Quantification of neoantigen-mediated immunoediting in cancer evolution

Tao Wu[1-3], Guangshuai Wang[1], Xuan Wang[1], Shixiang Wang[1], Xiangyu Zhao[1], Chenxu Wu[1], Wei Ning[1], Ziyu Tao[1], Fuxiang Chen[4] and Xue-Song Liu[1]

Affiliations of authors:

1 School of Life Science and Technology, ShanghaiTech University, Shanghai 201203, China;

2 Shanghai Institute of Biochemistry and Cell Biology, Chinese Academy of Sciences, Shanghai, China;

3 University of Chinese Academy of Sciences, Beijing, China;

4 Department of Clinical Immunology, Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, 200011, People's Republic of China.

Correspondence: Xue-Song Liu, School of Life Science and Technology, ShanghaiTech University, 230 Haike Road, Shanghai 201210, China. E-mail: liuxs@shanghaitech.edu.cn.

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Abstract

Immunoediting, which includes three temporally distinct stages, termed elimination, equilibrium, and escape, has been proposed to explain the interactions between cancer cells and the immune system during the evolution of cancer. However the status of immunoediting in cancer remain unclear, and the existence of neoantigen depletion signal in untreated cancer has been debated. Here we developed a distribution pattern based method for quantifying neoantigen mediated negative selection in cancer evolution. Our method provides a robust and reliable quantification for immunoediting signal in individual cancer patient. The prevalence of immunoediting signal in immunotherapy untreated cancer genome has been demonstrated with this method. Importantly, the elimination and escape stages of immunoediting can be quantified separately, tumor types with strong immunoediting-elimination tend to have weak immunoediting-escape signal, and vice versa. Quantified immunoediting-elimination signal predicts cancer immunotherapy clinical response. Immunoediting quantification provides an evolutional perspective for evaluating the immunogenicity of neoantigen, and reveals potential biomarker for cancer precision immunotherapy.

Significance

Neoantigen mediated negative selection has been demonstrated here, and the quantified signal reveals distinct features of cancer immunoediting and also potential biomarker for cancer immunotherapy response prediction.

Introduction

During cancer evolution, some genome DNA alterations can be positively selected, such as driver mutations. Some genome alterations could posit a deleterious effect, and consequently are negatively selected or depleted during cancer evolution. Some (or the majority of) genome DNA alterations do not have driving or deleterious effects on cancer, and follow neutral evolution pattern. The interactions between immune cells and tumor cells are reflected as immunoediting, which could mediate the negative selection of DNA alterations encoding high immunogenicity (also known as neoantigenic mutations) (1,2). Positively selected genome alterations can be readily detected in the final mutation reservoir, however, the quantification of negative selection in cancer evolution is still a significant challenge (3). The status of neoantigen mediated negative selection in cancer evolution has been evaluated in several studies, and controversial results have been reported (4-7).

Convincing cases of adaptive molecular evolution have been identified through comparison of synonymous (silent; dS) and nonsynonymous (amino acid-changing; dN) substitution rates in protein-coding DNA sequences. dN/dS is the ratio between the rate of non-synonymous substitutions per non-synonymous site and the rate of synonymous substitutions per synonymous site. dN/dS method was originally developed to quantified the molecular evolution from sequencing data (8,9). Recently, dN/dS method has been applied in cancer evolution study (3). An important consideration in dN/dS analysis is the selection of negative control regions. For example, a recent study reported that neoantigen depletion signal is undetectable in pan-cancer dataset (5), however the selection of negative control region is questionable (10). In addition, the percentage of depleted neoantigen could be tiny, and this prohibit the accurate detection of negative selection signal through dN/dS, especially in individual cancer patient. Population genetics based method has been used to identify the neutral pattern of cancer evolution, this method is based on the assumption

that the variant allele frequency (VAF) within a tumor follow a characteristic power-law distribution in case of neutral evolution (11,12). The detection of neutral evolution with this method has been questioned (13,14), and its application in immune mediated negative selection has not been fully established. In together, till now, the existence and the degree of neoantigen mediated negative selection in human cancer remain unclear.

To address these challenges, we build a new distribution pattern based method for quantifying neoantigen mediated negative selection in individual cancer patient. With this new analysis framework, we demonstrate the pan-cancer existence of neoantigen mediated negative selection signal. Importantly the elimination and escape phases of immunoediting can be quantified separately. In total, this study not only provides a novel method for quantifying negative selection in cancer evolution, but also reveals potential biomarker for cancer immunotherapy clinical response prediction.

Materials and Methods

Pan-cancer clinical and molecular data

The normalized gene-level RNA-seq data (TPM, transcripts per million) for 31 TCGA cohorts were downloaded from Xena (https://xenabrowser.net/). Pre-compiled curated somatic mutations for TCGA cohorts were downloaded from Xena, and missense variants are selected for downstream analysis. ABSOLUTE-annotated MAF file which contains cancer cell fraction (CCF) information of mutations was downloaded from GDC PanCanAtlas publications, and then we used liftover function from R package “rtracklayer” to convert the hg37 genome coordinates to hg38. Clinical data was obtained from GDC PanCanAtlas publications (https://gdc.cancer.gov/about-data/publications/pancanatlas). HLA typing data was downloaded from

Thorsson et.al study (15). The downloaded mutation data, HLA typing data and CCF values for TCGA samples have also been validated with in house algorithm. Immune cell infiltration data for all TCGA tumors was downloaded from ImmuneCellAI study (16), which estimates the abundance of 24 immune cells comprised of 18 T-cell subtypes and 6 other immune cells. For TCGA tumors which do not have HLA typing data in the mutation data set (2404 samples), we downloaded raw bam files, and performed HLA typing as described below. Driver mutation data was downloaded from Bailey et al study (17). This study used three different categories of tools to identify driver mutations: (1) tools distinguishing benign versus pathogenic mutations using sequence (CTAT population); (2) tools distinguishing driver versus passenger mutations using sequence (CTAT cancer); and (3) tools discovering statistically significant three-dimensional clusters of missense mutations (structure based). We keep mutations identified by $\geqslant$2 approaches as the final high confident driver mutations, including 2165 unique mutations.

Somatic mutation calling

Sequences were aligned to the reference human genome (hg38) using Burrows–Wheeler Alignment (BWA) tool (18). Preprocessing followed the GATK4 best practices workflow, including duplicate removal, base quality score recalibration. Somatic mutations were identified on processed data using Mutect2 (19). BCFtools was used to filter genome variants that passed all quality control filters (20). The resulting VCF files were annotated by VEP and further converted to MAF file by vcf2maf.pl (https://github.com/mskcc/vcf2maf). The MAF file was loaded into R, analyzed and visualized by Maftools (21).

Gene expression analysis

Paired-end RNA-seq data were processed using hisat2 (22) aligner on the basis of the hg38 human genome assembly with default parameters. Then the aligned SAM files were transformed to BAM files using samtools (23).

Normalized RNA expression values (TPM) were calculated by TPMCalculator (24).

Cancer cell fraction (CCF) calculation

We followed the GATK4 copy number analysis pipeline to get copy number segment files. CCF information for each mutation was calculated based on segment files and somatic mutation MAF files using ABSOLUTE software (25). Briefly, read counts for each of the exome targets were collected from all samples and calculated the coverage by count reads that overlap intervals which were formed by padding the target regions. Each of the tumor samples was compared to a panel of normal (PoN) controls for normalization and denoising. The tool standardizes counts by the PoN median counts. The normalization process includes log2 transformation and normalizing the counts data to center around one. Then, the tool denoised the standardized copy ratios using the principal components of the PoN. These normalized coverage profiles were then segmented using Gaussian-kernel binary-segmentation algorithm, which were fed into ABSOLUTE algorithm to determine CCF.

HLA typing and neoantigen prediction

HLA genotyping was performed with Optitype (26), using default parameters. Mutect2 mutation files were first transformed into VCF format by maf2vcf tools, and we used NeoPredPipe to predict neoantigen (27). Single-nucleotide variants leading to a single amino acid change are the focus of this study. From the output results, if the IC50 of a novel peptide is less than 50, the bind level is SB (strong binder, rank is less than 0.5%), and the expression level (TPM) is greater than 1, then this peptide is labeled as neoantigen. A mutation is considered neoantigenic if there is at least one peptide derived from the mutated site is predicted as neoantigen.

Enrichment Score calculation

The Kolmogorov–Smirnov (K-S) statistic can be used to quantify the distance between two cumulative distributions. We constructed a K-S like statistic to quantify the difference between the distribution of the CCF (or mRNA expression) of immunogenic mutations and non-immunogenic mutations in each individual sample.

ES$_{CCF}$ quantification in individual cancer patient

We equally divided the whole CCF range (0-1) into 100 intervals (in descending order) and assigned each interval a rank value (from 100 to 1). To make the heavier weights on two tails of the rank distribution, we further normalized the ranks:

$$R_i = |\frac{L}{2} - r| + 1$$

Where *Ri* is the normalized rank value, L is the total number of intervals (here L=100), and r is the original rank value.

Then we counted the number of mutations lied in each interval (m (i)) and assigned a value a(i) to each interval depending on mutation counts (m (i)) and interval rank (R (i)):

$$a_i = \frac{m_i \times R_i}{\sum m_i \times R_i}$$

We can calculate the empirical cumulative distribution of random variable a (i) by walking from top to bottom (Fig 2):

$$F(n) = \sum_{i}^{n} a_i, \ n = 1, 2, ...100$$

n is the index of intervals.

We then constructed two distributions for neoantigenic mutations (F_N(n)) and non-neoantigenic mutations (F_M(n)) of individual sample, respectively. Then K-S like statistics can be obtained by taking distance of two distributions:

$$D = F_N(n) - F_M(n)$$

Similar to GSVA (28), the enrichment score (ES) was defined as:

$$ES = |D(n)^+| - |D(n)^-| = max(0, D(n)) - |min(0, D(n))|$$

Where D(n)+ and D(n)- are the largest positive and negative random walk deviations from zero, respectively.

ES_{RNA} quantification in individual cancer patient

For a sample, using z to denote the mRNA expression. To reduce the influence of potential outliers, we first convert z to rank z', and normalize further to r = |P/2 - z'| + 1, make the ranks symmetric around 1 (P is number of mutations in a sample), making the heavier weights on two tails of the rank distribution. Then we got two cumulative distributions, for mutations which are neoantigens:

$$D_{neo}(S, i) = \sum_{r_j \in S, j \leq i} \frac{|r_j|}{\sum_{r_j \in S} |r_j|}$$

For mutations which are not neoantigens:

$$D_{noneo}(S, i) = \sum_{r_j \notin S, j \leq i} \frac{|r_j|}{\sum_{r_j \notin S} |r_j|}$$

Where S is the set of mutations which are neoantigens, the size of the set is P_s, P is the number of mutations in a sample, r is normalized rank of mutations. Then we constructed a K-S like statistics:

$$T = D_{neo}(S, i) - D_{noneo}(S, i)$$

We transform the K-S like statistic into neoantigen enrichment score (ES) as difference between the largest positive and negative distribution deviations from zero:

$$ES = max(0, T) - |min(0, T)|$$

Estimation of significance level of ES.

We employed a permutation method to derive a null distribution to calculate p value of the ES (ES_{CCF} or ES_{RNA}). For each sample, the same number of mutations as neoantigens are randomly selected from mutation list and the corresponding ES is calculated. This process is repeated 1000 times to get the ES null distribution. The p value is calculated from the positive or negative region of the empirical null distribution:

$$P = \begin{cases} \frac{1}{1000} \sum_{n=1}^{1000} I(ES_n \geq ES), ES \geq 0 \\ \frac{1}{1000} \sum_{n=1}^{1000} I(ES_n < ES), ES < 0 \end{cases}$$

Where I is an indicator function.

Neutral simulation

For each sample, we permute the neoantigen labeling (ie. randomly select the same number of mutations as the actual neoantigen number in the selected sample and label them as neoantigenic mutations) and calculate ES value. For pan-cancer or cancer type dataset, we can obtain the same number of simulated samples and corresponding ES values, then calculate the median ES of these simulated samples. This process was repeated many times (usually 2000 times) to get the simulated distribution of median ES. The actual pan-cancer or cancer type median ES values are compared with this simulated ES distribution, and p values are then reported.

Cancer immunotherapy datasets analysis

To investigate the predictive performance of the quantified immunoediting-elimination signal in immune checkpoint inhibitor (ICI) therapy clinical response prediction for individual patient, we searched for public ICI datasets with available raw WES data and RNA-seq data. Three melanoma ICI datasets have

been identified for this study. The Hugo et al dataset was related to anti-PD-1 therapy in metastatic melanoma (29). This dataset has 37 samples with WES data, 26 were also analyzed by RNA sequencing (RNA-seq). The Riaz et al dataset was related to anti-PD-1therapy in metastatic melanoma, and it has 56 samples with WES data, 40 with RNA-seq (30). The Liu et al cohort includes melanoma patients treated with anti-PD1 antibody, it has 119 samples with WES data and 112 samples with RNA-seq (31). All three melanoma studies used very similar definition for clinical endpoints. Clinical response for patients was defined by RECIST v1.1, responding tumors were derived from patients who have complete or partial responses (CR/PR) in response to anti-PD-1 therapy; non-responding tumors were derived from patients who had progressive disease or stable disease (PD/SD). We only chose pre-immunotherapy treatment sample for analysis. Mutation calling, neoantigen prediction, expression quantified, CCF calculation and ES calculation were performed as described above.

Stochastic branching process model for cancer evolution and power analysis

Tumor evolution model constructed by Lakatos et al has been applied in this study (32). In this model, tumor evolution was initiated by a single transformed cell. At any simulation step, a cell is randomly selected and has three events could happen: birth (divide to produce two offspring), death and waiting. For a birth event, new cells could acquire some new mutations (counts is sampled from Poisson distribution) and each mutation can become neoantigen as a specific probability. Under negative selection on neoantigen, the death rate of cells could increase from d_0 to d_i with neoantigen accumulation. Selection strength (s) of neoantigen mediated negative selection can be calculated as:

$$1 + s \times n = \frac{b - d_i}{b - d_0}$$

n is the number of neoantigens in a cell, b is birth rate (for simplicity, set b=1) In addition, every mutation has a probability (p_{esc}) to escape. Once a mutation is escaped, death rate of the cell which contains this mutation decrease to basal death rate d_0. This simulation step continues until the population reach pre-defined size. Similar to the original study (32), the following parameters were applied: neoantigen probability p=0.1, birth rate b=0.1, basal death rate d_0=0.1, Poisson distribution parameter (mutation rate) μ=1, escape probability $p_{esc}=10^{-6}$, selection strength $-0.25 \leq s \leq 0$, final population size $popSize=10^5$. At each selection strength, we run simulation 100 times. The model was implemented with Julia (v1.3.1, revised from original Julia code provided by Lakatos et.al).

Mutations harbored in at least 5 cells out of 10^5 were collected at the end of each simulation and the CCF was calculated. To account for imperfect sequencing measurements, CCF values were computed via a simulated sequencing step introducing noise to these frequencies with the indicated read depth. For a given read depth D, each frequency value f was substituted by a new frequency f' sampled from a binomial distribution with parameters D and f: $f' \sim Binom(D,f)/D$. We filtered for mutations with f' above 0 to discard mutations that are not picked up due to limited detection power. In addition to sequencing limitations, we also added different proportions of false positive neoantigen when evaluating the power of detecting negative selection: we randomly sampled nonantigenic mutations of simulated tumors (varied between 5 and 500% of the number of true neoantigen) that were falsely labeled as neoantigen. To calculate the power of derivation from neutral VAF distribution method (32), we used two side K-S test to detect the difference between the VAF distribution of all mutations and neoantigenic mutations and reported K-S statistic and corresponding p value.

Statistical analysis

All statistical tests were performed using R statistical language. In all boxplots, the center lines represent the median, low and upper box limits are the first and third quartiles, respectively, and whiskers represent the values up to 1.5 times of the interquartile range. P values for comparisons between boxplots were calculated by Wilcoxon rank sum test. Correlation and corresponding p values were calculated by Pearson method using R function cor.test. Kaplan-Meier survival analysis was performed using the R package “survival” with log-rank test, and Cox-proportional hazard analysis was performed using the R package “ezcox”. The cutoff value of ES_{CCF} in Kaplan-Meier overall survival analysis was determined by surv_cutpoint function of “survminer” package. R function ks.test was used to perform two-sided K-S test.

Software and data availability

Custom code for quantifying immunoediting-elimination and immunoediting-escape are available in Supplementary Source Data 1. All code required to reproduce the analysis outlined in this manuscript, and R markdown analysis report are available in Supplementary Source Data 2.

Results

Conceptual framework for the elimination and escape phases of cancer immunoediting

The interactions between cancer cells and immune cells are manifested as immunoediting, which consists of three sequential phases: elimination, equilibrium, and escape (1,2). In the elimination phase, tumor cells with genome alterations encoding high immunogenicity are partially or completely eliminated by immune cells, and this leads to the down-regulation of the cancer cell fraction (CCF) of genome alterations encoding high immunogenicity (Fig. 1A, B). In the

escape phase, tumor cells escape the surveillance of immune system through multiple mechanisms, including the following: 1. Suppress the transcription or expression of genome alterations encoding high antigenicity; 2. Antigen presentation pathway down-regulation; 3. Up-regulate the expression of immune suppressive molecules, including PD-L1, CTLA-4, etc. (Fig. 1a, b).

The elimination phase of immunoediting will lead to the down-regulation of CCF of neoantigenic mutations, and consequently this CCF down-regulation status of neoantigenic mutations can reflect the strength of the elimination phase of immunoediting. The mRNA down-regulation status of neoantigenic mutations is a partial reflection of the strength of immunediting-escape phase. Here we use TCGA pan-cancer dataset to investigate this immunoediting signal. TCGA dataset includes 31 cancer types and 9511 samples with available WGS or WES data and mRNA expression profiling (RNA-seq) data, and neoantigenic genome alterations can be found in 9166 samples (Supplementary Fig. S1) (33). In the following section we build a distribution pattern based method to quantify the selection strength acting on the CCF or mRNA expression of neoantigenic mutation.

Method for quantifying neoantigen mediated negative selection

For each genome mutation, we have CCF and normalized mRNA expression (transcripts per million, TPM) information. The immunogenicity value of genome mutation can be calculated as the possibility of the mutated peptide to be presented by HLA type I, and mutated peptides with predicted HLA I binding affinity (IC50) less than 50nM are labeled as neoantigens. A mutation was considered neoantigenic if there was at least one peptide derived from the mutated sequence is predicted as neoantigen. The consequence of immunoediting-elimination phase will leads to an unbalanced distribution of the CCF of neoantigenic mutations, and this CCF distribution pattern of genome alterations encoding immunogenicity can reflect the selection strength of

immunoediting-elimination phase. This distribution enrichment status of CCF was calculated following a similar principle of gene set variation analysis (GSVA) or gene set enrichment analysis (GSEA), which was originally developed in the estimation of the variation of pathway activity over a sample population in an unsupervised manner (28,34).

The mutations in an individual sample or a cancer type as a whole, are ordered by CCF or mRNA expression (TPM) as a ranked list L. The mutations with immunogenicity are defined as a set S. The goal of this analysis is to determine whether the members of S are randomly distributed throughout L or primarily found at the top or bottom. There are two key steps of this method (Fig. 2A, B):

1. Enrichment score (ES) calculation based on the distribution of neoantigen.
We calculate an ES that reflects the degree to which a set S is overrepresented at the extremes (top or bottom) of the entire ranked list L. The score is calculated by walking down the list L, increasing a running-sum statistic when we encounter a mutation in S and decreasing it when we encounter mutations not in S. The ES is calculated based on the maximum deviations from zero during the random walk, it corresponds to a weighted Kolmogorov–Smirnov (K-S) like statistic (see details in the Methods). The CCF values of mutations are in the range of 0-1, and in TCGA dataset, the CCF values of mutations do not show normal distribution, and many mutations have CCF values equal to 1 (Supplementary Fig. S2). A fixed CCF rank from 1 to 100 has been constructed in the quantification of CCF distribution enrichment status of neoantigenic mutation (ES_{CCF}).

2. Estimation of the significance level of ES.
We estimate the statistical significance (nominal P value) of the ES by using a permutation test procedure, this procedure permute the neoantigen labels and recomputed the ES of each patient, and this generates a null distribution for the

ES. The p value of the observed ES is then calculated according to this null distribution. For ES significance analysis in TCGA pan-cancer or individual cancer type cohort level, the observed median ES value of the test cohort is compared with the distribution of median ES values from 2000 simulations (Fig. 2C).

Tumor cells can evolve multiples strategies to escape the surveillance of immune system, and down-regulating the mRNA expression of neoantigenic mutation is one of these strategies (Fig. 1A, B). Similar to CCF values, the mRNA expression values of mutations are independent variables from immunogenicity IC50 values. Similar strategy can be applied to quantify this mRNA expression down-regulation mediated immunoediting, and the resulting ES_{RNA} is a partial reflection of the strength of immunoediting-escape signal (Fig. 1 and Fig. 2B).

The existence of significant immunoediting signal

Previous studies have debated the existence of neoantigen depletion signals in cancer evolution. Van den Eynden J. *et al.* reported that neoantigen depletion signal is undetectable in TCGA pan-cancer dataset (5). However as pointed out in a preprint, their method for neoantigen depletion signal detection is problematic, as the actual neoantigens with immunogenicity are not located in their defined “HLA-binding regions” (10). We investigate the status of this immunoediting signal with the new method developed in this study using TCGA pan-cancer dataset. The immunogenicity IC50 value is calculated based on the mutated DNA sequence and HLA status, and the CCF information is independently obtained from high-throughput sequencing. Mutation types do not influence the CCF values, and the distribution of immunogenicity are not influenced by mutation types either. The immunogenicity IC50 values are thus independent variables from CCF values, and this is different from the calculation of dN/dS, where the two variables dN, dS are interconnected and

438 are both significantly influenced by mutation types (3,35).

439

440 Since the variables (CCF and HLA binding IC50 status) are independent, we
441 use random simulation to generate a null distribution of ES_{CCF}. For TCGA pan-
442 cancer or individual cancer type cohort, the median ES_{CCF} values are recorded
443 after each simulation. The observed median ES_{CCF} values are compared with
444 the simulated ES_{CCF} values. In TCGA pan-cancer cohort with at least 1
445 neoantigenic and 1 subclonal mutation (CCF<0.6) (n=5900), the observed
446 ES_{CCF} is -0.017 (p=0.051) (Fig. 3A, D). In PAAD and LUAD, the observed ES_{CCF}
447 values are significant lower compared with the random simulations, suggesting
448 the existence of immunoediting-elimination signal (Fig. 3A and Supplementary
449 Fig. S3). Since some neoantigenic mutations can be cancer drivers, which are
450 known to undergo positive selection during the evolution of cancer.
451 Neoantigens that happens to be cancer drivers are not undergoing immune
452 based negative selection (Supplementary Fig. S4), probably because the
453 driving force could override the negative selection, or additional immune escape
454 mechanism could evolve. In TCGA pan-cancer cohort, when samples with
455 neoantigenic and driver mutations lied on same genes are not included, the
456 observed median ES_{CCF} is -0.023 (n=5420, P=0.006) (Fig. 3B, D). Several
457 cancer types including ACC, CHOL, UCEC, LUAD show significant low ES_{CCF}
458 values (Fig. 3B and Supplementary Fig. S5). This data demonstrates the
459 existence of immunoediting-elimination signal in TCGA dataset.

460

461 Similarly random simulations were performed to evaluate the significance of the
462 observed ES_{RNA} values. Compared with ES_{CCF}, the observed ES_{RNA} show much
463 strongly significant difference when compared with the random simulated
464 values. In TCGA pan-cancer dataset with at least 1 neoantigenic mutation and
465 accompanied mRNA expression information (n=7151), the observed ES_{RNA} =-
466 0.046 (p<0.0005) (Fig. 3C, D). In majority of cancer types (including KICH,
467 DLBC, CHOL, SARC, LUAD, PAAD, UCS, STAD, LGG, LUSC, HNSC, OV,

UCEC, BRCA, LIHC, COAD), a significant low ES_{RNA} values are observed (Fig. 3C and Supplementary Fig. S6). This study demonstrates that the immunoediting escape through down-regulating the expression of neoantigenic alteration is prevalent in human cancer (Fig. 3C). Furthermore, the immunoediting-escape signal is more prevalent than the immunoediting-elimination signal (Fig. 3A-C). This is in line with the fact that tumors need to escape the immune surveillance to provide specimen for analysis, and it is not practical to get the specimen of tumors that have already been eliminated by immune system.

Interesting we observed that in cancer types with strong immunoediting-elimination signal, a weak immunoediting-escape signal exist, and vice versa (Fig. 3E, F). In pan-cancer or individual cancer type level, the immunoediting elimination and escape signal exist, however in majority of cancer patients, both of immunoediting-elimination and escape signals are weak or undetectable (Supplementary Fig. S7 and Supplementary Fig. S8). Sufficient sequencing depth is required for the detection of this immunoediting signal, and the required sequencing depth is not reached in many TCGA samples.

Neoantigen enrichment score and immune negative selection strength quantification

Recently, immune based negative selection has been simulated using a stochastic branching process model (32). The neoantigen mediated negative selection strength (s) is an inherent feature of each patient. However method for accurately quantifying this immune based negative selection strength is still lacking. Here we investigate the connections between neoantigen enrichment score (ES_{CCF}) and immune negative selection strength *s* using a stochastic branching cancer evolution model as previously described (32). For each fixed selection strength s, the resulting ES_{CCF} was calculated. ES_{CCF} show near linear correlation with s values (Fig. 4A). This analysis suggests that the quantified

ES_{CCF} can be used to infer the immune selection strength in patient. The median ES_{CCF} in TCGA datasets is -0.023, suggesting a median immune negative selection strength s=-0.08 (Fig. 4A).

Proportional neoantigen burden measures the percentage of neoantigenic mutations in individual sample or cancer types. Proportional neoantigen burden was originally designed to compare the immune negative selection strength between two or more samples (32). The value of control proportional neoantigen burden in the condition of neutral selection cannot be obtained, and the proportional neoantigen burden method could not be applied in the quantification of immune negative selection strength in individual cancer patient, individual cancer type, or all cancer types combined. Derivation from neutral VAF distribution (*1/f* dependence of the cumulative VAF distribution) has been suggested to reflect the selection status (11,32). However neutral VAF distribution method is not suitable in negative selection quantification due to strict requirement in sequencing depth and neoantigen prediction accuracy (Supplementary Fig. S9).

Pan-cancer features and correlations of immunoediting signal

Human cancer evolve over a long time interval, usually in decades. The immunoediting-elimination signal quantified in this study suggest the existence of an already happened neoantigen mediated tumor elimination process. While the quantified immune cell infiltration level represent the current immune response status. We calculated the immunoediting status in TCGA pan-cancer datasets (Fig. 3A). The unbalanced distribution of CCF in neoantigenic vs non-neoantigenic mutations quantified as ES_{CCF} could reflect the status of neoantigen mediated tumor elimination. In tumors with detectable immunoediting-elimination signal ($ES_{CCF}<0$, $p<0.05$), a slightly increased $CD8^+$ T plus natural killer (NK) cell infiltration status compared with the remaining samples were observed, and the difference does not reach statistical

significance (p=0.2) (Fig. 5A, B). This data suggests that historically happened immunoediting-elimination process may not be reflected in the current immune cell infiltration status.

The down-regulation of immunogenic mutation encoded mRNA is a partial reflection of immunoediting-escape phase (Fig. 1). Pan-cancer status of this ES_{RNA} is shown, and different cancer types have different median ES_{RNA} score (Fig. 3B). The immunoediting-escape signal quantified as ES_{RNA} also do not show statistically significant difference between samples with detectable immunoediting-escape signal ($ES_{RNA}<0$, $p<0.05$) and the remaining samples in $CD8^+$ T plus NK cell infiltration (Fig. 5C). However we observe a significant up-regulated regulatory T cell (Treg) percentage in samples with detectable immunoediting-escape signal (Fig. 5D), and up-regulated Treg has been reported to stimulate tumor immune escape (36).

Quantified immunoediting-elimination signal predicts the clinical response of cancer immunotherapy

Immunotherapy, represented by immune checkpoint inhibitors (ICI), is transforming the treatment of cancer. However, only a small percentage of patients show response to ICI, and effective biomarkers for ICI clinical response prediction is still urgent needed (37). To investigate the predictive performance of the quantified immunoediting-elimination signal (ES_{CCF}) in ICI response prediction for individual patient, we searched for public ICI datasets with raw WES data and RNA-seq data available, and three melanoma ICI datasets have been identified (29-31) (Supplementary Fig. S10).

We calculate the immunoediting-elimination signal (ES_{CCF}) for each patient. In univariate Cox proportional hazards regression analysis, quantified ES_{CCF} value is significantly associated with cancer patients' survival (p=0.03), and low ES_{CCF} value (suggest the presence of high immunoediting-elimination signal) is

associated with improved ICI clinical response (Hazard ratio (HR)=3.74, 95%CI=1.11-12.6) (Fig. 6A). Patients are divided into three groups based on ES_{CCF} value, patients with lowest ES_{CCF} values (indicate the presence of immunoediting-elimination signal) show the best survival after ICI (Fig. 6B).

Logistic regression is the appropriate regression analysis to conduct when the dependent variable is dichotomous (binary). Here we use logistic regression to compare the efficiency of ES_{CCF}, tumor mutational burden (TMB) and neoantigenic mutation count in predicting immunotherapy clinical response. Relationship between prognosis (patients with clinical response or without clinical response) and ES_{CCF}, TMB and neoantigenic mutation count was analyzed. The goodness of fit was performed by Hosmer–Lemeshow test (H-L test). The H-L test P-value of TMB is 0.051 (Fig. 6C, middle), close to 0.05, implicate the difference between prediction and expectation is close to significant. The H-L test P-value of ES_{CCF} is 0.771 (Fig. 6C, right), higher than the H-L test P-value of TMB and neoantigen count, suggesting ES_{CCF} is more suitable for predicting prognosis of patients than TMB and neoantigen count. This study suggests that the quantified immunoediting-elimination signal can be biomarker for ICI clinical response prediction.

Discussion

The existence of neoantigen depletion signal has been debated. Here we provide reliable evidence to demonstrate the pan-cancer existence of immunoediting signal. Importantly, the elimination and escape phases of immunoediting can be separately quantified with our method. Cancer types with strong immunoediting elimination signal usually have low immunoediting escape signal, and vice versa. Furthermore, the quantified immunoediting elimination signal predict cancer immunotherapy clinical response.

This study provides an initial method to reliably quantify immunoediting signal in individual cancer patient. To quantify the immunoediting signal for individual patient, at least one neoantigenic mutation is required. The mechanisms employed by tumor cells to escape immune surveillance is very complex, and the shutdown of the expression of neoantigen mutation is only one of the mechanisms. In addition, the mRNA expression is the combination of both wild type and mutated alleles. Lack of ES_{RNA} signal does not mean that the immune escape signal does not exist in the specific cancer or cancer types.

The existence of neoantigen mediated negative selection status in untreated cancer has been debated (4-7). Existing method for negative selection study including dN/dS and population genetics method. Rooney *et al*. use TCGA pan-cancer CDS as the control sequence to calculate the expected neoantigen number per non-silent mutation (Bpred/Npred), then the actual observed neoantigen number per non-silent mutation (Bobs/Nobs) are compared with Bpred/Npred (38). Since the pan-cancer CDS sequence has already been immune edited, the neoantigen depletion signal reported in this study is systematically underestimated. In addition, as pointed out by Van den Eynden *et al*. There is HLA typing mistake in this study (5). Van den Eynden J. *et al.* reported that neoantigen depletion signal is undetectable in untreated cancer (5). This study select the “non HLA-binding regions” as the control, and compare the nonsynonymous vs synonymous mutation ratio (n/s) in “HLA-binding regions” vs “non HLA-binding regions”. They did not identify any difference in these two regions in regard to n/s using TCGA pan-cancer dataset. However their method is problematic, as the actual neoantigen with immunogenicity are not located in their defined “HLA-binding regions” (10). Martincorena *et al*. performed a comprehensive gene level evolution selection study with dN/dS method, and reported significant neutral and positive selection, but not negative selection in cancer genome (3). Since immunogenic mutations

618 occupy less than 5% of total mutations. In gene level, the selection on
619 neoantigen mutations are overshadowed by other driving or neutral mutations.
620 Neoantigen mediated negative selection cannot been observed in gene-level
621 does not mean the absence of immune based neoantigen depletion. Zapata *et*
622 *al*. investigated immune based negative selection with dN/dS method (4).
623 However same problem exist in the selection of control DNA sequence. Similar
624 to Van den Eynden J. *et al.* CDS was divided into epitope region and non-
625 epitope region, dN/dS was compared in these two regions. Since neoantigen
626 with immunogenicity are not necessarily located in “epitope region”, the results
627 reported in this study is also questionable. Population genetics model for
628 neutral evolution has been proposed to detect neutral evolution based on
629 cumulative VAF distribution. For instance, a recent study test the neutrality of
630 cancer based on the VAF of mutations in a limited subclonal frequency range
631 (11). However, that test of neutrality has been questioned, the frequency
632 distribution of mutated alleles in a limited frequency range is not an accurate
633 statistic for detecting selection in cancer (13,14). Furthermore the application
634 of this population genetics method in neoantigen mediated negative selection
635 quantification in individual cancer patient has not been established (32)
636 (Supplementary Fig. S9).
637
638 The quantification of negative selection in cancer evolution has been a major
639 scientific challenge, the method developed here for neoantigen mediated
640 negative selection quantification could be instructive for the future design of
641 strategies for studying negative selection in cancer evolution. The existence of
642 neoantigen mediated negative selection has been demonstrated with our new
643 method. Importantly we observed a strong immunoediting-escape signal
644 reflected as the down-regulation of mRNA encoded by neoantigenic mutations.
645 The quantification of immunoediting provides an evolutionary perspective for
646 the design of neoantigen vaccine for cancer therapy. The immune based
647 negative selection is an inherent feature of cancer patient, the quantified

immunoediting signal can be used in cancer precision stratification, including the clinical response prediction for cancer immunotherapy.

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Contributions

TW collected the data, developed the immunoediting quantification analysis method and performed the computational analysis. GW participated in data collection and preprocessing. XW participated in neoantigen prediction. SW help to build the method for immunoediting quantification. XZ, CW, WN, ZT, FC participated in critical project discussion. XSL conceptualized the idea, designed, supervised the study and wrote the manuscript.

Conflict of interest

The authors declare no competing interests.

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Figure legend

Figure 1. Conceptual framework for the quantification of elimination and escape phases of immunoediting.

A, Phases of immunnoediting and the manifestations of the elimination and escape phases of immunoediting.

B, Diagram showing the manifestations of immunoediting phases. Red star indicates neoantigenic mutation. The elimination phase will decrease the CCF of neoantigenic mutations, and cancer cell can eventually evolve multiple mechanisms to escape the surveillance of immune system, including shutdown the transcription of mRNA encoded by neoantigenic mutations.

Figure 2. Distribution pattern based method for the quantification of neoantigen mediated negative selection in cancer evolution.

A, Detailed steps for CCF down-regulation based immunoediting-elimination (ES_{CCF}) quantification. 1. Equally divide the whole CCF range (0-1) into 100 intervals and calculate the distribution of CCF of neoantigenic mutations and non-neoantigenic mutations in these intervals; 2. Construct the Kolmogorov–Smirnov (K-S) statistics based on difference between the two distributions; 3. Calculate the enrichment score (ES_{CCF}).

B, Detailed steps for mRNA down-regulation based immunoediting-escape (ES_{RNA}) quantification. 1. Rank mutations by corresponding mRNA expression and calculate the distribution of mRNA expression of neoantigenic mutations and non-neoantigenic mutations; 2. Construct the K-S statistics based on difference between the two distributions; 3. Calculate the enrichment score (ES_{RNA}).

C, Random simulation to obtain the null distribution of ES. For each sample, we permute the mutation labeling (ie. randomly select the same number of mutations as the observed number in the sample, and label them as neoantigenic mutations) and calculate ES value, the processes are repeated for 2000 times, and the actual ES values are compared with the simulated

values.

Figure 3. Pan-cancer distributions and features of the quantified immunoediting signals (ES_{CCF} and ES_{RNA}).

A, Distribution of ES_{CCF} in pan-cancer (left) and in specific cancer type (right). The p values are calculated from simulated median ES distributions. ns: p > 0.05, *: p <= 0.05, **: p <= 0.01, ***: p <= 0.001, ****: p <= 0.0001.

B, Distribution of ES_{CCF} in pan-cancer (left) and in specific cancer type (right), after removing samples with neoantigenic and driver mutations located in the same gene. The p values are calculated from simulated median ES distributions.

C, Distribution of ES_{RNA} in pan-cancer (left) and in specific cancer type (right). The p values are calculated from simulated median ES distributions.

D, From left to right, simulated median ES distribution and the observed median ES for Fig 3a, 3b and 3c respectively.

E, Correlation between median ES_{RNA} and ES_{CCF} of TCGA cancer types. Pearson correlation coefficient and p value are shown.

F, Correlation between the percent of escape samples ($ES_{RNA} < 0$ and $p < 0.05$) and median ES_{CCF} in TCGA cancer types. Pearson correlation coefficient and p value are shown.

Figure 4. Immunoediting-elimination signal (ES_{CCF}) and neoantigen-mediated negative selection strength quantification.

A, ES_{CCF} as a function of neoantigen-mediated negative selection strength s, computed from n=100 tumors, with simulated read depth of 200$\times$ for each indicated selection strength s. The observed median ES_{CCF} of TCGA samples is indicated with a horizontal dashed line.

B, The proportion of 100 simulated tumors with significant ES_{CCF} (FDR corrected p value less than 0.1) in each selection strength s.

Figure 5. Immunoediting-elimination and escape signals and tumor

immune cell infiltration status.

A, B, Comparisons between TCGA cancer patients with detectable Immunoediting-elimination signal (ES_{CCF}<0, p<0.05) and the remaining patients in $CD8^+$ T plus natural killer (NK) cell (**a**) and Treg cell (**b**) infiltration status.

C, D, Comparisons between TCGA cancer patients with detectable Immunoediting-elimination signal (ES_{RNA}<0, p<0.05) and the remaining patients in $CD8^+$ T plus NK cell (**c**) and Treg cell (**d**) infiltration status. Wilcoxon rank sum test p value is shown.

Figure 6. Quantified immunoediting-elimination signal (ES_{CCF}) predicts cancer immunotherapy clinical response.

A, Univariate Cox regression analysis was performed to estimate the hazard ratio (HR) associated with ES_{CCF} values. The length of horizontal line represents the 95% confidence interval (CI) and the vertical dashed line represents HR = 1.

B, Kaplan-Meier overall survival curves show the comparison between different groups stratified by ES_{CCF} value. Samples with ES_{CCF} values higher than the cutoff (-0.222, determined by surv_cutpoint function of “survminer” package) were classified as “high” group, and samples with ES_{CCF} value less than the cutoff were classified as “low” group. The remaining samples (without neoantigen or minimum CCF is higher than 0.6) were classified as “other” group.

C, The goodness-of-fit is performed by Hosmer-Lemeshow test, which shows that ES_{CCF} is more suitable for predicting the prognosis of patients after ICI than TMB or neoantigen burden.

Supplementary Figure Legends

Supplementary Fig. S1. Overview of the TCGA pan-cancer dataset included in this study.

A, Samples used for calculating ES_{CCF}. Number of the patient with CCF information and number of patient with at least one neoantigenic mutation and subclonal mutation (CCF<0.6) are shown for each cancer type.

B, Samples used for calculating ES_{RNA}. Number of the patient with mRNA expression information and number of patient with at least one neoantigenic mutation and accompanied mRNA expression information are shown for each cancer type.

Supplementary Fig. S2. CCF distribution of all mutations in TCGA dataset.

Supplementary Fig. S3. Simulated median ES distribution and corresponding p value (blue area) of TCGA cancer types. Related to Figure3a.

Supplementary Fig. S4. Comparison of ES_{CCF} between samples with and without neoantigenic and driver mutations located in the same gene. Wilcoxon sum test p value is shown.

Supplementary Fig. S5. Simulated median ES distribution and corresponding p value (blue area) of TCGA cancer types. Related to Figure3b.

Supplementary Fig. S6. Simulated median ES distribution and corresponding p value (blue area) of TCGA cancer types. Related to Figure3c.

Supplementary Fig. S7. Distribution of patients with significant immunoediting-elimination and expression based escape signal (ES_{CCF} or ES_{RNA} <0, p<0.05) in TCGA pan-cancer dataset.

Supplementary Fig. S8. Proportion of TCGA cancer patients with detectable immunoediting signal.

A, Proportion of TCGA cancer patients with ES_{CCF}<0 (and) p<0.05.

B, Proportion of TCGA cancer patients with ES_{RNA}<0 (and) p<0.05.

Supplementary Fig. S9. Comparison ES_{CCF} with other methods in negative selection strength quantification.

A, Derivation from neutral VAF distribution quantification as a function of negative selection strength s, computed from individual tumor of a simulation cohort (n=100), with a simulated read depth of 200×.

B, Proportion of 100 simulated tumors with significant signal (FDR corrected p value less than 0.1) quantified using derivation from neutral VAF distribution method under each negative selection strength s. Of note, no tumors show significant signal under the same simulated conditions as the data show in Fig. 4b.

C, Power to detect negative selection as a function of sequencing read depth (x axis) and false neoantigen rate (y axis) using the enrichment score method developed in this study. Power is the proportion of 100 simulated tumors with significant negative ES value (FDR corrected p value less than 0.1).

D, Power to detect negative selection as a function of sequencing read depth (x axis) and false neoantigen rate (y axis) using derivation from neutral VAF distribution method. Power is the proportion of 100 simulated tumors with significant difference (two-sided K-S test, FDR corrected p value less than 0.1) between the distribution of all mutations and neoantigenic mutations.

Supplementary Fig. S10. Clinical parameters of the three cancer ICI

datasets used in this study.

Figure 1

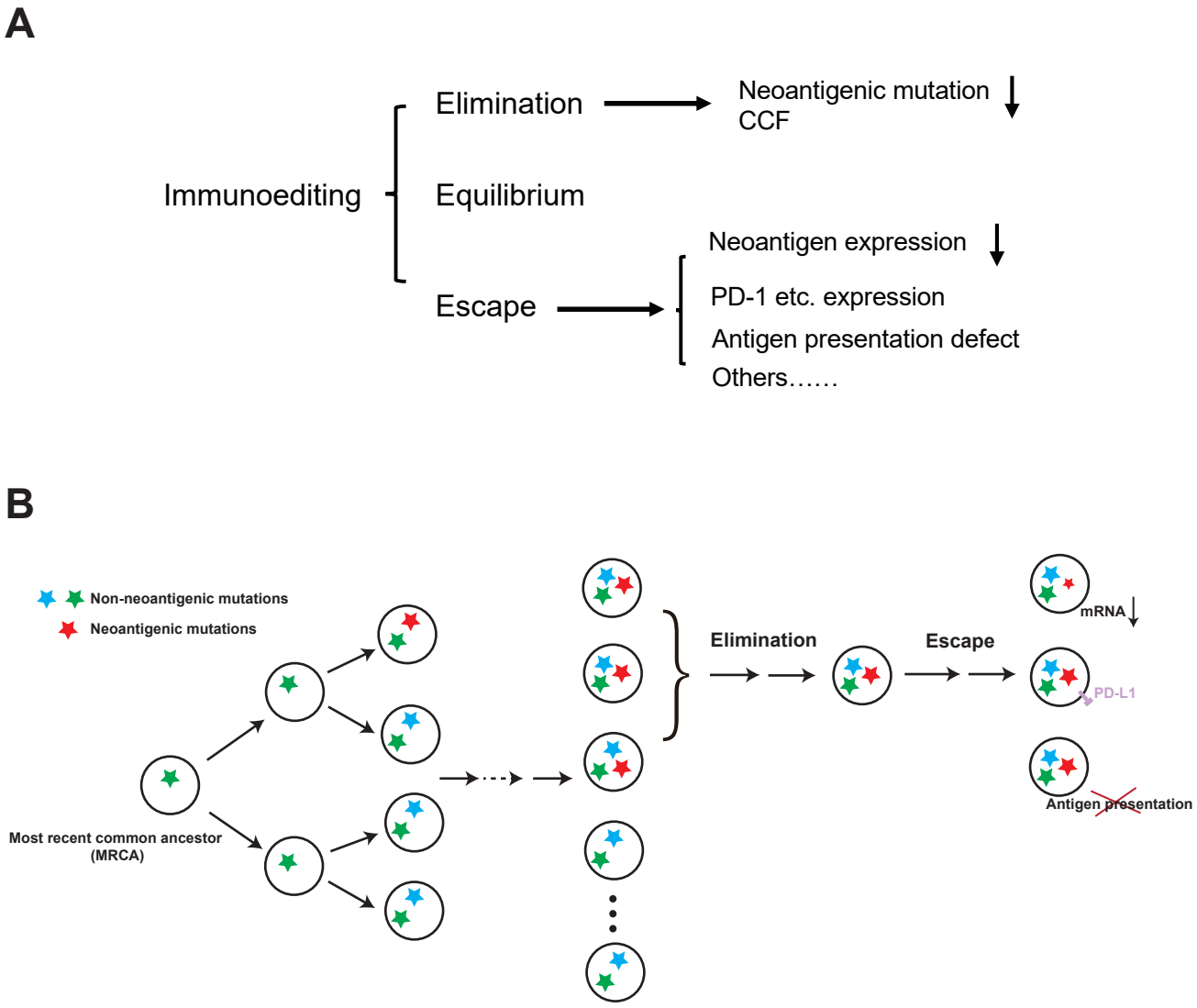
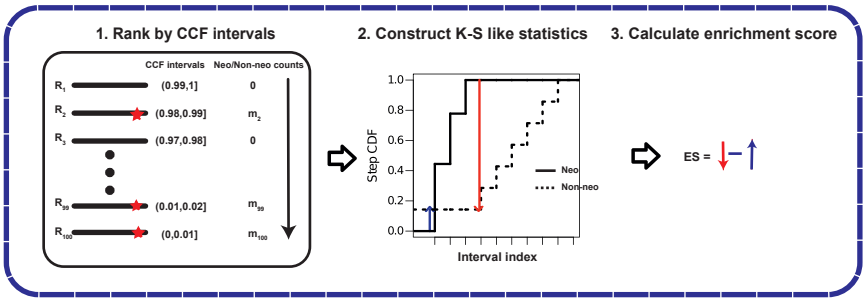

A
Immunoediting
Elimination
Neoantigenic mutation
CCF
Equilibrium
Neoantigen expression
Escape
PD-1 etc. expression
Antigen presentation defect
Others……
B
Non-neoantigenic mutations
Neoantigenic mutations
Most recent common ancestor
(MRCA)
Elimination
Escape
mRNA
PD-L1
Antigen presentation

Figure 2

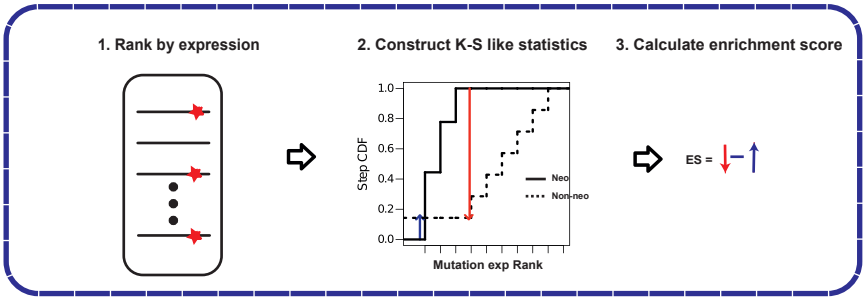
A

CCF down-regulation based immunoediting-elimination quantification

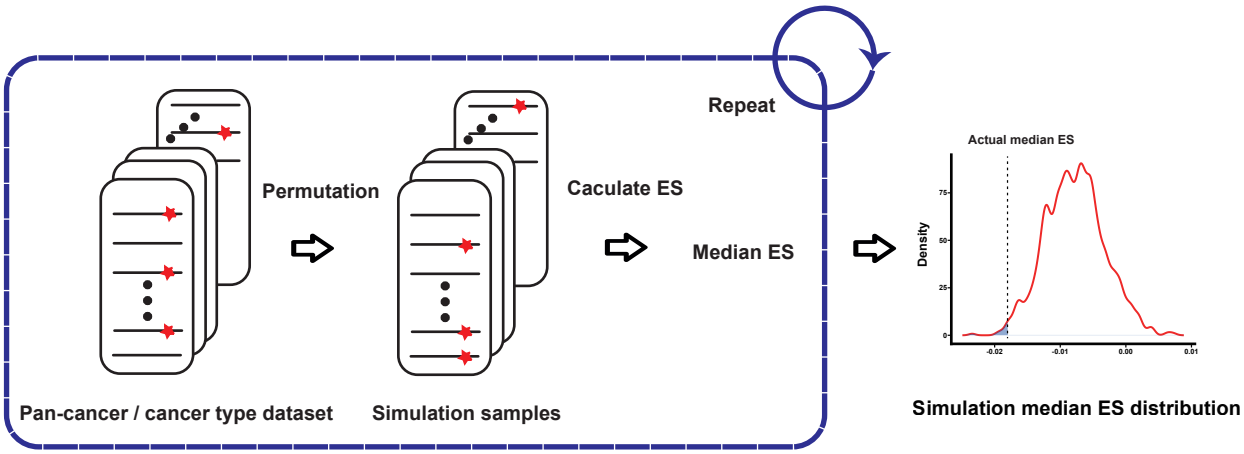


B

mRNA down-regulation based immunoediting-escape quantification



C



Permute neoantigen labeling, and calculate ES score

Figure 3

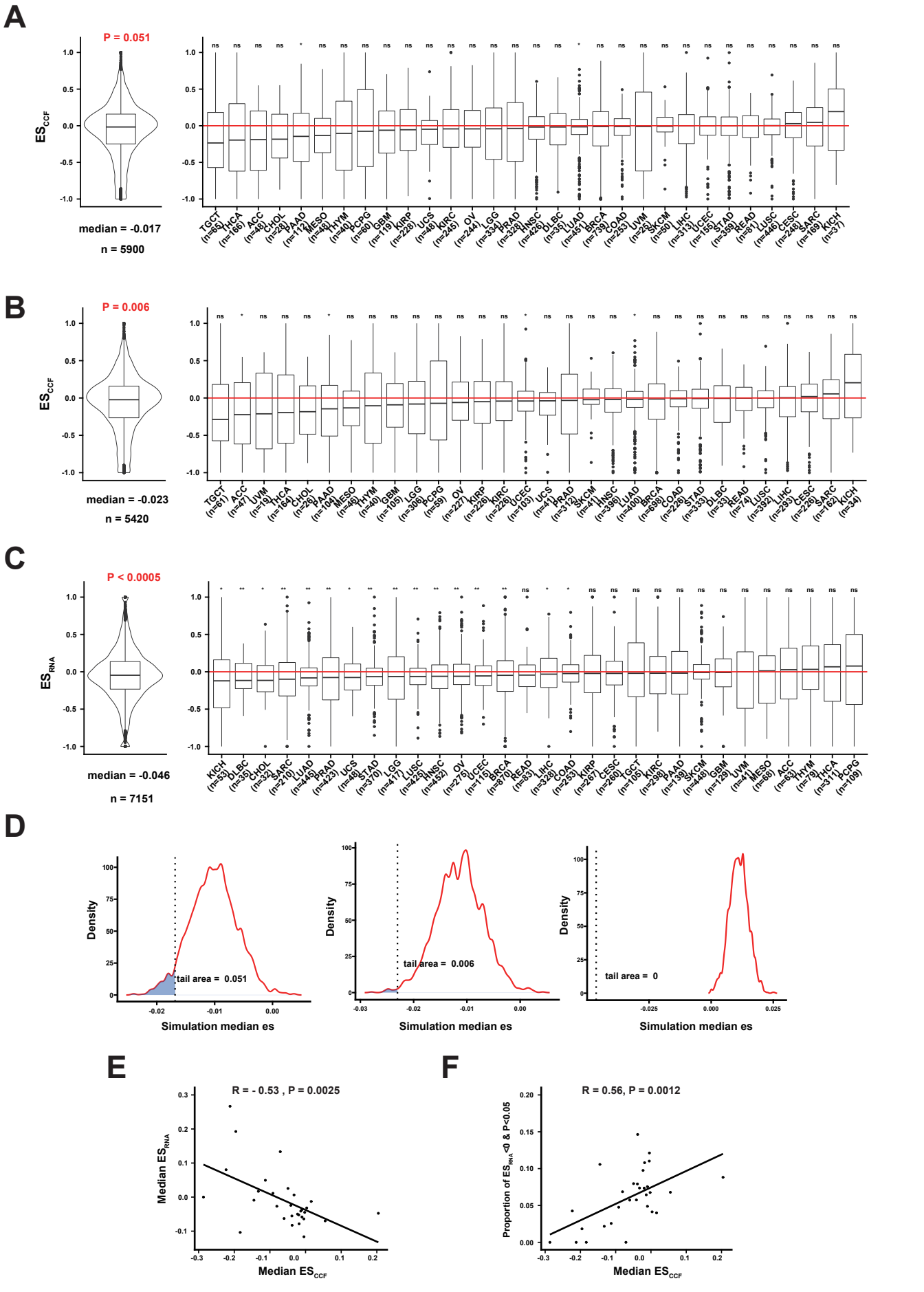

A
P = 0.051
ES_CCF
median = -0.017
n = 5900
B
P = 0.006
ES_CCF
median = -0.023
n = 5420
C
P < 0.0005
ES_RNA
median = -0.046
n = 7151
D
Density
tail area = 0.051
tail area = 0.006
tail area = 0
Simulation median es
E
R = - 0.53 , P = 0.0025
Median ES_RNA
Median ES_CCF
F
R = 0.56, P = 0.0012
Proportion of ES_RNA <0 & P<0.05
Median ES_CCF

Figure 4

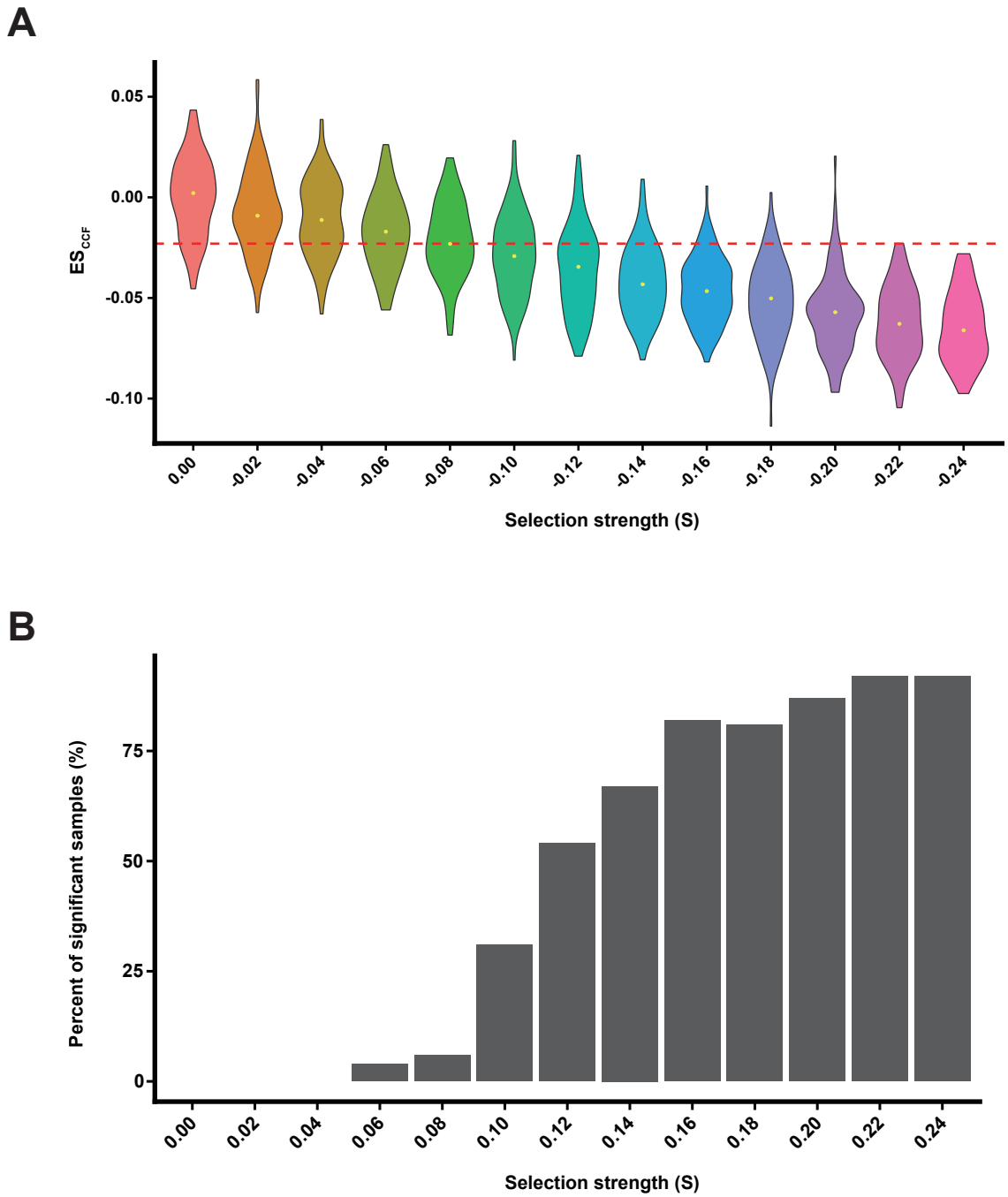

A
0.05
0.00
-0.05
-0.10
ES_CCF
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
-0.22
-0.24
Selection strength (S)
B
Percent of significant samples (%)
75
50
25
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
Selection strength (S)

Figure 5

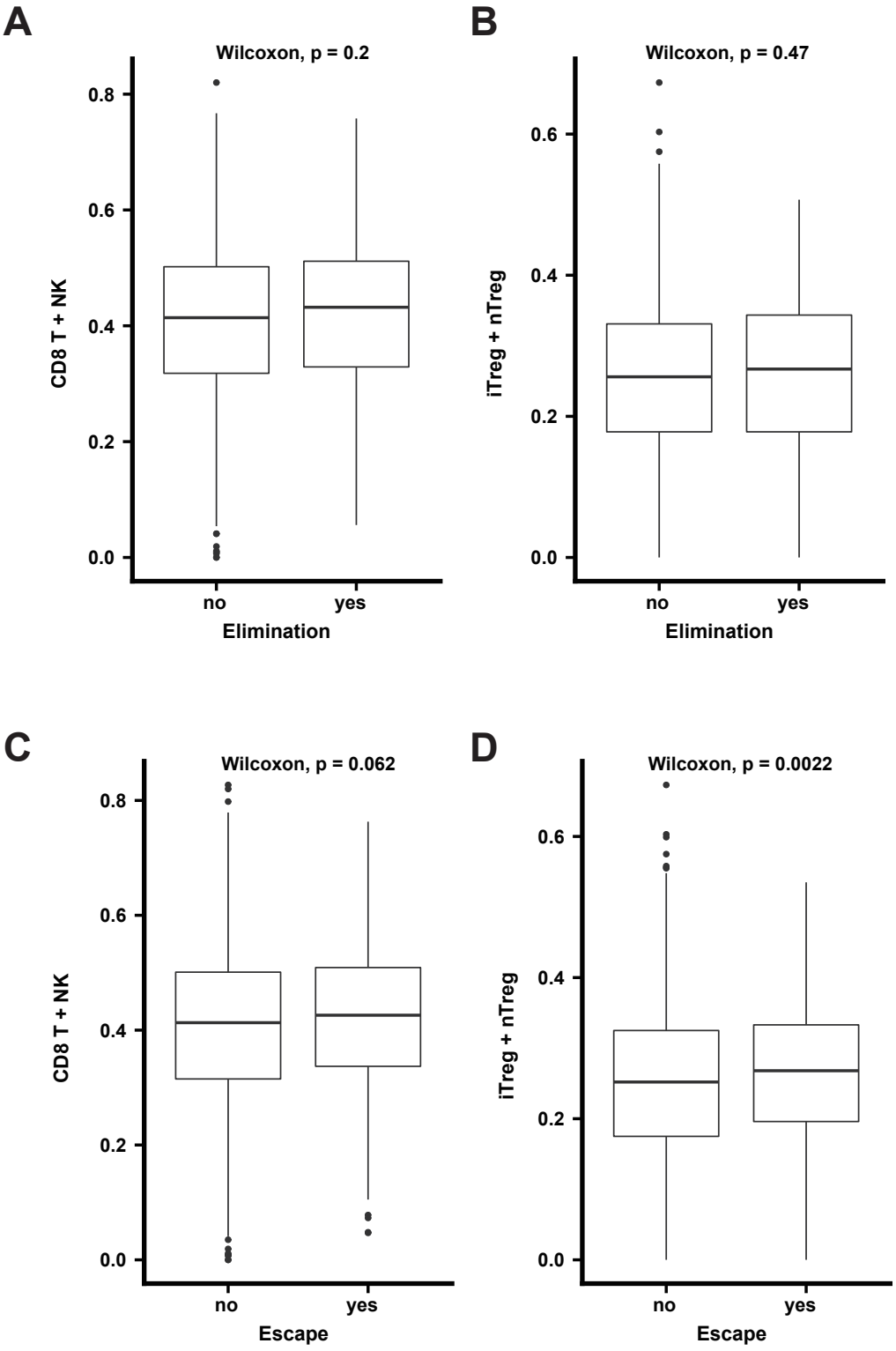
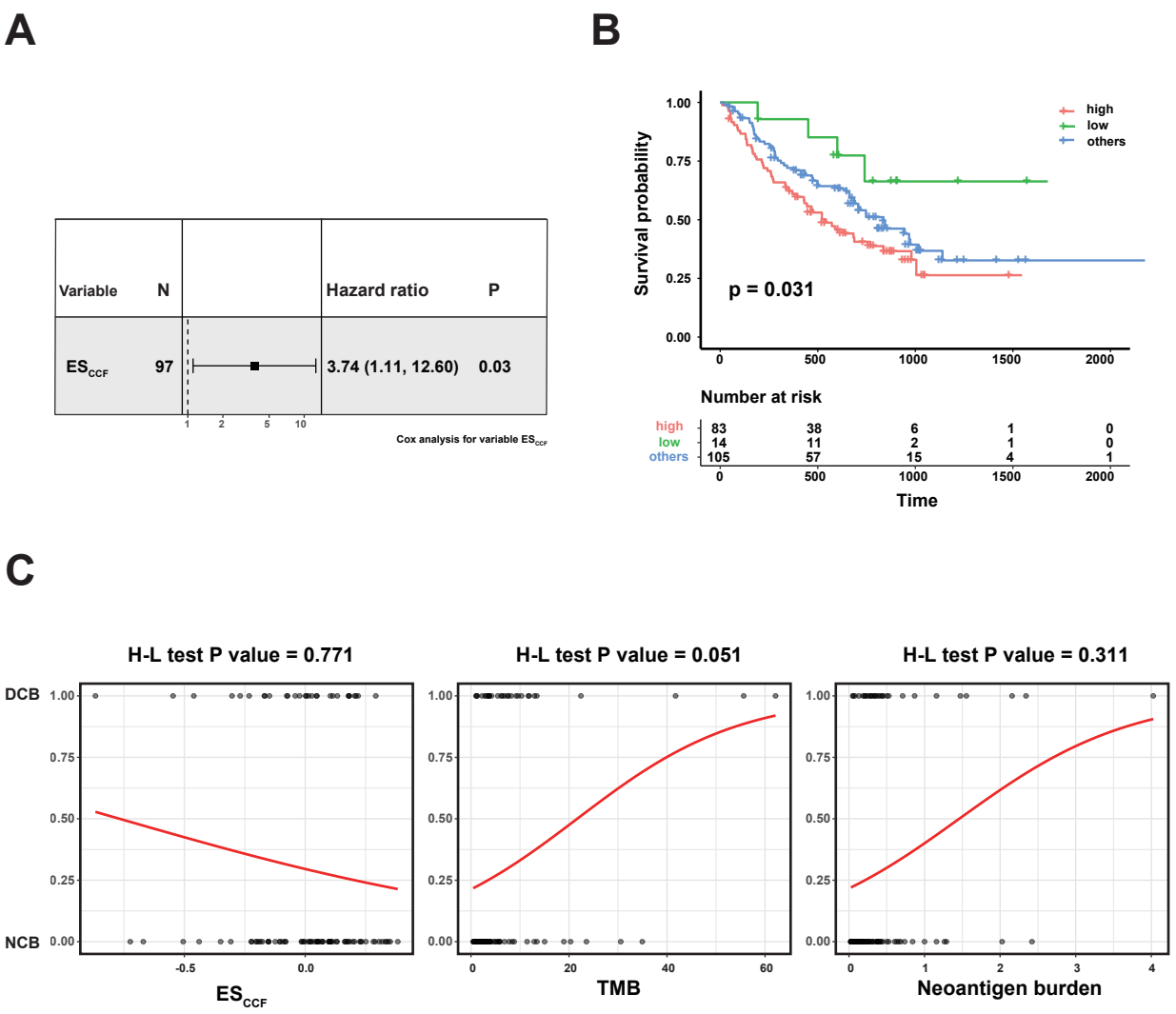

A
Wilcoxon, p = 0.2
CD8 T + NK
0.0
0.2
0.4
0.6
0.8
no
yes
Elimination
B
Wilcoxon, p = 0.47
iTreg + nTreg
0.0
0.2
0.4
0.6
no
yes
Elimination
C
Wilcoxon, p = 0.062
CD8 T + NK
0.0
0.2
0.4
0.6
0.8
no
yes
Escape
D
Wilcoxon, p = 0.0022
iTreg + nTreg
0.0
0.2
0.4
0.6
no
yes
Escape

Figure 6


A
Variable
N
Hazard ratio
P
ES$_{CCF}$
97
3.74 (1.11, 12.60)
0.03
1
2
5
10
Cox analysis for variable ES$_{CCF}$
B
Survival probability
1.00
0.75
0.50
0.25
0.00
high
low
others
p = 0.031
0
500
1000
1500
2000
Number at risk
high 83 38 6 1 0
low 14 11 2 1 0
others 105 57 15 4 1
Time
C
H-L test P value = 0.771
H-L test P value = 0.051
H-L test P value = 0.311
DCB
NCB
ES$_{CCF}$
TMB
Neoantigen burden