We have developed a chimeric antigen receptor (CAR) platform that functions as a modular system to address limitations of traditional CAR therapies. An inert form of the human NKG2D extracellular domain (iNKG2D) was engineered as the ectodomain of the CAR to generate convertibleCAR™-T cells. These cells were specifically directed to kill antigen-expressing target cells only in the presence of an activating bisppecific adapter comprised of an iNKG2D-exclusive ULBP2-based ligand fused to an antigen-targeting antibody (MicA-body™). Efficacy against Raji tumors in NSG mice was dependent upon doses of both a rituximab-based MicAbody and convertibleCAR-T cells. We have also demonstrated that the exclusive ligand-receptor partnering enabled the targeted delivery of a mutant form of IL-2 to selectively promote the expansion of convertibleCAR-T cells in vitro and in vivo. By altering the Fv domains of the MicAbody or the payload fused to the orthogonal ligand, convertibleCAR-T cells can be readily targeted or regulated.
The engineering of patient-derived T cells to express chimeric antigen receptors (CARs) has altered the landscape of adoptive cell therapies, providing scientists and clinicians the ability to harness the powerful cytolytic capabilities of T cells and direct them to specific antigen-expressing targets in an MHC-independent manner. Their initial application to treat hematologic malignancies has led to astounding responses and inspired a surge of research efforts to improve upon the original designs in order to strike the best balance of CAR-T cell potency, safety, and persistence and to drive their effective use in non-hematologic indications. Sufficient pre-clinical and clinical data have accumulated from the variations on prototype CAR architecture such that there is now a deeper appreciation of the subtleties that affect CAR-T function. However, CAR-T cell therapies are limited by their utilization of a single-purpose targeting domain, lack of dose control which can contribute to cytokine release syndrome, inability to address tumor antigen loss leading to disease relapse, and immunogenenicity of non-human targeting domains leading to lack of persistence. There is a need to develop a human-derived modular CAR-T cell system that enables sequential and multiplex targeting and that, ideally, would provide elements of dose controlled activity, expansion, and persistence. A number of creative solutions have been explored utilizing adapter molecules that can engage a constant CAR for differential antigen targeting (reviewed in ref. 6). However, there is no single bio-orthogonal human system that has been demonstrated to have the potential for all the following: flexible targeting to direct T cell activity to antigen of choice, multiplex capabilities to reduce the potential for antigen-loss related relapse, dose control for differential engagement of CAR-T cells, and selective delivery of modulatory agents to CAR-expressing cells.

NKG2D is an activating receptor expressed as a type II homodimeric integral membrane protein on natural killer (NK) cells, some myeloid cells, and certain T cells. Human NKG2D has eight distinct natural MIC ligands (MICA, MICB, ULBP1 through ULBP6) that are upregulated on the surface of cells in response to a variety of stresses and their differential regulation provides the immune system a means of responding to a broad range of emergency cues with minimal collateral damage. The structure of the NKG2D ectodomain, several soluble ligands, and the bound complex of ligands to the ectodomain have been solved, revealing a saddle-like groove in the homodimer interface which engages the structurally conserved αα domains of the ligands that are otherwise of disparate amino acid identities. Based upon this structure-function information, we have mutated the NKG2D ectodomain to render it incapable of engaging any natural ligands. Orthogonal ULBP2 αα domain ligand variants were then selected to exclusively engage the inert NKG2D (iNKG2D) but not wild-type NKG2D (wtNKG2D). iNKG2D serves as the extracellular component of our CAR construct while the orthogonal ULBP2-S3 variant (U2S3) is expressed as a fusion to antigen-specific antibodies, generating bispecific terms MicAbodies. MicAbodies are capable of directing and activating iNKG2D-CAR-expressing T cells only when the appropriate antigen is displayed on a surface. Keeping the iNKG2D-CAR receptor constant, we have demonstrated that with either single or multiplexed MicAbodies, convertibleCAR-T cells can be targeted to different tumor antigens to mediate cytolsis. In a disseminated in vivo Raji tumor model, efficacy required both iNKG2D-CAR T cells and MicAbody, both in a dose-dependent manner. Lastly, we have determined that U2S3 can be used as a means of addressing molecules for delivery to iNKG2D-expressing cells and that this feature can specifically target the iNKG2D-CAR cells for complement-mediated killing or drive their expansion in vitro and in vivo with a mutant cytokine fusion. This highly modular convertibleCAR system leverages the body of information behind antibody discovery, development, and manufacturing and nimbly integrates it with the tremendous potential of adoptive cell therapies.

**Results**

**Engineering an orthogonal NKG2D-ligand interaction.** Two central tyrosine residues in each NKG2D monomer have critical roles in driving receptor-ligand interactions (Fig. 1a). Mutations at these residues were heavily explored, with the Y152A mutant (“iNKG2D.YA”) and the Y152A/Y199F double mutant (“iNKG2D.AF”) selected for further study and confirmed by biolayer interferometry (BLI) (Supplementary Figs. 1a, 3a) and ELISA (Supplementary Fig. 1b) to have lost binding to all naturally occurring human ligands. The ULBP2 αα domain was chosen for phage display-based selection of mutants with high affinity binding to each of the iNKG2D variants since it is not polymorphic, NNK libraries interrogating helix 2 and helix 4 (Fig. 1b, c) returned only helix 4 variants and even then only in the context of a spontaneous R81W mutation which likely has a stabilizing role on the ULBP2 αα domain. Competitive selection with rounds of increasing concentration of wtNKG2D (Supplementary Fig. 2a) yielded three variants—U2S1, U2S2, and U2S3—that reproducibly bound exclusively to iNKG2D.YA even when reformatted as fusions to the C-terminus of the IgG1 heavy chain of the anti-FGFR3 antibody clone R3Mab (Supplementary Fig. 2b). Although the R81W mutation alone enhanced affinity toward both wtNKG2D and iNKG2D.YA (Supplementary Fig. 2b, c), its presence in the iNKG2D-selective variants was deemed essential since its reversion to the wild-type residue resulted in loss of binding to iNKG2D.YA. As U2S3 consistently exhibited a greater binding differential, it was characterized more thoroughly and shown as a monomer to have a 10-fold higher affinity toward iNKG2D.YA than wild-type ULBP2 had to wtNKG2D (Supplementary Fig. 2c). Picomolar binding to iNKG2D.YA was measured with a bivalent rituximab antibody fusion and orthogonalinity was retained by both light-chain (LC) and heavy-chain (HC) fusion configurations (Fig. 1d).

Candidate orthogonal variants were similarly identified for iNKG2D.AF and ELISAs comparing rituximab-LC fusions to Fc-wtNKG2D, Fc-iNKG2D.YA, and Fc-iNKG2D.AF identified four variants that selectively bound only iNKG2D.AF (Supplementary Fig. 3b) with the U2R variant being the most selective. ELISAs comparing binding of Rituximab-LC-U2S3 and Rituximab-LC-U2R to both iNKG2D.YA and iNKG2D.AF confirmed that these two independently selected orthogonal ligands exclusively engaged the inert NKG2D variant for which it was evolved (Supplementary Fig. 3c).

**Expression of iNKG2D.YA as a chimeric antigen receptor.** Lentiviral transduction of iNKG2D.YA fused to 4-1BB, CD3ζ, and eGFP into primary human T cells efficiently generated convertibleCAR-T cells with robust transgene expression on par with a rituximab-scFv based CAR construct (RTITscFv-CAR) with the same hinge, transmembrane, and intracellular architecture (Fig. 2b and Supplementary Fig. 4). Surface staining of iNKG2D.YA with the Rituximab-LC-U2S3 MicAbody and standard quantification beads, the median amount of iNKG2D.YA expressed on the surface was estimated to be 21,000 molecules. Direct engagement of iNKG2D.YA-CAR receptors by incubation of convertibleCAR-CDS+ cells to microtiter plates coated with wild-type or U2S3 ligands resulted in activation and liberation of IL-2
and IFNγ only with U2S3 while wtNKG2D-CAR bearing cells responded only to wild-type ligands confirming the selectivity of the orthogonal interaction in the context of T cells (Supplementary Fig. 5a). Furthermore, activation of convertibleCAR-T cell function was dependent upon the presence of the appropriate cognate ULBP2 variant. The iNKG2D.YA expressing or iNKG2D.AF expressing T cells only lysed Ramos (CD20+), target cells when armed with a MicAbody bearing its respective orthogonal ligand, i.e. U2S3 or U2R (Supplementary Fig. 3d). Co-culture of Ramos cells alone was not sufficient to drive activation of convertibleCAR-CAR8+ cells. Instead the appropriate antigen-targeting MicAbody was required since neither rituximab antibody nor Trastuzumab.LC-U2S3 activated CAR cells whereas Rituximab.LC-U2S3 triggered maximum cytokine release in the 32–160 pM range. Additionally, cytokine release by convertibleCAR-T cells with Rituximab.LC-U2S3 MicAbody exceeded that of the RITscFv-CAR cells (Supplementary Fig. 5b). These data demonstrated that the appropriate antigen-targeting MicAbody was
required to form a junction, likely similar to that characterized for scFv-CARs, between the target and convertibleCAR-T cells to drive robust activation of T cell function (Fig. 3a).

Engineering convertibleCAR-D8+ cells with a fluorescently labeled Rituximab.U2S3 MicAbody revealed saturation of total iNKG2D.YA-CAR receptors at 5 nM (Fig. 3b). However, in a co-culture killing experiment where convertibleCAR-D8+ cells were armed with decreasing amounts of Rituximab.U2S3, Ramos target cell lysis activity reached a saturation response at 30 pM, two orders of magnitude less than required for full occupancy of receptors (Fig. 3c). This result suggests the extra unoccupied iNKG2D.YA-CAR receptors could be armed with heterologous MicAbodies to guide activity against multiple targets simultaneously. To directly test this, convertibleCAR-D8+ cells were armed with Rituximab.LC-U2S3, Trastuzumb. LC-U2S3 (targeting Her2), or an equimolar mixture of the two MicAbodies and exposed to either Ramos cells or CT26-Her2. Although CAR cells armed with a single MicAbody directed lysis to only tumor cells expressing the cognate antigen, dual-armed CARs targeted both tumor cell lines without any compromise in lytic potency (Fig. 3d).

** convertibleCAR-T cells inhibit disseminated B-cell lymphomas.** The pharmacokinetics of both the HC and LC Rituximab-U2S3 MicAbodies (Supplementary Fig. 6a) in NSG mice revealed a β-phase that paralleled the parental antibody with the steeper α-phase of the MicAbodies attributed to retention of U2S3 binding to endogenous mouse wild-type NKG2D (Supplementary Fig. 6c). The LC-U2S3 fusion had a slightly longer terminal half-life than the HC-fused MicAbody, out-performed the HC fusion in an in vitro killing assay with Ramos target cells (Supplementary Fig. 6b), and appeared to be more efficacious at early time points in suppressing Raji B cell lymphoma expansion in NSG mice (Supplementary Fig. 6d, e). Accordingly, Rituximab.LC-U2S3 (Rit-S3) was deployed in further experiments exploring dosing parameters for lymphoma control (Supplementary Fig. 7). An intermediate Rit-S3 dose of 20 μg was shown to be the most efficacious as high concentrations may result in over saturation of receptors on the CAR cells and antigens on the tumor cells, thereby interfering with productive engagement. Additionally, a higher frequency of Rit-S3 administration of every 2 days versus every 4 days paired with a higher dose (10 × 10⁶) of convertibleCAR-T cells resulted in the greatest suppression of tumor growth. Rit-S3 alone was ineffective at tumor control while a graft-vs-tumor effect was consistently observed in both untransduced and convertibleCAR only cohorts (Supplementary Fig. 7a, b; Fig. 4b). Rit-S3 was detectable in the serum of mice throughout the course of the study with peak levels appearing earlier with more frequent dosing (Supplementary Fig. 7b).

A Raji disseminated lymphoma model with optimized convertibleCAR-T dosing was performed with 20 μg Rit-S3 dosing every...
2 days comparing $5 \times 10^6$ (5M) to $15 \times 10^6$ (15M) convertible CAR-T cells (Fig. 4a). As a positive control, RITscFv-CAR cells were also included which have in vitro Ramos killing potency comparable to convertible CARs (Supplementary Fig. 5b). At 5M total T cells, both RITscFv-CAR and convertibleCARs + Rit-S3 were effective at controlling tumor (Fig. 4b). Although the average tumor bioluminescence signal was lower for the RITscFv-CAR cohort (Fig. 4c), and four of five mice in that cohort appeared to have cleared tumor tissue, three of five mice in the convertibleCAR + Rit-S3 cohort appeared cleared (Fig. 4d). When total infused CAR-T cell doses were increased to 15M cells, both RITscFv-CAR and convertibleCAR + Rit-S3 were able to completely block tumor expansion (Fig. 4b, d). In all studies, peak levels of peripheral human CD3+ T cells consistently appeared around 7 days post-infusion with both scFv-CAR and convertibleCAR-T cells having contracted in the majority of mice by 14 days (Fig. 4f). There was a delayed expansion of CD3+ cells in the untransduced and convertibleCAR-only cohorts that was contemporary with the onset of the graft-versus-tumor response and likely the consequence of expansion of specific reactive clones. MicAbody associated convertibleCAR-T cells were observed in the blood of mice in convertibleCAR + Rit-S3 cohorts (Fig. 4g).
**convertible**CAR-T cells inhibit subcutaneous lymphomas.** Raji B cells were implanted subcutaneously to assess the ability of the convertibleCAR system to suppress growth of a solid tumor mass. Once tumors were established at 10 days, either 7 × 10⁶ (7M) or 35 × 10⁶ (35M) convertibleCAR-Ts were administered after a single IV dose of 60 µg Rit-S3 (Fig. 5a). Additionally, one cohort received 35M cells that were pre-armed with a saturating concentration of Rit-S3 prior to administration but no additional MicAbody introduced injections. Administration of 7M convertibleCAR-T cells along with Rit-S3 (7M + Rit-S3) resulted in reduced tumor size relative to convertibleCAR-T cells alone (Fig. 5b, c). Furthermore, in the 35M + Rit-S3 cohort, tumor growth was completely suppressed. Tumor growth in the cohort that received 35M pre-armed cells was also inhibited. By 2 days post-infusion, convertibleCAR-T cells that had been pre-armed did not have detectable surface associated Rit-S3 MicAbody (Fig. 5e), a result of disarming likely due to a combination of activation-induced cell proliferation and the turnover of armed receptors. Serum levels of Rit-S3 were comparable at both
Fig. 5 Control of subcutaneously implanted Raji tumors in NSG mice by convertibleCAR-T cells. **a** Schematic of study design with treatment initiated at day 10 with Rit-S3 administration followed by CAR-T infusion the next day. **b** Average tumor volumes for each cohort, n = 5. Tumors varied greatly in size within each group so error bars were not graphed. Two cohorts, blue and green lines, overlap and cannot be graphically distinguished beyond day 26. **c** Excised tumors at day 45 post-implantation with average tumor masses plotted in grams for each cohort, ±SEM, and * indicating p < 0.05 compared to the vehicle cohort as determined by unpaired, two-tailed t-test. Scale bar = 1 cm and all images adjusted to the same scale. **d** Serum Rit-S3 levels. Error bars indicated ±SD samples from mice in a given cohort. **e** CD3+ T cell dynamics in the blood and quantitation of the percentage of T cells with surface-associated MicAbody F(ab’)2 staining) with ±SD error bars shown. Groups are color coded to match across the different graphics.
CAR-T cell doses across the study and persisted through day 21 when it was detected at approximately 600 ng/mL (3.2 nM) (Fig. 5d) corresponding to high levels of armed peripheral CAR cells (Fig. 5e). By day 45 of the study, the cohort receiving 35M + Rit-S3 maintained relatively high CD3+ T cell numbers but were not well-armed with MicAbody while the 7M + Rit-S3 cohort did have cells that maintained surface-associated MicAbody. This suggested that as MicAbody levels fell below detectable limits in the plasma, CAR arming could not be maintained at high CAR-T cell levels. An alternative possibility is that the higher CD3+ cell numbers in the 35M + Rit-S3 cohort reflect expansion of a graft-vs-tumor subset of cells that do not express the CAR construct. However, the elevated CD3+ cell numbers were not seen in the 35M pre-armed cohort suggesting that this is not the case. In summary, pre-armed convertCAR-Ts were able to exert a potent anti-tumor response that inhibited tumor expansion. Furthermore, convertCAR-Ts were able to effectively control a solid lymphoma when an adequate in vivo level of convertCAR-T cell arming was maintained.

Selective delivery of biomolecules to convertCAR-T cells. The privileged interaction between iNKG2D variants and their orthogonal ligands enables the selective delivery of agents to iNKG2D-CAR expressing cells simply by fusing them as payloads to the orthogonal ligands themselves. To demonstrate the utility of this feature two disparate applications were explored: targeted ablation utilizing the complement system and selective delivery of activating cytokines. In the first application, the U2R variant was fused to either the N- or C-terminus of the wild-type human IgG1 Fc-domain or to mutant Fc domains previously described as enhancing C1q binding—S267E/H268F/S324T/G326A/I332E (“EFTAE”)20 and K326A/E333A (“AA”)21 (Supplementary Fig. 8a). Using just the Fc-portion, as opposed to a complete therapeutic antibody targeting an epitope-tagged CAR cell, avoids collateral effects from opsonization of non-iNKG2D expressing cells22-24. The enhanced C1q binding was confirmed by ELISA with relative order of Kd’s as EFTAE < AA < wt (Supplementary Fig. 8g). While iNKG2D.AF-CAR cells were susceptible to killing by human complement in a manner that was dependent upon both concentration and C1q affinity (Supplementary Fig. 8c), untransduced cells were unaffected. Interestingly, orientation of the U2R fusion was critical - N-terminal fusions, which orient the Fc in a manner consistent with an antibody were much more effective. Similar results were obtained with the U2S3 and iNKG2D.YA pairing (Supplementary Fig. 8d).

The potential ability of orthogonal ligands to deliver cytokines selectively to iNKG2D-CAR expressing cells has advantages to not only promote their expansion but also potentially leverage differential cytokine signaling to control T cell phenotype and function. As a general design principle, mutant cytokines with reduced binding to their natural receptor complexes were employed to reduce their engagement with immune cells not expressing the CAR and to minimize toxicity associated with wild-type cytokines. Additionally, cytokine fusions were kept monovalent to eliminate avidity-enhanced binding and signaling. To this end, the R38A/F42K mutations in IL-2 (mutIL2)25 and the V49D mutation in IL-15 (mutIL15)26 dramatically reduce binding to each cytokine’s respective Ra subunit while maintaining IL-2Rβγ complex engagement. Initial experiments using the iNKG2D.YA orthogonal variant U2S2 fused to either mutIL2 or mutIL15 promoted proliferation of iNKG2D.YA-CAR expressing cells but not those expressing wtNKG2D-CAR (Supplementary Fig. 9a). Both cell populations expanded in the presence of the ULBP2.R81W variant, which does not discriminate between wtNKG2D and iNKG2D.YA. Direct fusion to the ligand or via a heterodimeric Fc linkage27 (e.g., U2S2-hFc-mutIL2) promoted expansion of GFP+ convertCAR-T cells to densities above the untransduced cells present (Supplementary Fig. 9b), and these expanded convertCAR-T cells maintained their cytolytic capabilities (Supplementary Fig. 9c). Engagement of iNKG2D.YA by MicAbody, monovalent U2S3-hFc (without a cytokine payload), or by mutIL2 alone were insufficient to drive proliferation of convertCAR-CAR-CD8+ cells (Supplementary Fig. 9a, d). Flow cytometry characterization of STAT3 and STAT5 phosphorylation (pSTAT3 and pSTAT5) revealed that exposure to wild-type IL-2 or IL-15 resulted in an increase of pSTAT3 and pSTAT5 in both untransduced as well as convertCAR-CAR-CD8+ cells (Supplementary Fig. 9e). Treatment of untransduced cells with U2S3-hFc-mutIL2 resulted only in a minimal shift in pSTAT5 relative to the no cytokine control, consistent with mutIL2’s retention of IL-2Rβγ/γc binding. The convertCAR-CAR-CD8+ cells responded to both U2S3-hFc-mutIL2 and U2S3-hFc-mutIL15 with an increase in pSTAT5 levels via γc chain activation of JAK3. Unlike wild-type cytokines, no increase in pSTAT3 signal was observed, indicating a reduction in JAK1 activation through IL-2Rβγ28 in both scenarios as a consequence of disruption of Ra binding, a hypothesis supported by IL-15Ra’s role in increasing the affinity of IL-15 for IL-2Rβγ29. The kinetics of responses U2S3-hFc-mutIL2 and U2S3-hFc-mutIL15 were nearly identical, indicating functional redundancy in their mutant forms (Supplementary Fig. 9f).

U2S3-hFc-mutIL2 was shown to have an in vivo PK half-life of a few days (Supplementary Fig. 9g). convertCAR-T cells administered to NSG mice in the absence of tumor underwent a homeostatic expansion, peaking at 3 days following by contraction. Three injections of U2S3-hFc-mutIL2 staged 1 week apart resulted in a dramatic expansion of human T cells in the peripheral blood (Fig. 6a) and T cell numbers contracted after cessation of U2S3-hFc-mutIL2 support with CD8+ T cells driving the bulk of the expansion. In parallel with expansion, the proportion of GFP+ CD8+ T cells increased to 100% demonstrating selective expansion of iNKG2D-CAR expressing cells but not untransduced cells (Fig. 6b).

The effect of U2S3-hFc-mutIL2 on normal human PBMCs from three donors was explored in vitro by exposure to increasing concentrations of the agent for 4 days followed by flow-based quantification of cells positive for the proliferative marker Ki-67 (Supplementary Fig. 10). In addition to the -mutIL2 fusion, a wild-type IL2 fusion (U2S3-hFc-wtIL2) was included to directly demonstrate that the reduction in mutIL2 bioactivity was a consequence of the mutations employed and not the fusion format itself. The CD4+ and CD8+ T cells responded robustly to both anti-CD3 and wild-type IL-2 positive controls as well as to the lowest dose of U2S3-hFc-wtIL2. Proliferative responses to U2S3-hFc-mutIL2 occurred in a dose-dependent manner with expansion observed across donors at levels above 300 IU/mL but not achieving levels comparable to those of the IL-2 positive control until 30,000 IU/mL. Treg responses were comparable to those of CD4+ and CD8+ cells with the exception of cells from one donor (who additionally had a muted response to anti-CD3 stimulation) that responded to U2S3-hFc-mutIL2 at a lower concentration than the other donors. Taken together, these data support the hypothesis that normal human PBMCs do not respond to U2S3-hFc-mutIL2 except at super-physiologic levels which potentially provides a wide dosing window for selective delivery of ligand-fused mutIL2 to convertCAR cells while minimizing toxicity and Treg activation.

Discussion

We have described the engineering of a privileged receptor-ligand (iNKG2D.YA and U2S3) pairing comprising human components
for a highly adaptable CAR, resulting in a versatile and broadly controllable platform. The iNKG2D.YA-CAR receptor itself is held invariant on T cells with CAR function readily directed to potentially any antigen of interest by virtue of attaching the orthogonal ligand to the appropriate antigen-recognizing antibody. In this manner, the same convertibleCAR-T cells can be reactivated as needed if, for example, the original tumor antigen becomes downregulated during the course of therapy. This targeting flexibility is not limited to the sequential engagement of antigens, but can also be multiplexed to simultaneously direct T cells to more than one antigen in order to reduce the likelihood of tumor escape by antigen loss, address the issue of heterogeneity of intratumoral antigen expression, or even simultaneously target tumor and suppressive cellular components of the tumor microenvironment. Traditional scFv-CAR cells are generally committed to a fixed expression level of a receptor which reduces their ability to discriminate between antigen levels present on healthy versus aberrant cells. The use of switch/adapter strategies, like MicAbodies with convertibleCAR-T cells, may provide an opportunity to differentially engage CAR-Ts to achieve a therapeutic index that reduces the risk of severe adverse events. While all adapter strategies require the initial development of two components, once the CAR architecture has been established each iterative round of adapter development will involve relatively minor modifications to the original antibody-based adapter without alterations to the manufacturing process.

The use of the privileged receptor-ligand interaction for delivery of payloads specifically to iNKG2D-bearing cells without additional cellular engineering is another advantage. The capability of harnessing interleukin functions to drive expansion and activation, prevent exhaustion, or even promote suppression in a controlled and targeted manner could have beneficial consequences for efficacy and safety. Introduction of cytokine-ligand fusions during CAR manufacturing could address qualitative and quantitative limitations of patient T cells and their administration post-CAR infusion could expand the number of CAR-T cells and their persistence which, with CD19-CAR therapies, is correlated positively with response rates. Most CAR therapies require a preconditioning lymphodepletion regimen to promote engraftment and expansion of CAR cells, one rationale being that it provides a more verdant immunological setting for CARs to expand. Robust and controllable convertibleCAR-T expansion in patients may supplant the need for lymphodepletion, allowing for retention of endogenous immune functions that are fully competent to support the initial convertibleCAR-mediated antitumor activity. Another clinical strategy might be to deliver cytokine-ligand fusions to bolster convertibleCAR-T function, possibly with a cycling regimen to reduce T cell exhaustion and promote the maintenance of memory T cells. And lastly, as CARs have been demonstrated to persist in humans for years post-infusion, the ability to recall resident convertibleCAR-Ts to attack primary or secondary malignancies (either with the original targeting MicAbody or a different one) without having to re-engineer or generate a new batch of CAR cells should be highly advantageous. Unlike scenarios where CARs have been engineered to constitutively express cytokines, delivery of cytokines exclusively to convertibleCAR-T cells can be modulated depending upon the manufacturing or clinical needs.

By design, each component of the convertibleCAR system—the iNKG2D-based CAR receptor and the MicAbody (which is ADCC-deficient)—are functionally inert on their own. This has advantages during manufacturing, particularly in the context of indications such as T cell malignancies where traditional scFv-based CARs encounter expansion hurdles due to fratricide. Additionally, it provides enhanced control of CAR function during treatment. We have demonstrated that convertibleCAR-T cells can be armed with MicAbody prior to administration to provide an initial burst of anti-tumor activity on par with traditional scFv-CARs, an aspect that will be critical for first-in-human safety studies. In addition to activation-induced replication, these cells also internalize their engaged CAR receptors in a manner consistent with what has been observed with other 4-1BB/CD3ζ scFv-CARs (Supplementary Fig. 5c). As a consequence of these two processes, convertibleCAR-T cells will rapidly disarm after initial expansion and target engagement, which then provides an opportunity rearmand re-engage in a manner controlled by MicAbody dosing.

In addition to the iNKG2D-U2S3 pairing based upon ULBP2, we have also identified high-affinity orthogonal MicA and ULBP3 variants to iNKG2D.YA that are non-redundant in their amino acid compositions through the helix 4 domain. The fact that a convergence of sequence was not observed, despite the conserved tertiary structure of their MIC αα domains, indicates that there are many solutions for orthogonality. Additionally, we have engineered a completely independent iNKG2D.AF and U2R pairing suggesting that there is opportunity to explore a breadth of inert NKG2D variants that, in combination with mutational space afforded by the MIC ligands, can lead to the identification of additional orthogonal receptor-ligand pairings. Having mutually exclusive receptor-ligand pairs would enable, for example, their introduction into distinct cell populations (e.g., CD4 and CD8 T cells) to differentially engage them as needed.

**Fig. 6 In vivo response of convertibleCAR-T cells to U2S3-hFc-mutIL2.** a NSG mice were injected with 7 × 10⁶ total iNKG2D-transduced cells (CD4:CD8 1:1). After the contraction of T cells at 14 days, mice were injected with 30 μg U2S3-hFc-mutIL2 or PBS once per week—indicated by red triangles—and T cell dynamics monitored by flow cytometry. Shown are the % of human CD3⁺ T cells in the peripheral blood with each trace corresponding to an individual mouse, n = 5. b Plots for the expansion of CD8⁺ cells as well as the increase in proportion of GFP⁺ (CAR-expressing) cells upon U2S3-mutIL2 treatment.
Furthermore, within the same cell, the two iNKGD2 variants could be expressed with split intracellular signaling domains to provide dual antigen-dependent activation to enhance on-tumor selectivity38,40. Alternatively, the two iNKGD2 variants could be differentially linked to either activating or immunosuppressive domains to enhance the discriminatory power of the T cells between tumors or healthy tissue, respectively41.

In summary, the convertibleCAR system has demonstrated capabilities to not only be readily targeted to different cell-surface antigens but can also be selectively engaged exogenously to drive cell expansion. The privileged receptor-ligand interaction that has been developed is agnostic to cell type and can, in principle, be engineered into any cell of interest as long as the cell-appropriate signaling domains are provided. Additionally, the adoptive cellular therapy field is aggressively pursuing the development of allogeneic cells to bring down the time, complexity, and cost of manufacturing to provide a more consistent, readily accessible product42. A highly adaptable CAR system would be powerfully synergistic with allogeneic efforts and once a truly universal allogeneic CAR system has been validated, the therapeutic field has been changed considerably by the relative ease of development and implementing a library of adapter molecules from which personalized selections can be made. This strategy also broadens the potential areas of application to any pathogenic cell with a targetable surface antigen. For example, we have recently demonstrated the utility of convertibleCAR platform in the ex vivo reduction of latent reservoirs in the blood of HIV patients using a cocktail of MiAbodies derived from anti-HIV broadly neutralizing antibodies43.

**Methods**

**Cloning, expression, and purification.** The wild-type ectodomain of NKG2D (UniProtKB P26718, residues 78–216; https://www.uniprot.org) was expressed as a fusion to the C-terminus of human IgG1 Fc via a short factor Xa recognizable L-glutamylglycylarginyl linker (Fc-wtNKG2D). Inert NKG2D variants comprising either a single Y152A (iNKGD2.YA) or double Y152A/Y199A substitution (iNKGD2.AF) were generated by PCR-mediated mutagenesis or synthesized (gBlocks®, IDT). DNA constructs for Fc-NKG2D molecules were expressed in Expi293™ cells (Thermo Fisher Scientific) and dimeric secreted protein was purified by Protein A affinity chromatography (Pierce™ #20334, Thermo Fisher). Eluted material was characterized and further purified by size-exclusion chromatography (SEC) on an AKTA Pure system using Superdex 200 columns (GE Life Sciences). Correctly assembled, size-approximate monomeric material was fractionated into phosphate-buffered saline (PBS).

The αα domains of human MICA*001* (UniProtKB Q29983, residues 24–205), MICB (UniProtKB Q92890, 24–205), ULBP1 (UniProtKB Q9BZM6, 29–212), ULBP2 (UniProtKB Q9BZM5, 29–212), ULBP3 (UniProtKB Q9BZM4, 30–212), ULBP5 (UniProtKB Q9Y0106782, 29–213) were cloned with a C-terminal 6x-His tag. Monomeric protein was purified from Expi293™ supernatants Ni-NTA resin (HisPur™, Thermo Fisher) and eluted material exchanged into PBS with Sephadex G-25 in PD-10 Desalting Columns (GE Life Sciences).

MIC ligands and orthogonal variants were cloned by ligation-independent assembly (HiFi DNA Assembly Master Mix, NEB #E2621) as fusions to the C-terminus of either the kappa light-chain or the heavy-chain of human IgG1 antibodies via either an AP1SSGGGGS or GGGS linker, respectively. Additionally, D265A/N297A (Kabat numbering) mutations were introduced into the CH2 domain of human IgG1 Fc via a short factor Xa recognizable Ile-X linker were substituted for the NKG2D module to generate the rituximab scFv-CAR constructs (RIT-ScFvCAR). For each of bivalent Fc constructs, 6 × 10^6 Lenti-X 293T (Takara Bio #632180) cells were seeded in a 10 cm dish the day prior to transfection. Then 12.9 μg pCMV DR8.R1, 2.5 μg pM2D.G and 7.2 μg of pHR-PCG-CAR constructs were combined in 720 µl Opti-MEM™ (Thermo Fisher #31985062) then mixed with 67.5 µl of Fugene HD (Promega Corp. E2311), briefly vortexed, and incubated at room temperature for 10 min before adding to the dish of cells. After 2 days, supernatants were collected by centrifugation and passed through 0.22 µm filters. 5X concentrated PEG-6000 and NAcI were added to achieve final concentrations of 8.5% PEG-6000 (Hampton Research #HR2–533) and 0.3 M NaCl, incubated on ice for two hours, then centrifuged at 4 °C for 20 min. Concentrated viral particles were resuspended in 0.01 volume of PBS, and stored frozen at −80 °C.

For primary human T cell isolation, a Human Peripheral Blood Leuko Pak (Stemcell Technologies #70500.1) from an anonymous donor was diluted with an equivalent volume of PBS + 2% FBS, then centrifuged at 500 x g for 10 min at room temperature. Cells were resuspended at 5 × 10^5 cells/ml in PBS + 2% FBS and CD4+ or CD8+ cells enriched by negative selection (StemCell EasySep Human CD4 T Cell Isolation Kit #17952 or EasySep Human CD8 T Cell Isolation Kit #17953) by addition of 50 μl of isolation cocktail per ml of cells and incubating for 5 min at room temperature. Subsequently, 50 μl of RapidSpheres were added per ml of cells and samples topped off (to each 21 mL cells, 14 mL of PBS). Cells were isolated with an EasySep magnet followed by centrifugation and passed through 0.22 μm filters. Enriched cells were transferred into new tubes with fresh buffer and the magnet reapplied for a second round of enrichment after which cells were resuspended, counted, and cryopreserved at −15 to −16 x 10^6 cells/ml, cryovial (RFMI-1640, Corning #15–040-CV; 20% human AB serum, Biologicals #HP1022; 10% DMSO, Alfa Aesar #42780).

To generate CAR-T cells, one vial of cryopreserved cells was thawed and added to 10 ml T cell medium “TCM” (TexMACS medium, Miltenyi 130-097-196; 5% human AB serum, Valley Biomedical #HP1022; 10% neutralized N-acyethyl-L-cysteine; 1 x 2-mercaptoethanol, Thermo Fisher #21985052, 100×; 4 IU/ml rhIL-2, Miltenyi #55-107-997-2, Miltenyi 130-107-196; 5%) in 10 ml TCM preheated at 37 °C. Each vial was resuspended to 5 x 10^6 cells/ml and then transferred to T25 flasks with an added 60 μg rhIL-2. After 3 days of expansion, Dynabeads were removed (MagCellect magnet, R&D Systems MAG997), transduction efficiency assessed by flow cytometry for GFP, back-diluted to 5 x 10^5 cells/ml, and cell density monitored daily to ensure they did not exceed 4 x 10^5 cells/ml. When necessary, surface expression of iNKGD2 was verified with GFP expression linked to an antibody-recombinant human kappa chain (Abcam ab#79113) or by directly conjugating the Rituximab-MiAbody to Alexa Fluor 647 (Alexa Fluor Protein Labeling Kit #A20173, Thermo Fisher).
The amount of INKG2D expression on the surface of convertibleCAR-CAR-CD8+ cells was quantified using Alexa Fluor 467 conjugated Rituximab-MicAbody, and median fluorescence intensity was correlated with Quantum™ MUSE 647 beads (Banges Laboratories #647). All flow cytometry was performed on either Bio-Rad S3e Cell Sorter or Millenyi MACSQuant Analyzer 10 instruments.

**Line cells and in vitro assays.** Ramos human B cell lymphoma cells (ATCC #CRL-1596) were cultured in RPMI supplemented with 20 mM HEPEs and 10% FBS. The mouse colon carcinoma line CT26 transfected to express human Her2 were a kind gift from Professor Sherie Morris (UTA CLA). No additional cell culture steps were required for these cell lines. No further plasma processing nor authentication was performed except to verify by flow cytometry that target antigens were expressed.

For calcine-release assays, tumor cells were centrifuged and resuspended in 4 mM p-bromobenzenecarbonyl (MP Biomedicals #156370) + 25 μM calcein-AM (Thermo Fisher #C3424) at a concentration of 1 × 106 cells/mL. Cells were then incubated at 37 °C, washed once, and adjusted to 8 × 105 cells/mL. CAR-T cells were pelleted and resuspended in 4 mM p-bromobenzenecarbonyl with 60 μM/ml IL-2 in 4 × 106 cells/ml, then adjusted according to the desired effector:target ratio (unadjusted for transduction efficiency). 25 μL target cells were plated followed by 25 μL medium or diluted MicAbody. The medium (minimum invasive medium with 3% Trypsin (maximal lysis), or CAR-T cells were added and plates incubated at 37 °C for 2 h. Cells were pelleted and 75 μL supernatant transferred to black clear-bottom plates and fluorescence (excitation 485 nm, emission cutoff 495 nm, emission 530 nm, 6 flashes per read) acquired on a Spectramax M2 plate reader (Molecular Devices). For experiments with armed CAR-T cells, T cells were pre-activated and calcine-preloaded (A) as above. Target cells were pre-loaded with 30 μM calcine-loaded target cells.

In order to quantify the target-dependent activation of T-cells, experiments were set up as described except that calcine pre-loading was omitted and assays set up in T cell medium without IL-2 supplementation. After 24 h co-culture, supernatants were harvested and stored at −80 °C until the amount of liberated calcine could be quantified by ELISA MAX³D Human IL-2 or Human IFN-γ detection kits (BioLegend #431801 and #430101).

The calcine fluorescence data were generated by ProMab Biotechnologies, Inc. (Richmond, CA). 3 × 105 convertibleCAR-CAR-CD8+ cells were plated in 96-wells V-bottom plates and incubated with labeled Alexa Fluor 467 labeled Rituximab-LC-U2S3 MicAbody for 30 min at room temperature in a final volume of 100 μL RPMI + 1% FBS with a titration curve starting at 200 μM. Cells were then rinsed and medium fluorescence intensity determined for each titration point by flow cytometry.

**Animal studies.** All animal studies were conducted by ProMab Biotechnologies, Inc. (Richmond, CA) with the exception of the U2S3-hFc-mutUI2-labeled pharmacokinetic (PK) sampling which was conducted by Murigenics (Vallejo, CA). For PK analysis of serum levels of MicAbodies, 6-week old female NGS mice (NOD.Cg-Prkaçc−/−;Il2rg−/−;ldlr−/−;Cdx2−/− F1, The Jackson Laboratory # 005557) were injected intravenously (IV) with 50 μL of labeled convertibleCAR-LC-U2S3 strains. Alternatively, CET音樂2 mouse binding curves were generated by ProMab Biotechnologies, Inc. (Richmond, CA). 3 × 105 convertibleCAR-CAR-CD8+ cells were plated in 96-wells V-bottom plates and incubated with labeled Alexa Fluor 467 labeled Rituximab-LC-U2S3 MicAbody for 30 min at room temperature in a final volume of 100 μL RPMI + 1% FBS with a titration curve starting at 200 μM. Cells were then rinsed and medium fluorescence intensity determined for each titration point by flow cytometry.

**Delivery of mutant-IL2 to T cells expressing INKG2D-CAR.** To generate a reagent that was monomer for the U2S3 IgG, monomeric for a mutant IL-2 with the inability to bind IL-2Ra (mutIg, R38A/F42K)35,49 yet retained serum stability, a heterodimeric Fc strategy was employed27. U2S3 was fused to the N-terminus of the Fc-hinge of one chain with C326A/E333A (Kabat numbering) mutations while the mutIg was fused to the N-terminus of a G236A/I332E (Kabat numbering) linker chain which harbored E356K/D399K mutations. Additionally, D265A/N297A mutations were introduced in both Fc chains to render the Fc ADCC-deficient. Expression in Exp293T cells and purification was as described above. Appropriately assembled U2S3-hFc-mutIg2-labeled material was fractionated by SEC and the presence of individual isoform elution peaks confirmed by dot blotting with anti-human IL-2Rα and mouse anti-human IL-2 antibodies. A direct fusion between orthogonal ligand and mutIg expressed as a single polypeptide with a linker comprising glycine-serine linkages, a FLAG tag, and a 6×His tag was also generated and purified by Ni-NTA exchange chromatography25. Determination of Iu activity equivalents was calculated based on the 4.4 μM solution of wild-type U2S3-CAR induction being 100% effect, and a direct fusion between orthogonal ligand and mutIg expressed as a single polypeptide with a linker comprising glycine-serine linkages, a FLAG tag, and a 6×His tag was also generated and purified by Ni-NTA exchange chromatography25. Determination of Iu activity equivalents was calculated based on the 4.4 μM solution of wild-type U2S3-CAR induction being 100% effect, and a direct fusion between orthogonal ligand and mutIg expressed as a single polypeptide with a linker comprising glycine-serine linkages, a FLAG tag, and a 6×His tag was also generated and purified by Ni-NTA exchange chromatography25.
block (BioLegend #422301) followed by staining with BioLegend antibody panels for proliferating T cells (CD38 clone RPA-T8 #301050, CD4 clone OKT4 #31710, CD3 clone OKT3 #500430, KI-67 #305314), and Treg cells (Fox3 clone 20D6 #320106, CD4 clone OKT4, CD3 clone OKT3, KI-67).

Statistics and reproducibility. All statements of reproducibility were included in the figure legends and indicate the number of experiments that the presented data were representative of. All statistical tests were performed using GraphPad Prism and analysis tools implemented are detailed in the appropriate figure legends.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
No large datasets were generated or analyzed during this study therefore sharing is not applicable. Source data supporting the graphs and charts presented in the main text are available in the Supplementary Data 1 file. All relevant data are available from the authors upon reasonable request.

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Author contributions
K.E.L., K.C.K., K.T.R., and D.W.M. conceived the experiments. K.C.K. and K.E.L. supervised the study. S.R.W. performed most of the in vitro experiments while K.C.K., K.E.L., D.G., D.S., and S.L. performed or contributed to specific experiments. K.C.K. wrote the paper with editorial contributions provided by D.W.M., K.E.L., and K.T.R. All authors have read and approved the final submitted paper.

Competing interests
K.C.K., S.R.W., D.G., and D.W.M. declare no competing financial interests but are employees of Xyphos Biosciences, an Astellas Company. K.E.L., D.S., S.L., and K.T.L. declare no competing financial or non-financial interests. Aspects of the convertibleCAR platform are claimed in U.S. Patent No. 10,259,858.

Additional information
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Correspondence and requests for materials should be addressed to K.C.K.

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