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Designing Clinical Trials for Combination Immunotherapy: A Framework for Glioblastoma

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ABSTRACT

Immunotherapy has revolutionized treatment for many hard-to-treat cancers but has yet to produce significant improvement in outcomes for patients with glioblastoma. This reflects the multiple and unique mechanisms of immune evasion and escape in this highly heterogeneous tumor. Glioblastoma engenders profound local and systemic immunosuppression and is remarkably effective at inducing T cell dysfunction, posing a challenge to any immunotherapy-based approach. To overcome these mechanisms, multiple disparate modes of immune-oriented therapy will be required. However, designing trials that can evaluate these combinatorial approaches requires careful consideration. In this review, we explore the immunotherapy resistance mechanisms that have been encountered to date and how combinatorial approaches may address these. We also describe the unique aspects of trial design in both pre-clinical and clinical settings and consider endpoints and markers of response best suited for an intervention involving multiple agents.

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1 INTRODUCTION

Patients with glioblastoma survive for 12-15 months on average despite treatment with surgery, focal irradiation, alkylating chemotherapy and tumor treating fields (1-4). While several immunotherapies are currently under investigation for glioblastoma, none have yet demonstrated a significant survival benefit (5-7). Glioblastoma originates in an immune privileged compartment and is adept at escaping immune surveillance (8). Precision immunotherapy also requires a uniformly expressed tumor-specific antigen (TSA) which remains elusive in highly heterogeneous isocitrate dehydrogenase (IDH) wild type gliomas or glioblastoma (9). Further, glioblastoma disrupts immune function both locally and systemically, degrading the ability of immunotherapy to act (10).

Given these significant obstacles, it is clear that a single agent will be insufficient. To unlock the true potential of immunotherapy, combinations with additive and/or synergistic mechanisms of action is required. However, testing these combinations poses unique technical, logistical, and regulatory challenges. In this review, we will explore current opportunities and describe strategies for conducting trials of combination immunotherapy.

2 CURRENT AND FUTURE COMBINATORIAL STRATEGIES

Glioblastoma induces immune dysfunction through multiple mechanisms (10-15). To overcome these, several immunotherapy classes are under investigation, including immune checkpoint blockade (ICB), chimeric antigen receptor T cells (CAR-Ts), bi-specific T cell engagers (TCEs), tumor antigen vaccination, oncolytic viruses, and immunomodulatory cytokines (16-21). Given the large number of permutations for combination therapy, we must rationalize the available options.

2.1 Combinations of multiple immune checkpoint blockade

Single agent ICB has failed to yield benefit in patients with glioblastoma (22). Given this, studies have been performed using multiple ICB agents, based on effective strategies in other difficult malignancies such as melanoma or advanced renal cell carcinoma (23). A well described combination in oncology is that of nivolumab (anti-PD1) and ipilimumab (anti-CTLA4) which has been explored in multiple trials (NCT02017717 – Checkmate 143, NCT040145115, NCT03233152, NCT04003649, NCT03422094, NCT02311920 and NCT3707457). However, subsequent work has demonstrated that glioblastoma exhibits cancer lineage specific resistance to the reversal of T cell exhaustion, which may reduce the impact of this particular combination (24). Retrospective genomic and transcriptomic analysis of patients who received PD-1 inhibitors found that the degree of response to treatment was associated with specific evolutionary pathways resulting in certain molecular and immune expression profiles. This would indicate that only certain subsets of patient may benefit from this form of checkpoint blockade (25). The timing of checkpoint blockade therapies relative to standard of care treatment also may play a key role in efficacy. Cloughesy *et al* report upregulated T cell and interferon-γ (IFNγ) gene expression and downregulated cell-cycle gene expression within the tumor when anti-PD1 therapy was used in the neoadjuvant setting. This effect was however not observed for those patients that received adjuvant therapy alone, suggesting a transient window of opportunity for checkpoint blockade (26). Schalper *et al* also found positive immune

effects associated with neoadjuvant PD-1 blockade, reporting enhanced levels of immune cell infiltration and greater TCR diversity amongst tumor infiltrating lymphocytes, suggesting that this may be a useful partner with other immunotherapies (27).

Other checkpoint inhibitory molecules highly expressed by tumor infiltrating lymphocytes (TILs) in glioblastoma include indoleamine 2,3-doxygenase (IDO1), T cell immunoglobulin-mucin-domain containing-3 (TIM-3) and lymphocyte activation gene 3 (LAG3) (28). Phase I clinical trials exploring combination approaches against both PD-1, LAG-3 (NCT02658981) and IDO1 (NCT03707457) are now underway. Despite this, experience of combinatorial PD-1 and IDO1 blockade in the CNS (albeit in metastatic melanoma) have failed to improve outcomes in phase III studies (29). Other combination approaches using IDO1 inhibitors with temozolomide (NCT02052648) remain under evaluation in glioblastoma. While these findings may suggest that combinatorial ICB may still struggle in the CNS, lack of success may actually reflect incomplete checkpoint blockade. Opitz et al have described metabolic pathways in glioma such as activation of the aryl hydrocarbon receptor (AHR) by tryptophan catabolites which results in enhanced malignancy and immunosuppression (30). While the AHR pathway was initially associated with IDO1 or the tryptophan-2,3-dixoygenase 2 (TDO2) enzyme, recent work has demonstrated that interleukin-4-induced-1 (IL4I1) is more significantly associated with AHR activity. ICB can induce IDO1 and IL4I1, while IDO1 inhibitors previously trialed in combination with ICB do not result in IL4I1 blockade (31). Future combinatorial pairings of ICBs should consider the potential for anti-PD1 agents to induce metabolic agents which upregulate metabolic pathways of immunosuppression.

2.2 Immune checkpoint blockade and T cell directed immunotherapy

Intratumoral heterogeneity in glioblastoma poses a significant barrier to antigen-specific immunotherapies such as CAR-T cells or bispecific T cell engagers. CAR-T cells specific for epidermal growth factor receptor variant III (EGFRvIII) have proven ineffective when treating recurrent tumors due to antigen escape (9). The intended selective targeting of cells or spontaneous elimination of target cells at recurrence produces an outgrowth of antigen negative cells resulting in recurrence (9,32,33). A high degree of clonality and, contrary to other cancer, a high mutational burden in glioblastoma has also been associated with resistance to ICB (34,35). Of note for clinical trials, high tumor mutational burden can be induced by temozolomide (TMZ) which causes defects in DNA mismatch repair genes. One potential approach to overcoming this is by targeting IDH1-R132H - a shared clonal neo-epitope in IDH mutated gliomas. This uniformly expressed TSA in a subset of glioma patients has been successfully targeted in recent Phase I trials (NCT02454634), and was found to be both safe and immunogenic (36).

While prior phase Ib trials (NCT02287428) of neoantigen vaccination in glioblastoma have reported neoepitope-specific systemic immune responses with increased numbers of TILs, these have also been shown to express a profoundly exhausted phenotype (37). Combining ICB with a vaccine strategy targeting a shared clonal neoepitope may therefore work synergistically to overcome ICB resistance while enhancing the neo-epitope immune response. This is supported by pre-clinical evaluation of multivalent neoantigen vaccines with ICB which generated greater anti-tumor responses than monotherapy, even in models with

reduced anti PD-L1 sensitivity (38,39). Such an approach would therefore be logical to evaluate for other multi-epitope vaccine-based approaches such as that used in the GAPVAC trial (NCT02149225)(40). As mentioned previously, neoadjuvant anti-PD1 blockade has been associated with enhanced clonal expansion of T cells and greater immune infiltration/TCR diversity (26,27). This would also likely benefit immunotherapy approaches that rely heavily on T cell expansion such as vaccination or CAR-T cell therapy. Further, CAR-Ts targeting EGFRvIII have been shown to upregulate expression of programmed cell death ligand 1 (PD-L1) within gliomas, contributing to CAR-T cell dysfunction and treatment failure (9). The addition of anti-PD1 blockade to such approaches may therefore increase both the diversity and potency of the immune response to CAR-T therapy while reducing T cell exhaustion. This is supported by work by Choi *et al* who designed a CRISPR-Cas9 modified EGFRvIII CAR-T cell with the endogenous PD-1 receptor knocked out, thereby preventing PD-L1 binding. This CAR-T-EGFRvIII PD-1^{-} construct resulted in prolonged survival in mice bearing EGFRvIII^{+} glioma compared to CAR-T-EGFRvIII cells with an intact PD-1 receptor (41). In this vein, trials are underway evaluating CAR-T cell therapy (NCT04003649) and vaccination (NCT04201873, NCT02529072, NCT02287428) alongside ICB. Newer trial designs are also being deployed such as the AMPLIFY-NEOVAC surgical window-of-opportunity trial (NCT03893903). This will evaluate IDH1R132H vaccination with avelumab (anti-PD-L1) to explore predictive biomarkers for response to ICB in patients with IDH mutated gliomas.

It is notable that studies such as that performed by Choi *et al* report prolonged survival with direct intracerebral or intraventricular delivery of CAR-T therapy but that this therapeutic effect is lost with peripheral administration. This finding serves to demonstrate that transiting the blood brain barrier (BBB) remains a formidable obstacle for many systemically delivered immunotherapies (42). Even in the pathological glioma state, regions of the BBB likely remain intact, shielding sections of tumor from immunotherapy which may then act as the focal point for recurrence (43). While systemic anti-PD1 therapy has been noted to induce changes in the CNS, it is unclear where this interaction with the immune system occurs and indeed what concentration is necessary to induce an effect at the intracranial tumor site (44). Although one solution may be direct intracranial delivery of agents, this highly invasive approach will not be suitable for all patients and faces significant challenges in achieving equal and persistent drug distribution throughout the tumor (33,45,46). Another potential approach may be the use of *ex vivo* activated autologous T cells combined with T cell engaging therapies. These activated T cells would theoretically adhere to the brain microvascular endothelium and traffic into the brain, carrying their immunotherapy payload on their surface (18,47). However, this effect has also been associated with neurotoxicity and must therefore be investigated with caution (48). Accordingly, such an approach is entering Phase I safety trials where a hEGFRvIII-CD3 Brain Bi-Specific T Cell Engager (BRiTE) will be evaluated alongside peripheral autologous T cell infusion (NCT04903795).

2.3 Other strategies to enhance the T cell repertoire and overcome immunosuppression

Combination of immunotherapy with radiotherapy has been demonstrated in melanoma to expand the compartment of effector memory T cells and TILs, while also inducing a more diverse T cell receptor population when combined with ICB (49). Similar promise has been demonstrated pre-clinically in

glioblastoma where TIM-3 and PD-1 antibodies combined with radiotherapy achieved long-term survival (50). Other strategies to expand TCR diversity may involve the use of dendritic cell vaccines which carry antigen from the tumor to draining lymph nodes, presenting them to effector T cells. Chemokines such as the macrophage inflammatory protein-1 alpha (MIP-1α, CCL3) may aid in enhancing lymph node chemotaxis of dendritic cell subsets both to tumor and from tumor to lymph node, resulting in greater diversity of antigen presentation and more potent antigen-specific T cell responses (51). Dendritic cells may also enhance the polyfunctionality of adoptively transferred T cells targeting tumor specific antigens in glioblastoma (52).

Enhancing T cell functionality may be supported by the use of costimulatory agonists such as CD27, 4-1BB, OX40 or CD40, which are now entering early clinical trials (e.g., NCT04547777, NCT02658981, NCT03688178) (53-56). Newer constructs that combine both anti-inhibitory and pro-stimulatory strategies are under development such as bispecific antibodies targeting both CD27 and PD-L1 (NCT04440943) or TGFβ and PD-L1 (57). Novel CAR-T constructs including synNotch and armored CARs with expression of cytokines such as IL-12 have also been demonstrated to enhance anti-tumor efficacy in the context of oncogenic immunosuppression (58,59). When considering immunosuppression, thought should also be given to the role of dexamethasone, which may induce systemic depletion of memory and naïve CD4/CD8 T cells, reducing the efficacy of immunotherapy (60). In this context, agents that have failed to show efficacy when combined with checkpoint blockade such as bevacizumab (anti-VEGF) may also be worth re-evaluating as an adjunct, specifically for its ability to reduce the need for immunosuppressive corticosteroids (61,62).

A summary of potential combinatorial approaches is depicted in Figure 1. However, as described above, enhanced additive synergism between immunotherapies may well extend beyond a bimodal approach. It is reasonable to consider trial designs which involve 3 or more elements. This will require flexible trial designs to swiftly identify the optimal combinatorial schedule which are discussed in the following section.

3 RECOMMENDATIONS FOR COMBINATORIAL CLINICAL TRIAL DESIGN

3.1 Population Selection

When considering any new combinatorial therapy, a proof-of-principle study is necessary to determine efficacy. Outcome measures in this context usually consist of specific biologic endpoints. However, these studies are typically performed on small numbers of patients with late-stage disease who have received highly variable treatment courses. This can make interpretation of said biologic endpoints difficult. Selecting patients earlier in the disease course with a less heterogeneous and slower growing pathology may make interpretation of biological markers easier, while also allowing combination immunotherapies sufficient time to synergize and induce maximal biological effect. Particular consideration should also be given to patients with an unmethylated O6-methylguanine-DNA methyltransferase (MGMT) promoter gene, who are less likely to respond to TMZ. In such cases, omission of TMZ entirely would be clinically justifiable and would

allow evaluation of new therapies without additional toxicities from TMZ or inducing hypermutation as described previously (63,64).

3.2 Regimen selection

The optimal dosing schedule may be extremely broad when designing trials for two or more agents and is further complicated by the fact that true synergy may exist at non-maximal doses. Although it is generally not acceptable to reduce doses of standard of care agents in combination, an appreciation for the unique pharmacodynamic interplay between combined immunotherapy agents is required. Although this might suggest a need for extensive pre-clinical testing, newer designs such as Phase 0, translational, surgical 'window-of-opportunity' or neoadjuvant trials may offer a route to bypass potentially laborious steps (65,66).

Phase 0 trials use a micro-dosing strategy to allow for assessment of potential pharmacodynamic (PD) and pharmacokinetic (PK) properties while minimizing risk. This allows for rapid determination of the biological activity of a potential combination and allows for early termination if said combination does not meet its predefined PD/PK endpoints. Window-of-opportunity studies take an alternative route, using a pre-defined therapeutic dose and typically aim to define target engagement and/or immune modulatory endpoints. Both trial approaches aim to determine biological and immunomodulatory impact, rather than clinical effect, although window-of-opportunity trials also allow for correlation with eventual patient outcomes. While these are both useful approaches for evaluating new combinations, perhaps the most sensitive way to determine synergism between two agents is by using neoadjuvant studies in which treatment is administered pre-operatively and tumor samples are taken for analysis at time of resection.

Neoadjuvant studies have already been used successfully to determine the effect of immune checkpoint inhibition on the intratumoral T cell compartment (26). The neoadjuvant approach may also be superior to post-surgical biopsies of tissue, which are prone to sampling error and often have limited tissue availability, resulting in a non-representative immune analysis. A large volume of tissue will allow for not just a determination of raw numbers of TILs but functional activity. Such analyses would be superior to peripheral immune interrogation which may not be equivalent to events occurring at the tumor site.

3.3 Moving beyond Phase I

If a combination proves safe and tolerable while also demonstrating evidence of immune response, trials should proceed to phase II trials to assess clinical benefit. However, traditional single-arm phase II trials often use response rates (RR) based on historical controls as the main endpoint, which may be inappropriate for combined immunotherapy. An efficient approach would be to use seamless phase I/II, II/III clinical trials, whereby the protocol specifies when to transition the study from a certain phase (e.g., phase II to III) without the need for a new protocol or regulatory process (67,68). Similarly, large phase Ib trials and 'expansion baskets' of the combination in phase I trials allow for increasing the number of patients enrolled once the recommended phase II dose has been determined. This allows for the phase I study to aid establishing preliminary efficacy in addition to determining the safety of the combination. Basket and platform trial designs using master protocols allow for within-basket immune monitoring depending on the

approaches being evaluated (e.g., markers of T cell activation if blocking regulatory T cell receptors) (69). The use of adaptive designs in this setting allows for adjustment according to evolving data so that poorly performing combinations can be abandoned early, while additional treatment cohorts which test other combinations to be added.

Many basket trials to date (Lung-MAP, NCT02154490; NCI-MATCH, NCT02465060; and My Pathway, NCT02091141) use response rate (RR) to evaluate targeted therapies, as is typical for traditional single-arm early phase trials. However, this may not be an appropriate endpoint for the evaluation of immunotherapies which can yield clinical benefit without a high RR. Indeed, immunotherapies have been noted to induce imaging changes interpreted as indicative of progression (70). To address this, adaptive designs have been initiated including the INSIGhT adaptive platform trial (NCT02977780), the glioblastoma AGILE phase II/III adaptive platform trial (NCT03970447) (64,71) in the US and the NCT neuro master match umbrella phase I/IIa trial (NCT03158389) in Germany. Overall survival (OS) can be used in these trials as the primary endpoint rather than RR (72,73). These designs are mostly used to evaluate targeted therapies to circumvent lengthy pauses between trial phases, but their usage still lags behind for immunotherapy based approaches (74).

4 RECOMMENDATIONS FOR ENSURING SAFETY AND DETERMINING OUTCOMES

In the context of combinatorial immunotherapy, toxicity considerations are complicated by the need to determine the appropriate regimen for commencing two or more agents at once. Multiple agents may act synergistically in both efficacy and toxicity, which could result in potentially fatal complications such as cytokine release syndrome (CRS) (75). Model-assisted designs are a useful tool to assess the pre-study probability of toxicity and can inform dose-escalation decisions using real-time adverse event data (76,77). These can maximize the number of patients treated at or near the maximum tolerated dose (MTD) and outperform traditional designs such as 3 + 3 dose-escalation which have yielded inconsistent dose-toxicity or dose-escalation correlations (78,79). However, while the flexibility and accuracy of model-assisted designs may be of particular use when evaluating immunotherapy combinations, these require sustained biostatistical collaboration, which can be time and resource intensive. A detailed evaluation of the dose escalation strategy and how best to determine response is therefore vital before commencing clinical trials.

4.1 Determining the starting dose

Many combinatorial trials use agents with a known safety profile and where the biologically active dose is known. For that reason, such trials could begin at the optimal dose rather than using conservative escalations. When neither component is known to be effective or approved for the indicated use, and when neither will be effective alone, a two-arm design comparing combination to a control agent (or placebo) can be considered (shown in Figure 2). However, while this minimizes exposure of patients to inactive therapies, this design may not demonstrate the inactivity of specific components. When the safety profile or optimal dose is unknown for either component in a combination, the optimal immune response may be an appropriate endpoint for early phase trials, providing there are no significant toxicities. However,

establishing response with multiple agents and titrating each element to maximize efficacy may not be practical.

4.2 Measuring effect

Patients in phase I trials are likely to have relapsed or progressed on previous therapies but preliminary signals of activity can still be noted using RR, (PFS), recurrence-free or OS. However, in an advanced disease population, immunotherapies may not induce a strong immune effect that manifests as a reduction in disease burden. Patients may also not survive long enough to have time to generate the immune response that would provide a clinical benefit. A further complication is that OS can be extended by immunotherapy without radiological response or pseudo-progression (80). The modified response assessment in neuro-oncology (mRANO) and immune specific RANO (iRANO) aim to standardize determination of response, but their utility in trials using experimental combinations is yet to be validated (70). To determine response more accurately and avoid premature treatment discontinuation, the definition of progression will need to require confirmation on two separate observations or to not consider early progression within a prospectively defined time-interval as per modified RANO (81). In patients who do respond after early progression, PFS should be based on the start of therapy.

Determining potency, predicting clinical effects and understanding the impact of the manufacturing process on the final drug product and stability are all required for regulatory approval. However, demonstrating these effects in combination therapies poses practical and ethical problems. Evaluation of purity and potency can be difficult if a treatment is composed of a combination of heterogeneous components (e.g., autologous blood or tumor-derived cellular therapies) (82). One approach to overcome this is to use quantitative assessments such as the time to kill 50% of target tumor cells (KT_{50}) (83). Other approaches may involve correlating outcomes with serial immune assays to quantitatively measure the relative immunogenicity of a combination. Statistical modeling using toxicity and anti-tumor toxicity have also been considered (84,85). However, many of the techniques used including cytokine release, tetramer, cytotoxicity and the enzyme-linked immune absorbent spot (ELISpot) assays are often only technically validated in the research laboratory, and the frequency with which they are performed vary widely, leading to variable results (86).

To generate valid and transferable data based on immune assays, harmonization and standardization of techniques is required to establish the expected immune response from known effective immunotherapies, against which new combinations can be evaluated. Current FDA-approved biomarkers of tumor mutational burden (TMB) that are used to predict response to the checkpoint inhibition pembrolizumab in solid tumors, do not have the same predictive value in gliomas (35) and therefore a pathology specific assay is required.

5 CONCLUSION

Although immunotherapy holds significant promise for overcoming the challenges of immune dysfunction and tumoral heterogeneity, it is increasingly apparent that a single agent alone will not suffice. Exploration of combinations of ICB with neo-epitope vaccination strategies in IDH mutant gliomas is one promising approach, but IDH is expressed in a minority of glioblastomas. Further, the cancer-lineage specific ability of

glioblastoma to drive T cell anergy and apoptosis poses a significant obstacle for ICB therapies. Given this, more work is required on alternative strategies such as combinatorial T cell co-stimulation or blockade of tumoral metabolic pathways. Evaluating potential combinations in patients who may not benefit from TMZ and are therefore less prone to hypermutation will be helpful to accurately determine biological activity. The timing of administration relative to routine clinical interventions such as steroid administration, radiation therapy and the aforementioned alkylating chemotherapy, all of which possess varying immuno-modulatory effects, must also be weighed. Neoadjuvant and surgical window of opportunity studies (where tumor tissue can be collected after combinatorial immunotherapy) may offer the most sensitive pharmacodynamic and pharmacokinetic analysis, but other surrogate markers of effect such as KT_{50} are also useful. Model assisted trial designs may help assess dosage and schedules for different combinations, but it is important to consider that maximal synergistic effect may not occur at the maximal therapeutic dose. While combinatorial approaches may unlock the true potential for immunotherapy in glioblastoma, the lack of success in glioblastoma immunotherapy trials demands a tailor-made combinatorial approach. International collaboration will be necessary to develop trials which have the scope and recruitment necessary to integrate such biologic complexities into their design (see summary box).

6 SUMMARY BOX AND KEY MESSAGES

To date, immune based monotherapies have failed to improve survival of patients with glioblastoma.
Glioblastoma exerts cancer lineage specific mechanisms of immune escape and can induce profound local and systemic immunosuppression
Given the lack of efficacy seen when using combinations with anti PD1/ anti CTLA4 to date, cancer lineage specific checkpoint inhibition (e.g., IDO1, LAG3, TIM3) and costimulatory agonistic targets (e.g., CD40, CD27) are worth exploring.
Timing of combinatorial immunotherapy relative to standard of care treatment must be carefully weighed.
TMZ may induce hypermutation and drive heterogeneity, and drive resistance to immunotherapies and their combinations
Bevacizumab may help to reduce edema and therefore reduce the need for immunosuppressive corticosteroids, and can be used as an adjunct to combination immunotherapy
Harmonization, standardization of immune technologies and generation of reference values will help accelerate preclinical and early clinical development in glioblastoma
Flexible trials such as model assisted and adaptive designs are required to rapidly assess potential novel combinations.
Surgical window of opportunity, neoadjuvant and trials with primary biologic (PD, PK) endpoints are recommended as they may help shorten lengthy pre-clinical and often futile clinical investigation.

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FIGURE LEGENDS

6.1 Figure 1: Combination approaches using checkpoint inhibition and other therapies for glioblastoma.

1. TCR Diversity and Clonal Expansion. Combination radiation therapy and inhibitors of TIL exhaustion and drivers of apoptosis (PD-1, LAG-3, TIM-3) are being studied for synergistic effects on TIL expansion and clonal diversity. 2. VEGF Inhibitors. Anti-VEGF therapies such as bevacizumab are being utilized as steroid-sparing agents to harness immunotherapy-related toxicity in the CNS. 3. Tumor-Associated Macrophage Polarization. Glioma cells interact with and maintain a robust population of PD-1 expressing microglia with an anti-inflammatory phenotype (M2). Selective anti-PD-1 blockade on microglia populations is capable of inducing a tumoricidal M1 phenotype (87-89) 4. Neoadjuvant Checkpoint Inhibition. Treatment-naïve, IDH wild-type glioblastoma upregulates PD-L1 and CTLA-4 offering enhanced sensitivity to immune checkpoint combination approaches. Neoadjuvant checkpoint blockade increases clonal expansion of T cells. Chemotherapy with temozolomide can alter tumor mutational burden resulting in both increased resistance to checkpoint blockade and increased sub-clone heterogeneity thus limiting the potency of antigen-specific immunotherapies such as CAR-T cells. 5. Dendritic Cell Costimulation. Costimulatory agonists for 4-1BB, OX40, and CD40 and IDO inhibitors are being evaluated with checkpoint inhibitors to polarize cytotoxic T cell responses in the tumor microenvironment and within immunosuppressed tumor-draining lymph nodes. 6. Combination Immunotherapies. Multivalent neoantigen vaccines and CAR-T cell therapies in combination with checkpoint inhibitors are being evaluated for superior efficacy compared to single modalities even with reduced PD-L1 sensitivity. Abbreviations: CAR, chimeric antigen receptor; CTLA-4, cytotoxic T-lymphocyte-associated protein 4; DC, dendritic cell; IDH, isocitrate dehydrogenase; IDO, indoleamine 2, 3-dioxygenase; LAG-3, lymphocyte activation gene 3 (LAG3); M1 and M2, macrophage pro-inflammatory and anti-inflammatory phenotype; PD-1, programmed cell death protein 1; PD-L1, programmed death-ligand 1; TCR, T cell receptor; TIM-3, T cell immunoglobulin-mucin-domain containing-3; TMZ, temozolomide; VEGF, vascular endothelial growth factor; VEGFR, vascular endothelial growth factor. Adapted from an image created with BioRender.com.

9.2 Figure 2: Rationalizing Trial Designs for Combinatorial Immunotherapy

Regulatory approval of combinations of therapeutic agents in medicine usually requires a demonstration of each component's independent contribution. The ability to evaluate pharmacodynamic effects of single agents and/or combinations may help determine whether randomized studies require arms including both single agents and combinations. When neither component is known to be effective or approved for its indicated use, or when neither have efficacy as a single agent by itself, a two-arm design comparing the combination to a control agent (placebo) can be considered. Assessment of immune response must not only quantify the degree of immune activation but also the functional status of the response generated. Adapted from an image created with BioRender.com.

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Figure 1:

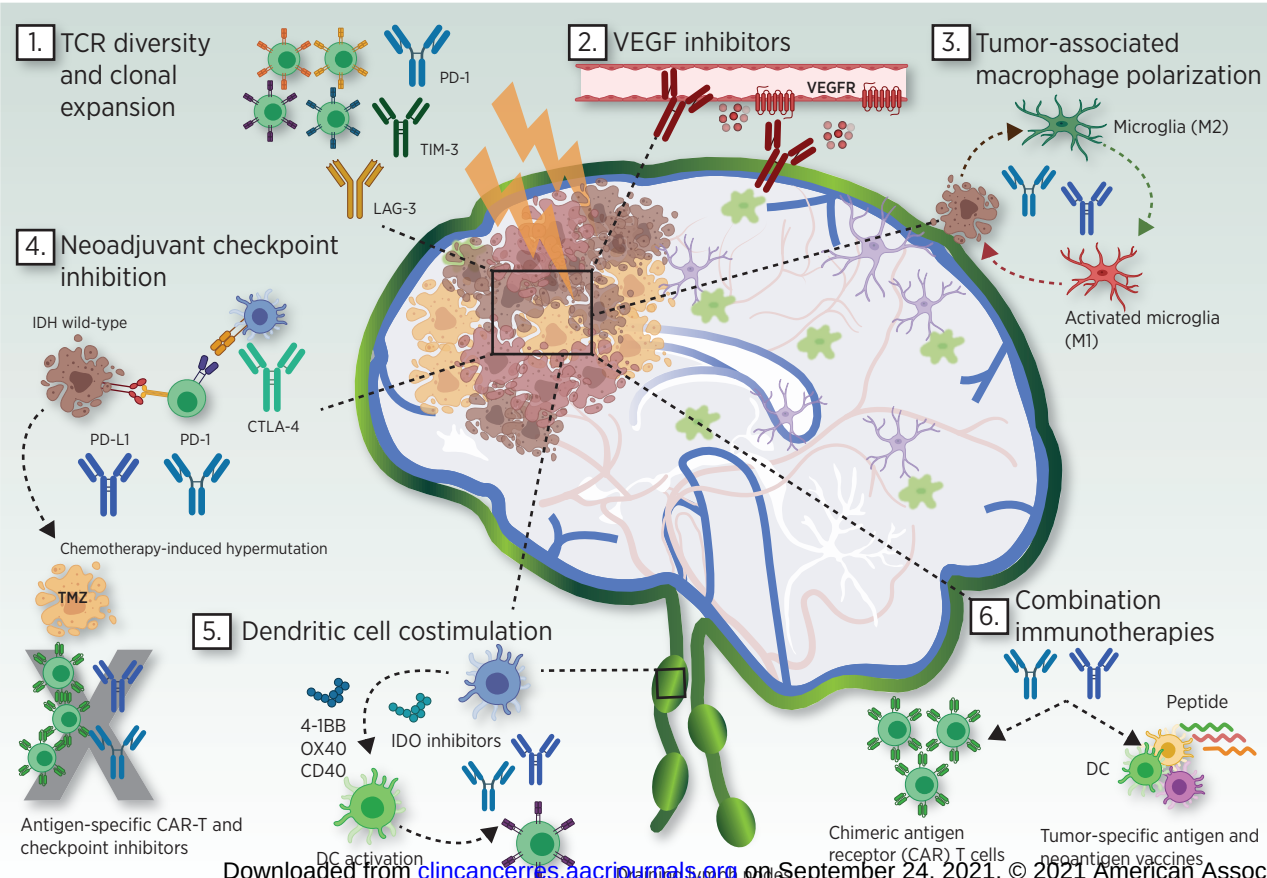
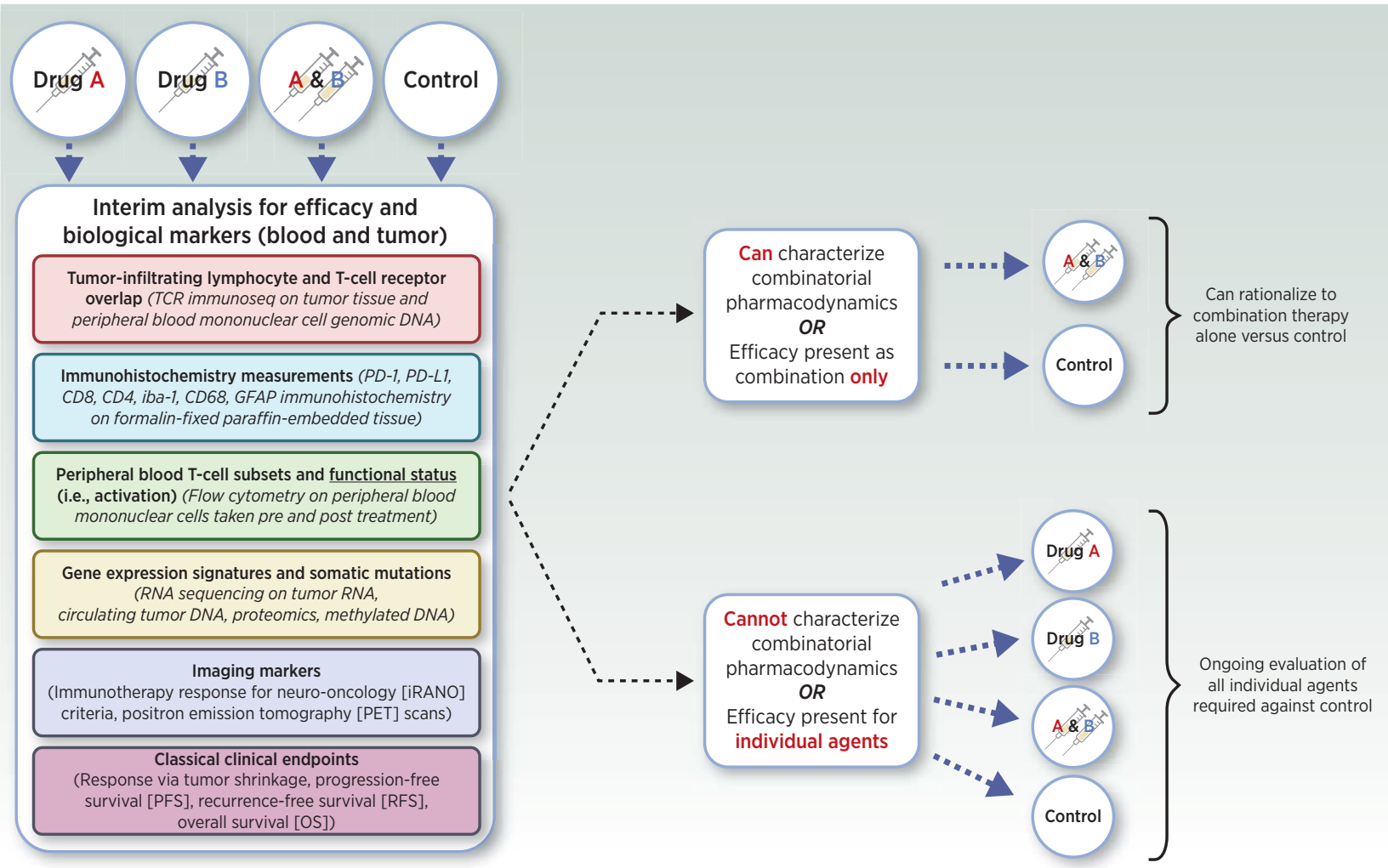


Figure 2:



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