD8$^+$ T cell infiltration in two studies [31,82], it coincided with and was upregulated by TIL infiltration in another [84]. In neuroblastoma-infiltrated bone marrow (BM), PD-1 was mainly detected on αβ T cells, γδ T cells and NK cells, indicating that these may be sensitive to high PD-L1 in the TME [85]. PD-L1 blockade on neuroblastoma cell lines induced CD4$^+$ and CD8$^+$ T cell activation *in vitro* [86]. In conclusion, the PD-1/PD-L1 checkpoint may contribute to the inhibition of TIL activation in neuroblastoma.

Other IC implicated in neuroblastoma are CD200/CD200R and B7–H3. CD200 was overexpressed on neuroblastoma tumour cells, and its receptor CD200R was (lowly) expressed on CD4$^+$ and CD8$^+$ TIL [87]. CD200^{high} tumours had lower numbers of CD4$^+$ and CD8$^+$ TIL, and TIL produced less IFNγ and TNFα [87]. High B7–H3 expression in neuroblastoma correlated with poor EFS [88], and blockade of B7–H3 resulted in enhanced NK cell-mediated killing of neuroblastoma cells *in vitro* [88,89].

The *in vivo* importance of IC activity in neuroblastoma was highlighted in a recently published elegant study demonstrating the formation of human neuroblastoma in mouse-human neural crest chimeras. Although the tumours were extensively infiltrated by tumour reactive mouse CTL, the tumours suppressed immunity by enhancing the expression of PD-L1 and infiltration of Tregs, supporting findings in human neuroblastoma [90]. In conclusion, several IC may be active in neuroblastoma, possibly affecting both T cell and NK cell functions.

3.2.4. Immunosuppressive myeloid and stromal cells

Besides hiding from T cells and NK cells, neuroblastoma employs indirect immunoregulatory mechanisms by chartering myeloid and stromal cells to dampen TIL reactivity.

While T cells have the direct killing capacity, their function depends on antigen presentation and co-stimulation by DC, which are therefore central to anti-tumour immunity. Neuroblastoma can interfere with T cell priming by DC on multiple levels, e.g. by inducing DC apoptosis through the expression of pro-apoptotic factors like FAS ligand [91,92]. FAS ligand expression was associated with high stage tumours independent of *MYCN* status [91], while decreased DC infiltration was

associated with a poor prognosis, underlining their importance for effective anti-tumour immunity [93]. In addition, neuroblastoma can induce DC dysfunction by modulating their antigen-presenting and co-stimulatory capacity through decreasing expression of HLA-DR, co-stimulatory molecules CD40, CD80, CD83, and CD86, and Th1 cytokines IL-12 and TNFα, while increasing IL-6 and regulatory IL-10 [94–96]. These effects were attributed to soluble factors, specifically gangliosides, secreted by the tumour [94–96]. Neuroblastoma-exposed DCs were unable to effectively activate T cells and iNKT cells, which resulted in reduced proliferation, activation and Th1 polarisation, including IFNγ production [94–96], and in some cases could even inhibit T cell proliferation [92]. Thus, neuroblastoma can induce DC dysfunction, which leads to an inability to stimulate effective TIL anti-tumour responses.

Myeloid-derived suppressor cells (MDSCs) are a notorious population of myeloid cells in the TME, which can suppress lymphocyte responses [62,63]. MDSCs accumulated during tumour progression in a murine TH-*MYCN* neuroblastoma model [97], and promoted tumour growth through secretion of reactive oxygen species, arginase-1 and TGFβ [98]. Treatment of neuroblastoma-bearing mice with polyphenol E, which reduced the number of MDSC, reinvigorated T cell proliferation and reduced tumour growth [99].

Next to myeloid cells, also stromal cells in the TME may contribute to immunosuppression. Mesenchymal stromal cells (MSC) isolated from neuroblastoma tumours exhibited an extraordinary immunosuppressive capacity on activated T cells, even more than BM-derived MSC [100]. *In vitro* and *in vivo*, NK cell-mediated antibody-dependent cellular cytotoxicity (ADCC) against neuroblastoma with anti-GD2 was suppressed by MSC and monocytes [101]. *In vivo* depletion of MSC, monocytes and endothelial cells restored NK cell activity, demonstrating the immunosuppressive capacity of the myeloid and stromal compartments in the TME [101]. In conclusion, neuroblastoma tumours are intermixed with myeloid and stromal cell populations with defective activating functions or enhanced suppressive functions, which can prevent TIL from effectuating an anti-tumour response.

3.2.5. Soluble mediators of immune suppression

Neuroblastoma cells secrete a variety of soluble mediators that can suppress lymphocyte activation, including TGFβ, galectin-1, MIF, soluble GD2 (sGD2), and arginase-2.

TGFβ, galectin-1 and MIF are well-known immunosuppressive molecules produced by neuroblastoma, which can impair CTL and/or NK cell function [52,102–106]. In experimental neuroblastoma models, NK cell function was directly modulated by TGFβ [107], and tumoural galectin-1 or MIF knockdown resulted in increased T-cell-mediated cytotoxicity, IFNγ secretion, $CD4^+$ and $CD8^+$ T cell recruitment, and more efficient tumour rejection [104,108,109]. Soluble galectin-1, as well as MIF overexpression, induced T cell apoptosis, inhibited T cell proliferation and inhibited DC maturation [104,110,111]. In patients, high tumoural MIF was associated with lower abundance of CTLs, NKT cells, B cells and DC, and a poor prognosis in stage 4 tumours independent of *MYCN* [112]. Elevated tumoural TGFβ was associated with shorter EFS [36]. Thus, TGFβ, galectin-1 and MIF secreted by neuroblastoma can reduce TIL anti-tumour activity and affect prognosis.

Surface expression of the ganglioside GD2 is a hallmark of human neuroblastoma. GD2 can be shed in a highly immunosuppressive soluble form, which was detected at >50-fold increased concentrations in patient serum and was particularly suppressive in patients with stage 3/4 tumours [113–115]. sGD2 inhibits T cell proliferation [114,116], and therefore, likely contributes to tumour immune evasion. Anti-GD2 therapy may possibly derive part of its effectivity from blocking sGD2.

Next to immunomodulatory molecules, neuroblastoma produces arginase-2, which reduces levels of arginine – an essential amino acid for lymphocytes – and thereby suppresses T cell proliferation *in vitro* and *in vivo*. High arginase-2 and low arginine were demonstrated in patients with neuroblastoma, both locally and systemically, and arginase activity correlated with poor survival [117]. Mice with a larger tumour burden had lower serum arginine [117], which may explain why those with a large tumour burden showed decreased infiltration of cytotoxic lymphocytes and decreased OS [61]. Thus, arginase-2 activity may have deleterious effects on TIL activity. Also, catecholamines produced by neuroblastoma can have immunoregulatory effects [118,119].

Several other immunosuppressive molecules have been described in neuroblastoma, including sMICA, sB7-H6, sHLA-E, sHLA-G, IL-10 and HMGB1. MICA and B7–H6, neuroblastoma surface-bound ligands for activating receptors on NK cells and CTL, are suppressive when secreted. sMICA was elevated in patient serum, downregulated its receptor NKG2D on CTL and decreased NK-mediated killing of neuroblastoma [77]. Serum sB7-H6 correlated with downregulation of its receptor NKp30, the occurrence of bone metastases and chemoresistance, and sB7-H6 inhibited NK cell function *in vitro* [120]. Both sMICA and sB7-H6 may thus have relevant immunosuppressive effects in neuroblastoma. HLA-E was highly expressed in neuroblastoma, especially in stage 4 tumours, and inhibited *in vitro* NK cell cytotoxicity while inducing IL-10 and TGFβ [121]. sHLA-G was produced by monocytes in the TME in response to neuroblastoma exposure, inhibited NK and CTL function, was increased in neuroblastoma patient

serum and prognostic for relapse [122]. sHLA-G and sHLA-E were highest in BM plasma of patients with metastatic disease [123]. Thus, HLA-E and HLA-G can reduce cytotoxic lymphocyte function and are related to tumour activity. The immunosuppressive HMGB1 was overexpressed in 11% of neuroblastoma patients and was associated with an increased risk of disease progression, relapse and disease-related death [124].

Concluding, a large variety of immunosuppressive factors in the TME can reduce NK cell and CTL function, thereby impairing anti-tumour immunity.

3.2.6. Systemic effects of immunosuppression

The immunosuppressive effects of these soluble factors may not be limited to the TME but may become systemic upon reaching the circulation and induce broad lymphocyte defects. These systemic effects are notable: in untreated neuroblastoma patients, the frequency of circulating T cells is reduced [117], and particularly those with large, invasive tumours and/or metastatic disease, can even present with lymphopenia [125–128]. Not only T cell numbers but also function is decreased. Circulating αβ T cells and γδ T cells from untreated neuroblastoma patients had reduced proliferative capacity [117,129], and γδ T cells showed reduced expression of granzyme B, perforin and IFNγ [129]. Moreover, untreated neuroblastoma patients had increased circulating IL-10, IL-4, IL-6 and reduced IFNγ and IL-12 levels compared to controls, suggesting Th2 dominance with reduced Th1-mediated cytotoxicity [129,130]. Although the lymphocyte defects are likely due to the combination of immunosuppressive signals, the lack of arginine may be crucial, as arginine supplementation reversed the suppressive effect of patient plasma on T cell proliferation [117]. In xenograft studies, T cells showed defective anti-tumour responses as well, both locally and systemically [131].

These defects may be induced directly by the plethora of immunosuppressive signals or indirectly through tumour-educated myeloid cells or Tregs. In untreated neuroblastoma patients, blood-derived myeloid cells suppressed allogeneic T cell responses [117], and circulating Treg frequencies were increased, which normalised after debulking surgery and increased upon tumour progression, suggesting a strong link between tumour activity and Treg induction as an additional immune evasion strategy [130,132]. Defective lymphocyte function was additionally underlined by suboptimal vaccination responses. Importantly, these lymphocyte defects were already present at diagnosis, before treatment, and therefore probably tumour-induced [133]. Subsequent rounds of chemotherapy and radiation therapy likely further reduce T cell numbers and function.

In conclusion, neuroblastoma creates a highly immunosuppressive environment, not only locally in the tumour, but also systemically, which represents a major challenge for immunotherapeutic interventions.

4. Implications for immunotherapy

4.1. Immunotherapy development

Immunotherapy in neuroblastoma has already proven its efficacy with the introduction of the anti-GD2 antibody Dinutuximab into the standard treatment regimen, which significantly improved survival rates [6,9–13]. Even in patients with relapsed disease, Dinutuximab may have a treatment value [134,135]. The success of Dinutuximab has sparked investigations into combination therapy with cytotoxic compounds (NCT04385277, NCT03794349) [135–137], as well as cellular immunotherapy with (haploidentical) donor NK cells (NCT02573896, NCT03242603, NCT02100891, NCT04211675, NCT01807468) [138,139,148,140–147], the results of which are promising. However, a disadvantage of NK cell-mediated therapy is its inability to induce immunological memory. Patients with minimal residual disease may, therefore, be at risk for relapse upon treatment withdrawal. Induction of a T cell memory response with durable effects may be a desirable, perhaps additional, strategy.

T cells can be engaged, c. q. exploited, by cellular therapy with engineered T cells expressing chimeric antigen receptors (CAR) or *ex vivo* activated T cells, by ICI, or vaccination. So far, cellular immunotherapies employing CAR T cells and *ex vivo* expanded cytotoxic lymphocytes have not had overwhelming success in neuroblastoma, with only a fraction of patients achieving measurable responses [149–155]. CAR T cell effectivity is limited by a rapid decline in CAR T cell numbers after infusion, suboptimal potency, a paucity of tumour-specific targets and an immunosuppressive TME [14,156]. Nevertheless, next-generation CAR T cells are currently under investigation in many clinical trials for neuroblastoma, targeted at L1CAM (NCT02311621) [157], B7–H3 (NCT04483778) [158], EGFR (NCT03618381) [159] and GD2 (NCT02919046, NCT02765243, NCT02761915, NCT01822652, NCT03635632, NCT03721068, NCT03294954, NCT02992210, NCT03373097, NCT01953900) [160–169]. Notably, encouraging results of CAR-NKT cell therapy for neuroblastoma were recently reported in an interim analysis [170]. A proof of principle for the exciting possibility of expanding TIL *ex vivo* for reinfusion therapy, which showed remarkable effectivity in melanoma and cervical carcinoma [171,172], was recently provided. Although expanded TIL did not show direct reactivity against neuroblastoma, they produced IFNγ and were able to migrate towards neuroblastoma cell lines [35].

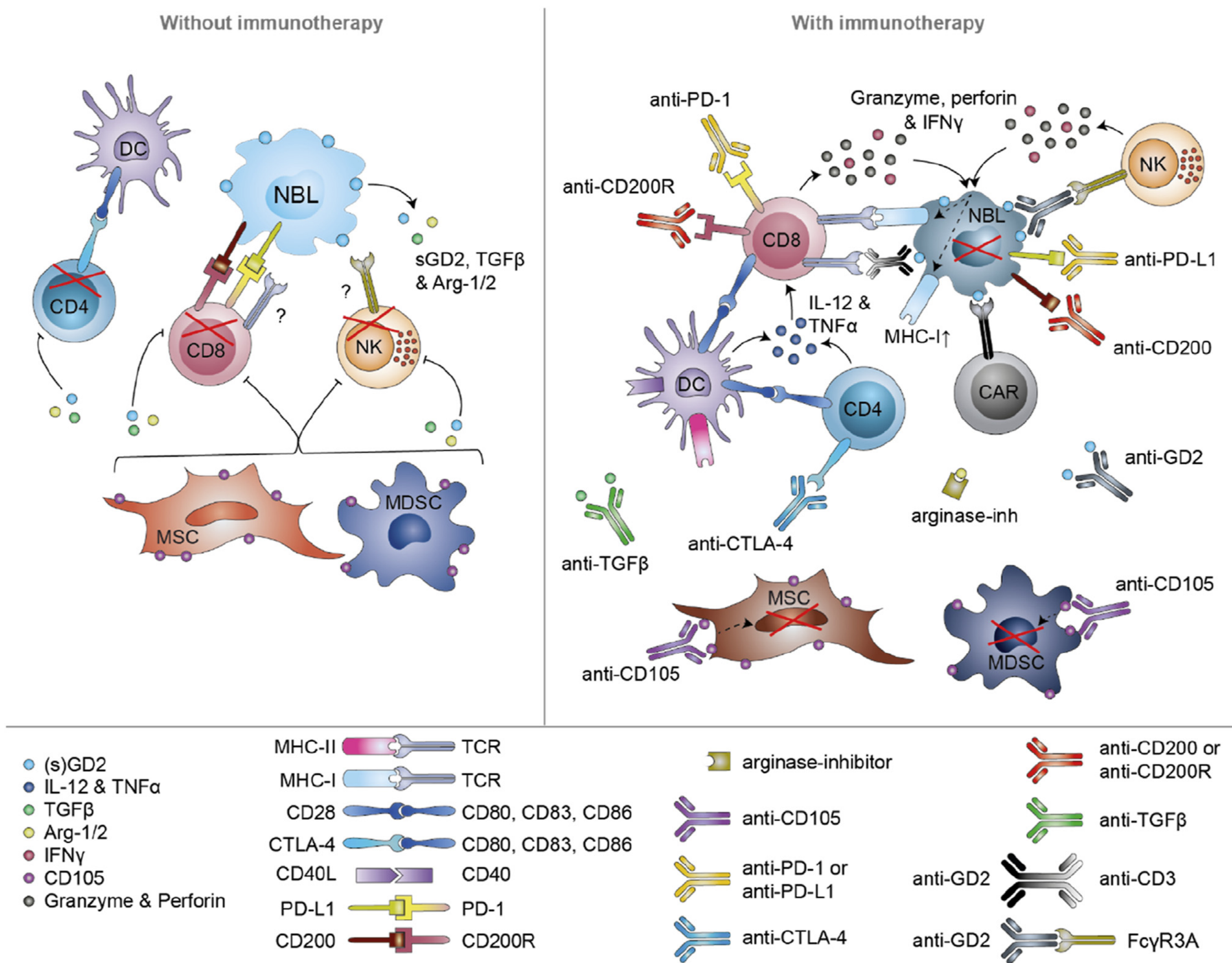

Fig. 4. **Immunotherapeutic strategies for neuroblastoma, two or more of which could be combined to increase effectivity.** Without immunotherapy, T cells cannot recognise neuroblastoma because of low MHC-I expression, and NK cell activity is hampered by low expression of activating ligands. Soluble immunoregulatory mediators in the TME, MSC and MDSC further inhibit T and NK cell function. Various targets for immunotherapy can be exploited. Checkpoint inhibition can reinvigorate T cell function, bispecific antibodies may induce T cell tumour reactivity, NK cells can be activated with anti-GD2 antibodies and MSC and MDSC can be depleted. The immunosuppressive effect of soluble mediators can be reduced, which will also increase the costimulatory capacity of DC. Successful activation of T and/or NK cells, resulting in secretion of IFNγ, can induce MHC-1 expression on neuroblastoma, which further enhances T cell reactivity, thereby creating a positive feedback loop.

As an alternative to cellular immunotherapy, T cell immunity can also be enhanced by ICI, which harnesses naturally occurring anti-tumour T cell responses. Recently, the first clinical trial of ICI among neuroblastoma patients, testing anti-PD-1 antibody Pembrolizumab, reported disappointing results with 4/11 neuroblastoma patients having progressive disease during treatment and none showing a response. Also, in other pediatric solid cancers [80], as well as murine models of neuroblastoma, ICI monotherapy did not show therapeutic effects [84,173–176]. Ongoing studies with ICI in neuroblastoma with Pembrolizumab (NCT02332668) [177], anti-PD1 Nivolumab and/or anti-CTLA4 Ipilimumab (NCT04500548, NCT02304458, NCT03838042, NCT02914405, NCT04412408, NCT01445379) [178–183], will hopefully provide more insight into their potential efficacy for relapsed neuroblastoma.

For redirecting T cells to the tumour, anti-GD2 x anti-CD3 bispecific antibodies (NCT03860207) [184], as well as *ex vivo* expanded autologous T cells armed with the anti-CD3 × hu3F8 bispecific antibody (GD2Bi, NCT02173093) are currently investigated in phase I/II trials [185].

Lastly, vaccination with tumour antigens or cytokine-producing tumour cells has been explored to induce T cell responses in neuroblastoma, but again with only limited or uncertain long-term responses [29,133,194,186–193]. Although immune activation and even induction of tumour-specific immunity were

observed in most studies, the long-term efficacy remained remarkably low. Novel strategies, including personalised vaccines with self-tumour antigens, may yield increased efficacy of vaccination therapy (NCT04239040, NCT02998983, NCT00911560, NCT04049864) [195–199].

Concluding, the promising results of NK-cell mediated therapies in neuroblastoma are so far not matched by T-cell mediated therapies, which demonstrate only moderate to low effectivity in clinical trials.

4.2. Combination immunotherapy

The limited success of T cell-mediated therapies illustrates the challenges for eliciting T cell reactivity in neuroblastoma, as outlined in the previous paragraphs. It has become clear that not only the natural immune response but also effectivity of immunotherapeutic approaches are hampered by the many immunosuppressive mechanisms at play. Combination immunotherapy, targeting multiple immunomodulatory processes simultaneously, may, therefore, be required (Fig. 4). Especially for cellular therapy or ICI, restoration of an environment conducive to immunity may be necessary to unleash the full T cell potential and increase persistence. This may include restoration of arginine levels [117], depletion of MDSC [101,200], blockade of (soluble) anti-GD2 and TGFβ [201], and/or induction of MHC-I expression [202]. Indeed, treatment regimens combining multiple immunotherapeutic strategies, some of which even engage innate and adaptive immunity, were more effective in neuroblastoma patients than monotherapies [139,154,193]. Arginase activity impaired CAR T cell proliferation and cytotoxicity, which could, however, be rescued by inhibition of arginase [117], and resistance to ICI could be overcome by supplementary blockade of TGFβ [203,204]. In murine neuroblastoma models, monotherapy with ICI was not effective either, whereas combination therapy with anti-GD2, vaccination, Treg depletion, or myeloid inhibition strongly enhanced anti-tumour immunity [84,173–176,205]. Anti-TGFβ improved NK-cell mediated anti-tumour activity [201]. Combining adoptive T cell therapy with ICI to amplify the response is another promising strategy [154,206,207].

Lastly, combining NK cell and T cell-mediated therapies could have the additional benefit of ‘cornering’ the tumour with regard to its MHC-I expression [74]. The combination of anti-PD-1 and anti-GD2 proved encouraging in a recent case report of 2 refractory neuroblastoma patients [208] as well as in a murine neuroblastoma model [205]. However, especially for combination therapy, it will be important to balance effectivity with the risk of immunotoxicity [209].

4.3. Biomarkers predicting immunotherapy response

With only a fraction of patients responding to immunotherapy, the identification of biomarkers predicting therapy responses will be an important aspect of implementing immunotherapy in neuroblastoma. In the adult cancer space, it has become clear that the efficacy of immunotherapy depends on various patient and tumour specific factors, such as tumour mutational load, expression of immune checkpoint molecules, tumour infiltration of T cells and B cells, and presence of lymphoid aggregates [49–51,210–212]. Multifactorial predictive models are being designed to provide more accurate predictions [212–214].

In neuroblastoma, the balance between activating and suppressive NK cells ligands, genotypes of Fcγ-receptors, NKp30, KIR and NKG2D, as well as *MYCN* expression were shown to strongly correlate with the response to anti-GD2 immunotherapy [57,120,215–221]. Biomarkers for T-cell mediated immunotherapy have not been explored yet. In conclusion, personalised (combination) immunotherapy based on response prediction will likely be a valuable approach in neuroblastoma.

5. Conclusion and future perspectives

The success of immunotherapy in various adult cancers has demonstrated its outstanding potency and warrants investigations into the application of existing immunotherapeutics, as well as the development of novel immunotherapeutic interventions for pediatric solid cancers. As discussed in this review, successful implementation of immunotherapy for HR-neuroblastoma is challenging due to the low immunogenicity of HR-neuroblastoma and a large number of immunomodulatory mechanisms at play, both locally and systemically, leading to low numbers and questionable tumour reactivity of TIL. It may, therefore, be an attractive strategy to convert the immunosuppressive environment into an immunostimulating one with targeted therapies. For accelerating novel immunotherapy development for HR-neuroblastoma, some considerations may be taken into account [222].

First, the development of suited *in vitro* and *in vivo* models to study the effect of immune interventions within the context of the TME will be of key importance since cellular crosstalk within the TME heavily shapes the outcome of any intervention. 3D culture systems (e.g. organoids or cell-laden hydrogels) or air-liquid interface cultures that include stromal, endothelial, myeloid, lymphoid and tumoural components, representing the entire TME, could be used to study these interactions [223–225]. Since the murine and human immune systems bear fundamental differences, immunotherapy testing in neuroblastoma models may

require specific, humanised models, preferably with a tumour-autologous immune system [60,226].

Second, to develop targeted interventions, a detailed view of the immunological landscape in neuroblastoma will be essential. So far, published studies show rather conflicting findings, which suggests that the current results may be hampered by low patient numbers and/or suboptimal analysis techniques. Although several studies have confirmed the presence of TIL and their relation to prognosis, the functional specialisation and differentiation of lymphocytes in neuroblastoma are still elusive. For exploiting their cytotoxic functions, e.g. in the context of ICI, it is crucial to gain insights into the phenotype, composition, polarisation, clonality, functionality, and differentiation state in single-cell resolution. Also, the spatial organisation of lymphocytes, e.g. formation of tertiary lymphoid structures, may provide important prognostic and functional clues, as has been demonstrated in adult cancers [22,50,51,227,228]. Moreover, differences in the immune landscape between neuroblastoma patients may serve as biomarkers for the prediction of immunotherapy response.

One of the biggest challenges in neuroblastoma so far is the creation of immunological memory to induce a durable response, preventing relapses. Combination immunotherapy is likely the most promising strategy to overcome low T cell reactivity. Next to combining existing immunotherapies to overcome immune-resistance, novel approaches may improve efficacy. For example, the identification of novel immune checkpoints in the TME with functional relevance, such as TIGIT, TIM-3 and phagocytosis checkpoints [229–231], identification of novel tumour antigens serving as target proteins [232,233], the development of trispecific antibodies for T cell activation [234], reinvigorating myeloid cell function [235,236], personalised CRISPR-engineering of T cells [237,238], CAR-NK cells [239], and nanomedicine [240] are all promising novel approaches currently explored in the adult cancer space.

Also, the timing of immunotherapy may require reconsideration. Early application of ICI in the induction phase may improve efficacy by optimally exploiting the autologous immune response and immunostimulatory effects of chemotherapy [241,242]. This upfront setting will shortly be explored for Dinutuximab in HR-neuroblastoma.

In conclusion, the low immunogenicity of neuroblastoma and widespread immunosuppressive effects of the tumour result in a lack of TIL infiltration, activation and tumour reactivity, which severely hampers the effectivity of current immunotherapeutic strategies. Combination therapy, engaging different cell types or targeting multiple immunological mechanisms simultaneously, may provide more effective therapies. Translation of the here mentioned principles to neuroblastoma, and perhaps pediatric oncology in general, may warrant a deeper understanding of pediatric tumour immunology and how we should harness it to improve immunotherapy and increase patient survival with optimal quality of life.

Author contributions

Judith Wienke: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Miranda Dierselhuis:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Lieve Tytgat:** Writing - Review & Editing. **Annette Künkele:** Writing - Review & Editing. **Stefan Nierkens:** Writing - Review & Editing, Supervision. **Jan Molenaar:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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