Gut microbiota and metabolites associate with outcomes of immune checkpoint inhibitor–treated unresectable hepatocellular carcinoma

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ABSTRACT

Background Immune checkpoint inhibitors (ICIs) are promising agents for unresectable hepatocellular carcinoma (uHCC), but lack effective biomarker to predict outcomes. The gut microbiome can modulate tumor response to immunotherapy, but its effect on HCC remains unclear.

Methods From May 2018 to February 2020, patients receiving ICI treatment for uHCC were prospectively enrolled; their fecal samples were collected before treatment. The fecal microbiota and metabolites were analyzed from 20 patients with radiology-proven objective responses (OR) and 21 randomly selected patients with progressive disease (PD). After March 2020, 33 consecutive Child-Pugh-A patients were recruited as a validation cohort. Additionally, feces from 17 healthy volunteers were collected for comparison of background microbes.

Results A significant dissimilarity was observed in fecal bacteria between patients with OR and patients with PD before immunotherapy. Prevotella 9 was enriched in patients with PD, whereas Lachnoclostridium, Lachnospiraceae, and Veillonella were predominant in patients with OR. Ursodeoxycholic acid and urscholic acid were significantly enriched in the feces of patients with OR and strongly correlated with the abundance of Lachnoclostridium. The coexistence of Lachnoclostridium enrichment and Prevotella 9 depletion significantly predicted better overall survival (OS). In the validation cohort, better progression-free survival (PFS) and OS were noted in patients who had a preferable microbial signature in comparison with counter-group (PFS: 8.8 months vs 1.8 months; OS: not reached vs 6.5 months, both p<0.001).

Conclusions Fecal microbiota and bile acids were associated with outcomes of immunotherapy for uHCC. These findings highlight the potential role of gut microbiota and metabolites as biomarkers to predict outcomes of ICI-treated HCC.

INTRODUCTION

Hepatocellular carcinoma (HCC) is the sixth most common cancer and the third leading cause of cancer-related death worldwide, which constitutes a major global health problem.1 2 Despite the implementation of universal hepatitis B vaccination, direct-acting antiviral agents for hepatitis C, and active surveillance for high-risk populations, a significant portion of patients still present with or progress to unresectable, advanced-stage diseases that require systemic therapy.2

Immunotherapies with immune checkpoint inhibitors (ICIs) have recently emerged as immunotherapeutic agents for unresectable HCC, including nivolumab and pembrolizumab that block programmed cell death-1 (PD-1), as well as atezolizumab, which blocks programmed death-ligand 1 (PD-L1).3-5 In general, the response rate of HCC to ICIs treatment is around 16%–20% for ICI monotherapy, and 30%–36% for ICI
combinations. The PD-L1 expression level is not recommended as a selection marker for ICI treatment for HCC. CTNNB1 mutation represents an immune-exclusive subclass of HCC and may be resistant to immunotherapy, but further validation is required. On-treatment decline of alpha fetoprotein (AFP) has been reported to predict the tumor response to immunotherapy. To date, pretreatment tumor or host-related biomarkers associated with the outcomes of HCC to ICI treatment are unmet needs.

Humans harbor nearly 10^{12} trillion gut bacteria that contribute to digestion, intestinal homeostasis and regulate the immune function of the host. Dysbiosis is defined as the imbalance between protective and pathogenic bacteria both in quality and quantity; it has been reported to be associated with carcinogenesis. Emerging studies also indicate that the gut microbiome has a role in response to cancer therapy across cancer types. For example, intestinal bacteria can regulate the efficacy of immunotherapy in a xenograft model of melanoma. A similar phenomenon was also observed in patients with melanoma that supported the correlation between microbial composition and clinical response.

Despite accumulating evidence that gut microbiota could modulate tumor responses to immunotherapies, limited data have been demonstrated with regard to the concept of targeting the gut microbiota–liver axis for the treatment of HCC. In this study, we investigated the role of gut microbiota and metabolites in the treatment response to ICI therapy and outcomes of patients with unresectable HCC (uHCC).

**MATERIALS AND METHODS**

**Patients**

From May 2018 to February 2020, 94 ICI treatment-naïve patients with uHCC were prospectively enrolled from Taipei Veterans General Hospital in a biomarker study before starting ICI treatment as their first-line or second-line systemic treatment. The diagnosis of HCC was according to the criteria of American Association for the Study of Liver Diseases (AASLD) clinical practice guidelines for HCC; typical radiological characteristics and/or pathology in patients with cirrhosis and pathological confirmation in patients without cirrhosis were needed. During the study period, the ICIs approved by the manufacturer’s protocols, which included a bead-beating process for 1 min. The V3-V4 regions of bacterial 16S rRNA genes were amplified by PCR using 341F and 806R primers. Next-generation sequencing was performed by the Illumina MiSeq Desktop Sequencer following the standard protocol.

The 16S rRNA gene sequencing raw reads were processed using Quantitative Insights into Microbial Ecology (QIIME) V1.9.1 and annotated the taxonomy classification based on the SILVA database V1.122. Taxonomic compositions were identified. Alpha diversities were examined by Shannon and PD whole tree indices and compared by Kruskal-Wallis test. The principal coordinate analysis (PCoA) of microbiota was measured by Bray-Curtis dissimilarity and compared by permutation multivariate analysis of variance (PERMANOVA) test. Linear discriminant analysis (LDA) effect size (LEfSe) analysis size was also calculated based on the assumption that 50% of patients with OR had preferable gut microbiota, and 10% of patients with PD had preferable gut microbiota, at least 20 cases in each arm were required for 80% power with 5% chance of alpha error. Tumor response was based on RECIST 1.1. After March 2020, 33 consecutive, ICI-naïve, Child-Pugh A patients who received ICI as their first-line or second-line treatment for uHCC were recruited in the validation cohort. As immuno-oncology (IO) monotherapy was shifted to IO combination for uHCC after 2020, this cohort recruited 28 patients with IO combinations to validate the findings in the era of IO combinations. 16S ribosomal RNA (rRNA) gene sequencing data were also collected from the feces of 17 healthy volunteers for comparison of background microbiota.

**Treatment and outcome assessment**

ICIs were administered according to the recommended dosing and safety information (2–3 mg/kg, every 2 weeks for nivolumab and 2–3 mg/kg or 200 mg every 3 weeks for pembrolizumab). The safety assessment and grading were performed using the National Cancer Institute Common Terminology Criteria for Adverse Events (CTCAE, V.5.0). Clinical evaluations were performed regularly during treatment, including Child-Pugh class, albumin-bilirubin grade, hemogram, serum chemistry, and AFP level. The tumor response was assessed using RECIST V1.1 based on contrast-enhanced abdominal CT scans or MRI; the objective response rate (ORR) as well as disease control rate (DCR) were analyzed. Image examinations were performed every 8 to 9 weeks during ICI treatment. The overall survival (OS) was measured from the date of starting ICIs until death.

**Processing and analysis of fecal bacterial genomic data**

Fresh feces were collected from patients or healthy volunteers at our hospital based on hygienic standard procedure and then frozen and stored at −80°C within 1 hour. Microbial genomic DNAs were extracted using the CatchGene Stool DNA Kit (CatchGene, New Taipei City, Taiwan) according to the manufacturer’s protocols, which included a bead-beating process for 1 min. The V3-V4 regions of bacterial 16S rRNA genes were amplified by PCR using 341F and 806R primers. Next-generation sequencing was performed by the Illumina MiSeq Desktop Sequencer following the standard protocol.

The 16S rRNA gene sequencing raw reads were processed using Quantitative Insights into Microbial Ecology (QIIME) V1.9.1 and annotated the taxonomy classification based on the SILVA database V1.122. Taxonomic compositions were identified. Alpha diversities were examined by Shannon and PD whole tree indices and compared by Kruskal-Wallis test. The principal coordinate analysis (PCoA) of microbiota was measured by Bray-Curtis dissimilarity and compared by permutation multivariate analysis of variance (PERMANOVA) test. Linear discriminant analysis (LDA) effect size (LEfSe) analysis
Measurement of fecal bile acids
Fecal samples (25 mg) were extracted with 1000 μL extraction solution (MeOH:ACN: H2O = 2:2:1) containing an internal standard mixture and then incubated at 4°C for 1 hour. Samples were then centrifuged at 12,000 g for 30 min at 4°C. The supernatant was transferred for bile acid (BA) analysis as described previously,25 using Waters ultra-high-performance liquid chromatography coupled with a Waters Xevo TQ-S mass spectrometer (Waters, USA) equipped with an electrospray ionization source operating in positive mode. The final concentration results were processed and quantified by TargetLynx software (Waters). Thirty-nine BAs were measured in the fecal samples using methods created from the retention times and mass spectra acquired from standard solutions, and were analyzed under the same conditions as the samples.

Measurement of fecal short-chain fatty acids
Lyophilized fecal samples (25 mg) were mixed with 500 μL of 70% methanol and sonicated for 30 min. The mixtures were centrifuged at 12,000 rpm for 10 min, and the supernatants were retrieved for derivatization and detection of short-chain fatty acids (SCFAs) as described previously.26 SCFAs were measured with a high-performance liquid chromatography (HPLC) system (SunFire C18 Column, 100Å, 5μm, 4.6mm × 250 mm, Waters) equipped with a UV detector (Agilent 1260 Infinity HPLC, USA). The derivatized SCFAs were quantified using the chromatogram area ratio to the internal standard (2-ethylbutyric acid, 1 mM). The peak integrations were calculated using Agilent ChemStation software (Agilent).

Statistical analysis
Continuous variables were expressed as the median (IQR), while categorical variables were analyzed as frequencies and percentages. Pearson χ² analyses or Fisher’s exact tests were used to compare categorical variables, and Student’s t-tests or the Mann-Whitney U tests were applied for continuous variables. The optimal cut-off values of bacterial abundance to predict tumor response were assessed using the area under receiver operating characteristic curves (AUROC). The value with the highest Youden’s Index (sensitivity +specificity − 1) was considered as the optimal cut-off.27 OS or progression-free survival (PFS) from the beginning of ICI treatment to death or tumor progression was estimated by the Kaplan-Meier method and compared by the log-rank test. Additionally, Cox’s proportional-hazard model was used to identify prognostic factors for survival. Albumin-bilirubin grade and Child-Pugh class were not included in the same multivariate model to avoid the effect of collinearity. For all analyses, p < 0.05 was considered statistically significant. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS V.26.0 for Windows, SPSS) and GraphPad Prism V.9 (GraphPad Software, San Diego, California, USA).

RESULTS
Demographic characteristics of the study cohort
Patients were ICI-naïve and predominantly male (85.4%) and most had chronic hepatitis B virus infection (63.4%). On enrollment, most patients were at Child-Pugh class A (82.9%); but 63.4% of them were classified beyond ALBI grade 1. No significant differences in liver reserves were observed between patients with OR or PD to ICI treatment.

Twenty-eight patients were classified in BCLC stage C. The incidences of portal vein invasion or extrahepatic metastasis were comparable between two groups. Compared with patients with PD, more patients with OR were treated with combination therapy by ICI plus tyrosine kinase inhibitor (TKI) (60.0% vs 23.8%, p = 0.019). The detailed baseline characteristics of patients are presented in table 1.

Association of treatment response with gut microbial composition
Generally, Firmicutes and Bacteroidetes were the most abundant fecal bacteria in patients with uHCC. At the family level, Lachnospiraceae and Veillonellaceae were enriched in the feces of patients with OR. In contrast, apparent increases of Prevotellaceae and Enterobacteriaceae but reduced abundance of Lachnospiraceae and Veillonellaceae were observed in patients with PD after immunotherapy (online supplemental figure 1A,B). The richness and evenness of microbiota measured by the Shannon index and the phylogenetic diversity whole tree index were not significantly different between patients with HCC and healthy controls (online supplemental figure 1C,D). The PCoA of Bray-Curtis metrics showed a significant microbial dissimilarity between these three groups (p = 0.019, < 0.001, and < 0.001 according to PERMANOVA tests for patients with HCC vs PD, healthy controls vs patients with OR and healthy controls vs PD HCC patients, respectively; figure 1A). The results of LEfSe analysis (figure 1B,C) showed a prominence of Prevotella 9 (LDA score [log10]>4) in the feces of patients with PD. In contrast, Veillonella, Lachnospiraceae and Lachnooldoridium were predominant in the feces of patients with OR to immunotherapy.

The pattern of the microbial dissimilarity and the composition of gut microbiota were further analyzed for the subgroup of 24 patients receiving ICI monotherapy. A marginal microbial dissimilarity between OR and PD groups (p = 0.075 by PERMANOVA test) was still observed in the PCoA of Bray-Curtis metrics (online supplemental figure 2A). Prevotellaceae, Prevotella 9, and Faecalibacterium...
were consistently predominant in patients with PD; whereas *Veillonella*, *Lachnoclostridium*, *Lactobacillales*, and linked taxa were predominant in patients with OR according to the LEfSe analysis (online supplemental figure 2B,C). On the other hand, no significant differences of microbial composition as well as alpha and beta diversities were identified between patients with prior experience of TKI (n=23) or not (n=18). Besides, the relative abundance of *Prevotella* 9 and *Lachnoclostridium* as well as the concentration of fecal bile acids were not significantly different according to the prior experience of TKI (online supplemental figure 3).

**Association of treatment response with gut microbial metabolites**

BAs, SCFAs, and other untargeted metabolites in the feces were measured to understand the metabolic profiles associated with tumor response to immunotherapy. Fecal concentrations of primary BAs were generally higher in the OR patients but the difference lacked statistical
Interestingly, secondary bile acids, including ursodeoxycholic acid (UDCA), tauro-UDCA, ursocholic acid (UCA), and murideoxycholic acid (MDCA) were significantly enriched in the feces of patients who had OR to immunotherapy compared with their counterparts (figure 2, online supplemental table 1). Acetic acid was the most abundant fecal SCFA in both patients with OR and patients with PD followed by propionic acid and butyric acid. However, no significant differences in the fecal concentration of all detected SCFAs could be identified between these two patient groups. In addition, the non-target analysis also indicated certain
metabolites with significant alterations in the fecal of patients with OR such as increased concentration of isohyodeoxycholic acid and nutriacholic acid as well as reductions in oxypurinol, inosine, D-glucuronic acid, and so on (online supplemental figure 4).

**Positive association of fecal metabolites with bacterial species**

According to the Spearman correlation analysis (figure 3), the fecal concentrations of UDCA, UCA, and MDCA had significantly positive correlations with the relative abundance of *Lachnoclostridium*. Positive correlations were also observed between these BAs and fecal *Ruminococcus gnavus* group (a prominent genus of gut microbe in patients with OR according to LEfSe analysis, LDA score [log10]: 3–4). In contrast, these secondary BAs were negatively correlated with the fecal abundance of *Prevotella 9*, which was predominant in patients with PD.

**The association between gut microbiome and survival**

During a median follow-up period of 12.4 (IQR 3.8–21.4) months, the median OS of the study cohort was 13.5 months (95% C.I. 11.1 to 15.9). According to the ROC analyses, the genera *Prevotella 9* and *Lachnoclostridium* were acceptable discriminating microbes to predict tumor response (AUROC: 0.698 and 0.700, respectively). Therefore, the abundances of these two taxa were investigated in survival analyses. Patients with enriched fecal *Prevotella 9* had significantly worse OS than the counterparts (median OS: 8.6 months vs 17.2 months, p=0.039, figure 4A). A survival benefit was also observed in patients with enriched fecal *Lachnoclostridium* (median OS: 22.8 months vs 5.6 months, p=0.032, figure 4B). The best OS was identified in patients with coexistence of *Lachnoclostridium* enrichment and *Prevotella 9* depletion in the feces (median OS: 22.8 months, figure 3C). Tumor volume, AST level, Child-Pugh class, gut microbial abundance, and fecal UDCA concentration were associated with survival in the univariate analysis. In the multivariate analysis, a good signature of fecal microbiota (coexistence of *Lachnoclostridium* enrichment and *Prevotella 9* depletion) was a significant predictor of better OS (table 2).

**Validation cohort**

Of the 33 patients in the validation cohort (baseline characteristics in online supplemental table 2), fecal enrichment of *Lachnoclostridium* was significantly associated with a better ORR and DCR of HCC. The best ORR of 52.6% and DCR of 94.7% were observed in patients with a good microbial signature, in which depleted *Prevotella 9* and enriched *Lachnoclostridium* were coexisted (online supplemental table 3). Patients with depleted *Prevotella 9* or enriched *Lachnoclostridium* had better PFS than those without this signature (figure 5A,B); and the best PFS (8.8 months) was also observed in patients with a good microbial signature (figure 5C). Importantly, patients with a good microbial signature also had a significantly
better OS than those with poor signature (coexistence of enriched *Prevotella 9* and depleted *Lachnoclostridium*) or fair signature (coexistent depletion or enrichment of these two taxa) (figure 5D–F).

**DISCUSSION**

This is the first study including validation cohort to support the significant role of gut microbiota–liver axis in the treatment response to ICI treatment and survival in patients with uHCC. The gut microbiota and metabolites were distinct between immunotherapy responders and non-responders in patients with HCC. Furthermore, a fecal microbial signature with enrichment of *Lachnoclostridium* and depletion of *Prevotella 9* was an independent survival factor.

Accumulating evidence suggests that gut microbiome and individual bacterial species contained in the intestine can profoundly affect the host immune system.11–13 A
Dysregulated gut microbiome is involved in tumorigenesis and progression through multiple regulatory pathways. In a melanoma orthotopic xenograft mouse model, commensal Bifidobacterium enhanced the anti-tumor immunity in vivo. Oral administration of Bifidobacterium alone improved tumor control to the same degree as PD-L1-specific antibody therapy, and combination treatment almost stopped tumor outgrowth. A human study demonstrated that patients with melanoma who were responders to anti-PD-1 immunotherapy had a higher alpha diversity of fecal microbiota and higher relative abundance of Ruminococcaceae than non-responders. Besides, reconstitution of germ-free mice with fecal material from responding patients could lead to improved tumor control, augmented T cell responses, and greater efficacy of anti-PD-L1 therapy.

Concurrent administration of antibiotics or early exposure during immunotherapy can have controversial impacts on tumor response and survival in patients with advanced HCC, thus underscoring the role of gut dysbiosis in HCC immunotherapy. The association between gut microbiota and HCC immunotherapy was preliminarily reported in a small case series with only three responders and five non-responders to anti-PD-L1 treatment. Our previous study with 10 ICI responders failed to reveal a positive association of gut microbiota with the response to ICI. In this study, we recruited 20 ICI responders and 21 non-responders for analysis, and a significant pretreatment microbial dissimilarity was observed between patients with OR and patients with PD. Furthermore, a preferable fecal signature with Lachnospiracidium enrichment and Prevotella 9 depletion was identified and validated to predict better survival benefits.

Lachnospiracidium belongs to family Lachnospiraceae and is highly homologous to Ruminococcus gnavus. The anti-inflammatory potential of Lachnospiracidium has been reported, but its role in tumor control has not been clarified. In addition, the benefits of Lachnospiraceae and Ruminococcaceae are well known in patients with chronic liver diseases and cirrhotic complications. In patients with HCC, decreased fecal levels of Lachnospiraceae and Ruminococcaceae were observed, whereas enrichment of Ruminococcaceae was found in three ICI-responding cases. Prevotella is genetically diverse between species, and many studies have linked increases in its abundance to inflammatory disorders, including chronic liver inflammation. The alterations of Lachnospiracidium and Prevotella 9 in HCC may affect inflammatory processes and are associated with tumor response to ICI treatment.

Maintenance of BA homeostasis is essential for the protection of the liver reserve. Accumulating evidence indicates that alterations in BAs, which are regulated by the gut microbiota, can affect hepatic metabolic homeostasis and contribute to the pathogenesis of liver cancer. Lithocholic acid is a secondary BA derived from the dehydroxylation of chenodeoxycholic acid (CDCA). It is toxic to hepatocytes and increases the risk of developing hepatic neoplasms. In contrast, UDCA, which is produced by epimerization of CDCA, is thought to be chemopreventive, and dietary supplementation with UDCA was reported to reduce experimentally induced hepatic carcinogenesis in rats. In this study, the fecal concentration of UDCA was significantly higher in ICI responders compared with non-responders to immuno-therapy, whereas the fecal concentration of lithocholic acid was increased in patients with PD. Besides, a strong positive correlation between UDCA and fecal abundance of Lachnospiracidium was observed. Clostridium scindens belongs to the genus Lachnospiracidium, and is known to convert CDCA to UDCA by oxidation and epimerization of specific hydroxy groups; it may explain our findings in correlation analysis.

SCFAs, especially butyrate, are important for regulating gene expression, inflammation, differentiation, and apoptosis of host cells. They might be involved in the development of HCC. However, no significant association could be identified between fecal SCFAs and the treatment response of HCC to ICI treatment in this study.
## Table 2  Factors associated with overall survival in patients with HCC treated with immune checkpoint inhibitors

| Factor                          | Univariate | Multivariate (model 1)* | Multivariate (model 2)† |
|---------------------------------|------------|-------------------------|-------------------------|
|                                | HR 95% CI  | P value                 | HR 95% CI               | P value |
| Age, years >60 vs ≤60          | 0.643      | 0.242 to 1.706          | 0.375                   | NA      |
| Sex Male vs female             | 1.313      | 0.299 to 5.770          | 0.718                   | NA      |
| HBsAg-positive Yes vs no       | 1.152      | 0.404 to 3.286          | 0.791                   | NA      |
| Anti-HCV-positive Yes vs no    | 0.593      | 0.168 to 2.085          | 0.415                   | NA      |
| Tumor size, cm >7 vs ≤7        | 2.121      | 0.792 to 5.674          | 0.134                   | NA      |
| Tumor number Multiple vs single| 24.183     | 0.027 to 2310.445       | 0.357                   | NA      |
| Tumor/Liver volume >50% vs ≤50%| 2.974      | 1.067 to 8.293          | 0.037                   | 0.916   | 0.877   | 0.221 to 3.481 | 0.852 |
| Portal vein invasion Yes vs no | 2.663      | 0.979 to 7.238          | 0.055                   | 1.254   | 0.375 to 4.197 | 0.999 |
| Extrahepatic metastasis Yes vs no| 1.042    | 0.394 to 2.753          | 0.934                   | NA      | NA      |
| BCLC stage Stage C vs B        | 1.274      | 0.447 to 3.630          | 0.650                   | NA      | NA      |
| AFP, ng/mL >400 vs ≤400        | 1.667      | 0.638 to 4.357          | 0.297                   | NA      | NA      |
| NLR >2.5 vs ≤2.5               | 2.233      | 0.719 to 6.933          | 0.165                   | NA      | NA      |
| Prothrombin time, INR >1.2 vs ≤1.2| 1.268    | 0.464 to 3.461          | 0.644                   | NA      | NA      |
| Platelet count >100K vs ≤100K  | 0.722      | 0.254 to 2.053          | 0.541                   | NA      | NA      |
| ALT, U/L >40 vs ≤40            | 1.825      | 0.699 to 4.766          | 0.220                   | NA      | NA      |
| AST, U/L >40 vs ≤40            | 10.423     | 1.377 – 78/908          | 0.023                   | 5.168   | 0.528 to 50.533 | 0.158 |
| Child-Pugh class Class B vs A  | 2.950      | 1.027 to 8.473          | 0.044                   | 1.238   | 0.345 to 4.443 | 0.774 |
| ALBI grade Grade 2, 3 vs 1     | 2.062      | 0.715 to 5.946          | 0.181                   | NA      | 1.490   | 0.380 to 5.841 | 0.567 |
| Prior sorafenib treatment Yes vs no| 0.841    | 0.324 to 2.185          | 0.722                   | NA      | NA      |
| Combined treatment† Yes vs no  | 0.778      | 0.288 to 2.102          | 0.621                   | NA      | NA      |

*Model 1 enrolled parameters with p value<0.2 in univariate analysis into multivariate analysis, except ascites and ALBI grade.
†Model 2 enrolled parameters with p value<0.2 in univariate analysis into multivariate analysis, except Child-Pugh class.
‡Combined treatment: combined immune checkpoint inhibitors with tyrosine kinase inhibitors, including sorafenib, lenvatinib, and regorafenib.
§Intermediate abundance of *Lachnoclostridium* and *Prevotella* 9: either both low abundance of these two taxa or both high abundance.
AEs, adverse events; AFP, alpha fetoprotein; ALBI grade, albumin-bilirubin grade; ALT(S)T, alanine(aspartate) aminotransferase; BCLC stage, Barcelona-Clinic liver cancer stage; HBsAg, hepatitis B virus surface antigen; HCV, hepatitis C; ICI, immune checkpoint inhibitor; INR, international normalized ratio; NA, not adopted; NLR, neutrophil-lymphocyte ratio; UDCA, ursodeoxycholic acid.
ICI combinations can provide a higher tumor response rate and better survival and may be a potential bias in this microbiota study.\(^5\)\(^6\) However, the pattern of the microbial dissimilarity and the compositions of gut microbiota between responders and non-responders to ICI mono-therapy remained the same. Combination treatment was not a significant factor associated with survival in the studied cohort. Besides, prior experience of TKI did not have significant confounding effects on microbial composition and fecal bile acids in our patients. In addition, the line of systemic treatment was not a significant factor to OS.

There are several limitations in this study. First, we could not determine the causal relationship between differential bacteria or metabolite and tumor outcomes. The mechanistic associations between \textit{Lachnoclostridium} and secondary bile acids also need to be investigated in vitro. Second, dynamic investigations of gut microbiota or metabolites were not performed. However, our previous study showed that the composition of gut microbiota remained unchanged between paired fecal samples of the same patient collected at baseline and 8 weeks post-ICI treatment, thus indicating that ICI treatment would not alter the features of gut microbiome, and the effects of microbial changes might be less prominent on the treatment outcomes.\(^33\) Third, atezolizumab plus bevacizumab is currently the recommended first-line systemic therapy for uHCC. Whether our findings could be applied to predict the response to atezolizumab plus bevacizumab requires further exploration. Fourth, not all patients had paired peripheral blood mononuclear cells or biopsy samples before and after ICI treatment to identify ICI-induced immune changes correlated with the identified microbes or bile acids in our cohort. This would be an important study in the future. Fifth, most of the studied patients were viral-related HCC; whether these findings could be generalized to non-viral HCC patients on ICI therapy requires further study.\(^50\)

In conclusion, the gut microbiome and fecal bile acids were associated with treatment response to ICIs in patients with uHCC. A preferable signature of fecal microbiota could independently predict the survival benefits of these patients. These findings highlight a potential therapeutic strategy to improve treatment outcomes of ICI-treated HCC by modifying the gut microbiota and metabolites.

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Figure 5: Progression-free survival and overall survivals of patients in validation. Progression-free survival and overall survival depended on the relative abundance of (A, D) fecal \textit{Prevotella 9}; (B, E) fecal \textit{Lachnoclostridium}; and (C, F) signature of combined these two taxa.
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