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ORIGINAL ARTICLE

GALAD demonstrates high sensitivity for HCC surveillance in a cohort of patients with cirrhosis

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Abstract

Background and Aims: Most patients with HCC are diagnosed at a late stage, highlighting the need for more accurate surveillance tests. Although biomarkers for HCC early detection have promising data in Phase 2 case–control studies, evaluation in cohort studies is critical prior to adoption in practice. We leveraged a prospective cohort of patients with Child-Pugh A or B cirrhosis who were followed until incident HCC, liver transplantation, death, or loss to follow-up. We used a prospective specimen collection, retrospective, blinded evaluation design for biomarker evaluation of GALAD (gender × age × log alpha-fetoprotein [AFP] × des-gamma-carboxy prothrombin), longitudinal GALAD, and the HCC Early Detection Screening (HES) algorithm—compared to AFP—using patient-level sensitivity and screening-level specificity.

Approach and Results: Of 397 patients with cirrhosis, 42 developed HCC (57.1% early stage) over a median of 2.0 years. Longitudinal GALAD had the highest c-statistic for HCC detection (0.85; 95% CI, 0.77–0.92) compared to single–time point GALAD (0.79; 95% CI, 0.71–0.87), AFP (0.77; 95% CI, 0.69–0.85), and HES (0.76; 95% CI, 0.67–0.83). When specificity was fixed at 90%, the sensitivity for HCC of single–time point and longitudinal GALAD was 54.8% and 66.7%, respectively, compared to 40.5% for AFP. Sensitivity for HCC detection was higher when restricted to patients with biomarker assessment within 6 months prior to HCC diagnosis, with the highest sensitivities observed for single–time point GALAD (72.0%) and longitudinal GALAD (64.0%), respectively. Sensitivity of single–time point and longitudinal GALAD for early-stage HCC was 53.8% and 69.2%, respectively.

Conclusion: GALAD demonstrated high sensitivity for HCC detection in a cohort of patients with cirrhosis. Validation of these results is warranted in large Phase 3 data sets.

Abbreviations: AFP, alpha-fetoprotein; AUROC, area under the receiver operating characteristic curve; BCLC, Barcelona Clinic Liver Cancer; DCP, des-gamma-carboxy prothrombin; EDRN, Early Detection Research Network; HES, HCC Early Detection Screening; PEB, parametric empirical Bayes.

INTRODUCTION

HCC is the fastest-increasing cause of cancer-related death in the United States and one of the leading causes of death in patients with compensated cirrhosis.[1] However, prognosis is driven by tumor stage, with curative options available if patients are detected at an early stage, affording long-term survival.[2,3] In contrast, patients detected with more advanced tumor burden are only eligible for palliative therapies and have a median survival of 1–2 years. The close association between early detection and improved survival underlies the recommendation of HCC surveillance in patients with cirrhosis by multiple professional societies.[4,5]

HCC surveillance is performed using semiannual abdominal ultrasound, with or without alpha-fetoprotein (AFP); however, data have shown that these tests typically have a sensitivity of only 60% for early-stage HCC detection.[6] Further, poor ultrasound performance may be increasingly problematic as the epidemiology of cirrhosis changes given inadequate ultrasound visualization in patients with obesity and NAFLD.[7,8] This poor performance can also lead to increased risk of screening-related harms due to false-positive or indeterminate screening results.[9,10] Finally, the dependence on ultrasound-based surveillance often requires patients to come in for separate radiology appointments, which can drive underuse of HCC surveillance in clinical practice.[11,12] Overall, these limitations highlight the need for more effective HCC surveillance tests, which can increase early HCC detection.

Several serum-based biomarkers and biomarker panels have promising data suggesting high sensitivity and specificity for HCC in patients with cirrhosis.[13] AFP remains the only serum biomarker to undergo all five phases of biomarker validation for HCC surveillance[14]; however, single biomarkers have suboptimal performance for early HCC detection, likely related to tumor heterogeneity. More recent algorithms, such as GALAD (gender × age × log AFP × des-gamma-carboxy prothrombin [DCP]) and HCC Early Detection Screening (HES), combine multiple biomarkers, with or without demographic and clinical features, and have achieved higher sensitivity for early HCC detection, exceeding 70%; however, prior data are largely limited to Phase 2 case–control studies, which can overestimate biomarker performance.[13] An expert panel guidance document from the International Liver Cancer Association recently stressed the critical importance of longitudinal cohort studies (Phase 3 validation) to determine if biomarkers can detect cancer early before it becomes clinically evident; however, this has been limited by a dearth of cohorts with available clinical samples.[14] Further, most prior Phase 2 studies have evaluated a single biomarker or biomarker panel, and there are few data comparing several HCC early detection biomarkers in a single cohort. Finally, recent data suggest that incorporation of longitudinal data may improve biomarker performance by identifying earlier increases in biomarker values suggesting early-stage HCC as well as reducing the risk of false-positive results; however, most data evaluate biomarkers at a single time point (i.e., single threshold).[15] Therefore, the aim of our study was to compare multiple biomarkers—including single-threshold AFP, AFP-L3%, DCP, the HES algorithm, single-threshold GALAD, and longitudinal GALAD—in a longitudinal cohort of patients with cirrhosis.

PATIENTS AND METHODS

Study population

We leveraged a previously described cohort of patients with cirrhosis from the University of Michigan who were enrolled into a surveillance program between January 2004 and September 2006.[16] In brief, all patients had Child-Pugh A or B cirrhosis, without known HCC or suspicious liver lesions, at enrollment. Cirrhosis was defined based on compatible histology or imaging showing a cirrhotic-appearing liver with signs of portal hypertension. Other exclusion criteria included significant hepatic decompensation (refractory ascites, Grade 3–4 encephalopathy, or hepatorenal syndrome), comorbid medical conditions with a life expectancy of less than 1 year, prior solid organ transplant, and known extrahepatic primary tumor.

Patients were prospectively followed with semiannual ultrasound-based HCC surveillance until incident HCC, liver transplantation, death, or loss to follow-up. HCC was defined using American Association for the Study of Liver Diseases criteria, i.e., histology or characteristic imaging in lesions ≥1 cm; and early-stage HCC was defined as Barcelona Clinic Liver Cancer (BCLC) stage 0 or A. The Social Security Death File and the State of Michigan Death Records were used to ascertain date of death for any patients lost to follow-up. Patients were not directly involved in the design, conduct, or reporting of the research. The study was approved by institutional review boards at the University of Michigan (HUM00046376) and the University of Texas Southwestern Medical Center (STU 082017-013). All patients provided informed consent at cohort inclusion, although a waiver of consent was provided for retrospective analysis of the stored samples.

Data and blood collection

Demographic and clinical data were collected at enrollment, including age, gender, race/ethnicity, liver disease etiology, and Child-Pugh score. Liver disease

etiology was classified as HCV-related (presence of HCV antibody or RNA), HBV-related (presence of HBsAg), alcohol-associated (alcohol intake >40 g/day for >10 years), NASH (absence of other etiologies with metabolic syndrome), other (e.g., hereditary hemochromatosis, primary sclerosing cholangitis, primary biliary cirrhosis), or cryptogenic. Serum and plasma were collected from all patients at each visit and stored at −80°C, without interval thawing.

Biomarker evaluation

Biomarker evaluation was performed using a prospective specimen collection, retrospective, blinded evaluation design.[17] For this study, biomarkers were evaluated at multiple time points during follow-up, so we were able to evaluate algorithms that incorporate serial biomarker measurements into the screening decision. We compared these algorithms to approaches that only consider biomarker levels measured at a single visit in screening decisions.

Serum from each visit for cases and controls was transferred to Wako Diagnostics lab for AFP, AFP-L3, and DCP measurements.[18] AFP, AFP-L3%, and DCP were performed using a microchip capillary electrophoresis and liquid-phase binding assay on a μTASWako i30 auto analyzer (Wako Pure Chemical Industries, Ltd., Osaka, Japan). For this study, we evaluated highly sensitive AFP-L3, which can be measured at lower AFP levels and lower AFP-L3 percentages than the older AFP-L3 assay.[19] All assays were performed blinded to HCC versus non-HCC status.

AFP, AFP-L3, and DCP were assessed based on the biomarker levels at each single visit.

HES is an AFP-adjusted algorithm that combines current AFP and change in AFP over the last year with age, platelets, alanine aminotransferase, and interaction terms.[20,21] The algorithm was recently updated to include etiology of cirrhosis, and this version was used for this analysis.[21]

GALAD was calculated at each time point using the following equation: Z = −10.08 + (0.09 × age) + (1.67 × male sex) + (2.34 × log AFP) + (0.04 × AFP-L3) + (1.33 × log DCP).[22] In addition, we used the parametric empirical Bayes (PEB) algorithm to evaluate longitudinal GALAD where a personalized threshold that incorporates GALAD screening history was used for every patient at each screening occasion.[15,23] In this analysis, a weighted average of mean GALAD in the non-HCC population and an average of prior GALAD values for each patient define a patient-specific threshold for defining an abnormal screening result. If a patient has no screening history, the longitudinal and single-threshold rules are equivalent; however, longitudinal GALAD depends more on screening history as an individual accumulates more screening tests.

Statistical analysis

We evaluated single–time point biomarkers and longitudinal biomarkers using the entire cohort (Figure S1). To incorporate longitudinal screening history for GALAD, we used the PEB estimate, a weighted average of mean biomarker values in the non-HCC population and an average of prior biomarker values for each patient to obtain a subject-specific threshold.[23] Parameters of the PEB model were estimated using only data from patients without HCC to define the control population mean. In those without prior results, the PEB algorithm reduces to a standard fixed threshold approach, while for those with prior results, the PEB algorithm depends more on the history as the individual accumulates more results.

Biomarker performance was evaluated using three complementary measures: (1) area under the receiver operating characteristic curve (AUROC), (2) sensitivity (i.e., patient-level true-positive rate) and screening-level specificity (1 – false positive rate) at established cutoffs from prior literature, and (3) sensitivity at a cutoff fixing screening-level specificity at 90%. Specificity was assessed at the screening level because each false positive can lead to diagnostic evaluation resulting in physical, financial, and psychological harms. We estimated sensitivity at the patient level, so this was defined as the proportion of HCC cases with at least one positive screening during the prediagnostic period. The prediagnostic period was also separated into two windows (0–6 months and 7–12 months) prior to HCC diagnosis. Our primary outcome was any-stage HCC detection, and a secondary outcome was early-stage HCC detection. To calculate 95% CIs for biomarker performance, we used a bootstrap procedure among 2000 data sets, each of which was constructed by randomly sampling patients with replacement. All analyses were conducted using R, version 4.0.3.

RESULTS

Patient characteristics

Of 397 eligible patients with cirrhosis, 42 developed HCC over a median follow-up of 2.0 years (interquartile range 0.5–4.25 years). Patient characteristics are detailed in Table 1. Median age of the cohort was 52.0 years, 59.9% were male, and the majority (>90%) were non-Hispanic White. The most common etiologies of liver disease were hepatitis C infection (47.4%), alcohol-associated liver disease (15.4%), and NAFLD (19.6%). Median Child-Pugh score was 7, with 40.1% having Child-Pugh A cirrhosis and 55.2% Child-Pugh B cirrhosis. Of the 42 patients who developed HCC, 57.1% had BCLC stage 0/A HCC, with the majority (59.5%) having unifocal HCC and a median tumor size of 2.4

cm. Patients had a median of 3 (range 1–9) longitudinal visits in the analysis data set for biomarker evaluation.

Biomarker performance

Overall discrimination

The overall accuracy for each biomarker at any time prior to diagnosis is illustrated in Figure 1A. DCP and HES had the lowest AUROCs (0.71 and 0.76, respectively), single–time point GALAD had an AUROC of 0.79, and longitudinal GALAD had the highest AUC of 0.85, although these differences were not statistically significant. When considering performance for early-stage HCC, similar results were seen, with DCP and HES continuing to have the lowest AUROCs (0.70–0.71), single–time point GALAD having an intermediate AUROC (0.78), and longitudinal GALAD having the highest AUROC (0.83) (Figure 1B).

Accuracy using established cutoffs

The performance for each biomarker using previously reported cutoffs is shown in Table 2. AFP, DCP, and HES each had sensitivity <50% for any-stage and early-stage HCC but maintained specificity around 90%. Higher sensitivity was observed with AFP-L3% (66.7%; 95% CI, 52.0–81.3%) and single–time point GALAD (57.1%; 95% CI, 41.9–72.4%), although AFP-L3% had lower specificity than GALAD (82.7% vs. 86.5%). Both AFP-L3% and GALAD had lower specificity than AFP, DCP, and HES. Subgroup analyses, stratified by sex, liver disease etiology, and Child-Pugh score, are described in Table S1. Sensitivity of both AFP-L3% and GALAD notably improved when restricted to results within 6 months of HCC diagnosis, with both demonstrating a sensitivity of 73.7% (95% CI, 52.6%–93.3%) for early-stage HCC.

Accuracy with specificity at 90%

We next explored biomarker thresholds that correspond to an acceptable threshold of 90% for screening-level specificity in our cohort. A higher threshold of −0.33 (compared to the previously reported threshold of −0.63) was identified for single–time point GALAD, whereas estimated thresholds for other biomarkers were comparable to previously published thresholds (AFP, 17.4 ng/mL vs. 20 ng/mL; AFP-L3, 11.9% vs. 10%; DCP, 5.0 ng/mL vs. 7.5 ng/mL). At these cutoffs AFP, DCP, AFP-L3%, and HES each had sensitivity <50% for any-stage HCC, whereas the highest sensitivity was observed with single–time point GALAD (54.8%; 95% CI, 39.5%–70.2%) and longitudinal GALAD (66.7%; 95% CI, 51.3%–80.8%) (Table 3). DCP, AFP-L3%, and HES also had the lowest sensitivity for early-stage HCC detection, with each demonstrating lower sensitivity than that of AFP (50.0%; 95% CI, 28.0%–69.0%). Single–time point GALAD had a sensitivity of 53.8% (95% CI, 33.3%–73.3%) for early HCC detection, although this was higher at 73.7% (95% CI, 52.0%–93.3%) when restricted to results within 6 months of HCC diagnosis. Longitudinal GALAD appeared to have preserved high sensitivity for early HCC detection, exceeding 65%, independent of time frame.

DISCUSSION

Abdominal ultrasound with or without AFP has served as the backbone of HCC surveillance testing for over two decades. Increasing data demonstrating suboptimal sensitivity for early HCC detection highlight the importance of surveillance strategies. Our study extends prior literature by evaluating several biomarkers in a cohort of patients with cirrhosis, serving as a transition from Phase 2 to pilot Phase 3 biomarker evaluation. Our results highlight the need to improve upon AFP's performance given sensitivity of only 50% for early-stage HCC detection. We found that other single-biomarker strategies, such as AFP-L3% and DCP, also fail to achieve sufficient sensitivity, and the highest sensitivity was observed with biomarker panels. Our results demonstrate that GALAD is a promising biomarker panel, with high sensitivity for early HCC detection—whether used in a single–time point or a longitudinal manner. However, we show that GALAD thresholds may require further adjustments when validated in larger longitudinal cohorts to optimize performance.

GALAD incorporates three biomarkers (AFP, AFP-L3%, and DCP) and has demonstrated promising accuracy in several case–control studies—higher than each of the biomarkers alone.[22,24,25] GALAD also incorporates two demographic risk factors for HCC—gender and age—which are readily available and increase performance compared to biomarkers alone. The increased accuracy of a panel including several biomarkers, compared to a single biomarker, is not surprising given the observed heterogeneity of HCC.[26,27] For example, GALAD, at a cutoff of −0.63, had a sensitivity and specificity of 79% each for early HCC detection in the multicenter Early Detection Research Network (EDRN) case–control data set from the United States.[26] Similarly, GALAD demonstrated sensitivity and specificity exceeding 80% for early HCC detection in a multinational study including over 6500 patients from the United Kingdom, Germany, Japan, and Hong Kong.[27] Model performance of GALAD in this study did not appear to significantly differ between patients with viral and nonviral etiologies of liver disease. GALAD was also shown to have high test performance

TABLE 1 Patient Characteristics

Characteristic	Patients without HCC (*n* = 355)	Patients who developed HCC (*n* = 42)	*p**
Age	52.0 (23.0–82.0)	53.5 (42.0–67.0)	0.32
Sex (% male)	208 (58.6%)	30 (71.4%)	0.13
Race/ethnicity (%)			0.27
Non-Hispanic White	324 (91.3)	36 (85.7)	
Non-Hispanic Black	8 (2.3)	2 (4.8)	
Hispanic White	7 (2.0)	2 (4.8)	
Asian	4(1.1)	1 (2.4)	
Other/unknown	12 (3.4)	1 (2.4)	
Etiology of liver disease (%)			0.83
Hepatitis C	164 (46.2%)	24 (57.1%)	
Alcohol-associated	55 (15.5%)	6 (14.3%)	
NASH/cryptogenic	71 (20.0%)	7 (16.7%)	
Hepatitis B	16 (4.5%)	1 (2.4%)	
Other	49 (13.8%)	4 (9.5%)	
Child-Pugh Class (% Child A)	145 (40.8%)	14 (33.3%)	0.41
MELD	9 (6–17)	10 (6- 17)	0.32
Number of HCC lesions			N/A
1	N/A	25 (59.5%)	
2		11 (26.2%)	
3		2 (4.8%)	
>3		4 (9.5%)	
Maximum HCC diameter (cm)	N/A	2.4 (0.5–6.0)	N/A
Vascular invasion	N/A	9 (21.4%)	N/A
Extrahepatic metastases	N/A	0 (0%)	N/A
BCLC stage			N/A
0/A	N/A	24 (57.1%)	
B		8 (19.0%)	
C		2 (4.8%)	
D		8 (19.0%)	
BMI	28.9 [17.4, 68.6]	28.6 (20.4–50.5)	0.32
Diabetes	82 (23.1%)	7 (16.7%)	0.44
Presence of ascites	211 (59.4%)	28 (66.7%)	0.41
Presence of HE	114 (32.1%)	17 (40.5%)	0.30
Presence of esophageal varices	208 (58.6%)	28 (66.7%)	0.41

*Wilcoxon rank-sum tests were used to compare continuous variables and Fisher's exact test was used to compare categorical variables.

Abbreviations: BMI, body mass index; MELD, Model for End-Stage Liver Disease; N/A, not available.

in a multisite case–control study among patients with NASH-related HCC.[28] However, case–control studies can overestimate biomarker performance, highlighting the importance of cohort studies to evaluate the performance of a biomarker in detecting preclinical disease. In this cohort study, GALAD achieved a sensitivity of 70% for HCC detection when assessed within 6 months of HCC diagnosis. This performance compares favorably to the performance of ultrasound, which has a sensitivity of <50% for early HCC detection—both as assessed in a systematic review of the literature and as reported in the original description of this cohort.[6,16] A single-center study from Mayo Clinic suggested that GALAD may be complementary to ultrasound, with an AUC of 0.97 compared to 0.92 and 0.82 for GALAD and ultrasound alone, respectively[26]; however, this strategy would still require patients to attend both ultrasound and phlebotomy visits. Our results suggest that biomarkers with sufficiently high sensitivity in larger cohorts may instead supplant imaging-based surveillance.

Our work extends this prior literature by demonstrating that single–time point GALAD, as evaluated in prior

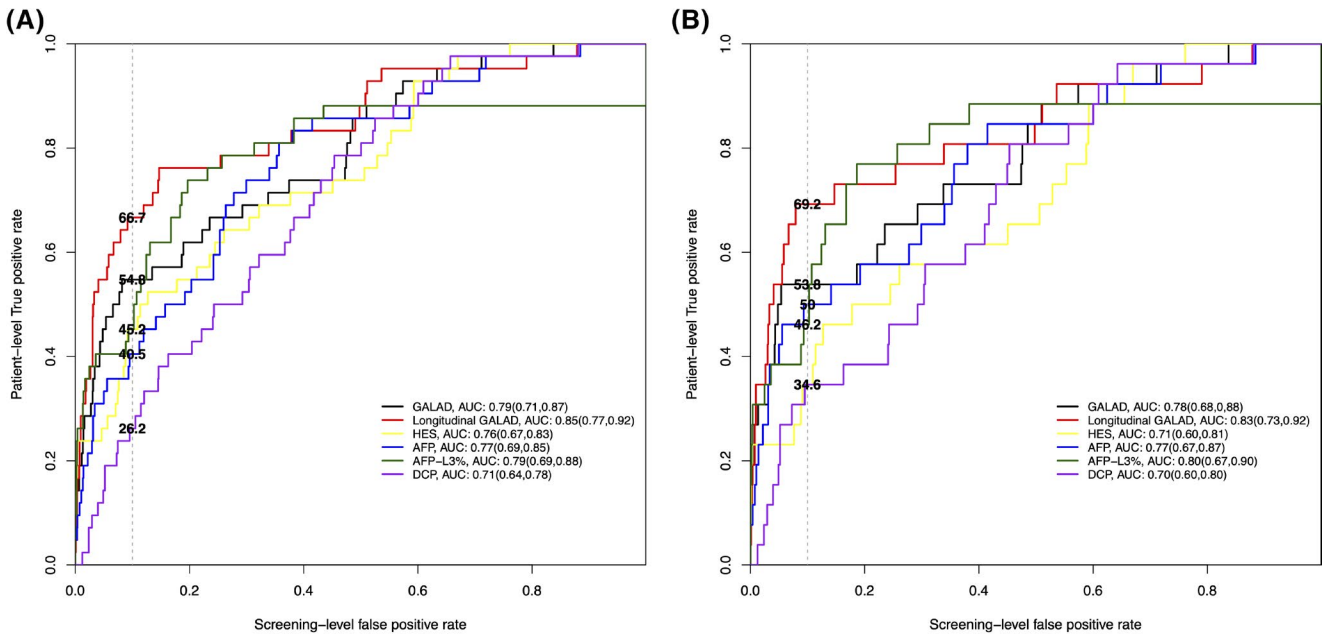

FIGURE 1 (A) Receiver operating characteristic curves where patient-level true positive rate is estimated based on positive screens any time prior to HCC diagnosis in the overall cohort. (B) Receiver operating characteristic curves where patient-level true positive rate is estimated based on positive screens any time prior to early-stage HCC diagnosis.

TABLE 2 Biomarker performance (and 95% bootstrap CIs) using established thresholds

		Any stage HCC		Early-stage HCC	
		Any time prior to HCC	0–6 months prior to HCC	Any time prior to HCC	0–6 months prior to HCC
GALAD (−0.63)	Patient-level sensitivity	57.1 (41.9–72.4)	72.0 (53.8–89.3)	53.8 (33.3–73.3)	73.7 (52.6–93.3)
	Screening-level specificity	86.5 (83.0–89.9)			
HES algorithm (10.17)	Patient-level sensitivity	45.2 (30.4–60.0)	44.0 (23.8–62.5)	34.6 (15.4–54.2)	42.1 (19.0–66.7)
	Screening-level specificity	90.5(87.7–93.1)			
AFP 20 ng/mL	Patient-level sensitivity	35.7 (21.7–51.4)	48.0 (28.0–68.8)	46.2 (26.1–65.4)	57.9 (33.3–80.0)
	Screening-level specificity	91.7 (88.9–94.3)			
AFP-L3% 10%	Patient-level sensitivity	66.7 (52.0–81.3)	72.0 (52.4–88.9)	73.1 (54.2–88.9)	73.7 (52.4–93.3)
	Screening-level specificity	82.7 (78.5–86.5)			
DCP 7.5 ng/mL	Patient-level sensitivity	23.8 (11.6–37.5)	20.0 (5.0–37.5)	30.8 (13.6–50.0)	26.3 (6.7–48.5)
	Screening-level specificity	92.3 (89.8–94.6)			

studies, has high sensitivity when conducted within 6 months of HCC diagnosis, although its sensitivity is lower at earlier time points. This limitation may be partly addressed by incorporating longitudinal changes in GALAD measurements over time, which demonstrated more consistent sensitivity to detect preclinical disease over longer periods of time prior to HCC diagnosis. Incorporation of PEB longitudinal analysis was previously shown to significantly increase sensitivity of AFP for HCC detection in a secondary analysis of the Hepatitis C Antiviral Long-Term Treatment Against Cirrhosis trial.[29] Similarly, a pilot study of a small Japanese cohort suggested that GALAD scores may increase approximately 1.5 years before HCC diagnosis.[28] Notably, longitudinal measures of a single biomarker, such as that evaluated by the HES algorithm, did not achieve similar early HCC detection in our cohort as longitudinal changes in multiple biomarkers, as evaluated by longitudinal GALAD.

HCC surveillance effectiveness is driven by both test accuracy as well as use.[30] Several studies have shown that ultrasound is operator-dependent, with large site-to-site variation in quality and test performance.[6,31] Biomarker-based surveillance may offer a path to standardize test performance across sites. Further, ultrasound-based surveillance is underused in clinical practice due to both patient-level and provider-level barriers, with only one fourth of patients with cirrhosis

TABLE 3 Biomarker true positive rate (and 95% CI) with screening-level false positive rate fixed at 10%

	Any stage HCC			Early-stage HCC		
	Any time prior to HCC	0–6 months prior to HCC	7–12 months prior to HCC diagnosis	Any time prior to HCC	0–6 months prior to HCC	7–12 months prior to HCC diagnosis
GALAD (−0.33)	54.8 (39.5–70.2)	72.0 (52.6–88.9)	50.0 (23.1–73.7)	53.8 (33.3–73.3)	73.7 (52.0–93.3)	44.4 (10.0–80.0)
Longitudinal GALAD	66.7 (51.3–80.8)	64.0 (42.9–83.3)	62.5 (35.3–85.7)	69.2 (50.0–86.4)	68.4 (44.4–88.9)	66.7 (28.6–100.0)
HES algorithm 10.05	45.2 (26.1–62.1)	44.0 (21.1–62.5)	43.8 (20.0–72.2)	34.6 (14.3–56.5)	42.1 (18.2–66.7)	22.2 (0–60.0)
AFP 17.4 ng/mL	40.5 (24.2–57.1)	52.0 (30.4–75.0)	18.8 (0.0–42.9)	50.0 (28.0–69.0)	63.2 (35.3–85.7)	22.2 (0–57.1)
AFP-L3% 11.9%	45.2 (30.2–68.8)	43.8 (33.3–80.8)	43.8 (21.0–72.7)	46.2 (25.0–73.5)	33.3 (25.0–82.4)	33.3 (0–75.0)
DCP 5.9 ng/mL	26.2 (13.0–42.9)	20.0 (5.0–38.1)	37.5 (13.3–64.3)	34.6 (15.4–52.6)	26.3 (6.7–48.5)	55.6 (14.3–87.5)

undergoing surveillance.[12,32,33] For example, patients report transportation, financial, and logistical barriers to surveillance, which translate into lower adherence with surveillance recommendations.[12] These barriers appear to be particularly problematic among racial/ethnic minority and socioeconomically disadvantaged patients, which are also the populations disproportionately impacted by HCC. Blood-based biomarkers have the advantage of being easy to implement in practice, across all types of clinical settings, as they can be checked with routine labs at the time of a clinic visit. Patients also appear to prefer biomarker-based surveillance to ultrasound, if it can achieve adequate sensitivity for early-stage HCC detection.[34] Therefore, a blood-based biomarker could improve surveillance effectiveness even if it has similar sensitivity for early HCC detection as ultrasound-based surveillance.

While our results are encouraging for biomarker-based surveillance, the limited number of incident HCCs resulted in wide CIs and hence preclude us from making statements about statistically significant improvements. Similarly, the potential performance of longitudinal GALAD may have been underestimated in this study given the relatively short duration of follow-up compared to larger Phase 3 studies such as the EDRN's HCC Early Detection Strategy (HEDS) and the Texas HCC Consortium. Our study's sample size also limited our ability to conduct meaningful subgroup analyses to see if biomarker performance differed by important factors such as sex and liver disease etiology. There are ongoing large Phase 3 HCC biomarker efforts including the EDRN HEDS and Texas HCC Consortium cohorts, which should allow further evaluation of early detection biomarkers in the near future.[35,36] We also acknowledge other limitations of our study, including the older nature of our cohort with a higher proportion of active hepatitis C infection than observed in contemporary cohorts. While all patients with HBV infection were on antiviral treatment, all but two patients without HCC but with HCV infection had active viremia. Notably, prior studies have not suggested any difference in performance of GALAD by liver disease etiology,[27] and we did not find any significant difference in performance by viral versus nonviral liver disease etiology. Finally, we leveraged a prospective cohort study including a standardized blood collection protocol; however, some patients did not have available samples at each time point. We feel these limitations are outweighed by the study's strengths including its prospective nature, comparison of several biomarkers in a single cohort, and incorporation of longitudinal biomarker assessments.

In summary, we found the GALAD has high sensitivity for early HCC detection and performs favorably compared to other surveillance biomarkers, particularly when used in a longitudinal manner. While further validation in larger Phase 3 biomarker cohorts and

Phase 4 studies assessing the benefit-to-harm ratio for biomarker-based surveillance is necessary, these results show the promise of blood-based biomarker panels for early detection of HCC, addressing a significant unmet need in HCC surveillance.

CONFLICT OF INTEREST

Dr. Singal consults for and received grants from Exact Sciences. He consults for Bayer, FujiFilm Wako Diagnostics, Roche, Glycotest, and GRAIL. Dr. Mehta consults for, received grants from, owns stock in, holds intellectual property rights with, and is employed by GlycoPath. He advises, received grants from, and holds intellectual property rights with Glycotest. He owns stock and holds intellectual property rights with N-Zyme Scientific. Dr. Marrero consults for Glycotest. Dr. Parikh received grants from Glycotest.

AUTHOR CONTRIBUTIONS

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.
Supplementary Material

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