

Investigating the Microbiota and Colorectal Cancer: The Importance of Community

Marc A Sze¹ and Patrick D Schloss^{1†}

† To whom correspondence should be addressed: pschloss@umich.edu

¹ Department of Microbiology and Immunology, University of Michigan, Ann Arbor, MI

Co-author e-mails:

- marcsze@med.umich.edu

Abstract

Background. An increasing body of literature suggests that there is a crucial role for the microbiota in colorectal cancer (CRC) pathogenesis. Important drivers within this context have ranged from individual microbes to the whole community. Our study expands on a recent meta-analysis investigating microbial biomarkers for CRC by testing the hypothesis that the bacterial community is an important driver of both early (adenoma) and late (carcinoma) stage of disease. To test this hypothesis we examined both feces (n = 1737) and tissue (492 total samples from 350 individuals) across 14 different studies.

Results. Fecal samples had a significant decrease from control to adenoma to carcinoma for both Shannon diversity and evenness (P-value < 0.05) after correcting for study effect and variable region sequenced. Only evenness for adenoma (P-value < 0.05) resulted in a slightly increased relative risk while lower Shannon diversity and evenness in fecal samples resulted in a significant increase in relative risk for carcinoma (P-value < 0.05). Previously associated colorectal cancer genera (*Fusobacterium*, *Parvimonas*, *Peptostreptococcus*, or *Porphyromonas*) followed a similar pattern with a significantly increased relative risk by their presence for carcinoma (P-value < 0.05) but not adenoma (P-value > 0.05) with the exception of *Porphyromonas* (P-value < 0.05). Using the whole community versus only CRC associated genera to build a prediction model resulted in higher classification success based on Area Under the Curve (AUC) for both adenoma and carcinoma using fecal and tissue samples. For the included studies, most were adequately powered for large effect size differences. This may be more amenable for carcinoma than for adenoma microbiota research due to the smaller community level changes observed in our results.

Conclusions. This data provides support for the importance of the bacterial community to both adenoma and carcinoma genesis. The evidence collected within this study on the role of the microbiota in CRC pathogenesis is much stronger for carcinoma than adenoma.

26 A strong reason for this may be in part due to the low power to detect more subtle changes
27 in the majority of studies that have been performed to date.

28 **Keywords**

29 microbiota; colorectal cancer; polyps; adenoma; meta-analysis.

Background

Colorectal cancer (CRC) is a growing world-wide health problem [1] in which the microbiota has been purported to play an active role in disease pathogenesis [2]. Numerous studies have shown the importance of both individual microbes [3–7] and the overall community [8–10] in polyp formation using mouse models of CRC. There have also been numerous case/control studies investigating the microbiota in the formation of both adenoma and carcinoma. Recently, a meta-analysis was published investigating whether specific biomarkers could be consistently identified using multiple data sets [11]. Many of the studies, along with the previous meta-analysis, focus on identifying biomarkers or individual microbes but do not critically investigate the role the community has in CRC.

Using both feces (n = 1737) and tissue (492 samples from 350 individuals) totalling over 2229 total samples across 14 studies [12–25] [Table 1 & 2], we expand both the breadth and scope of the previous meta-analysis to investigate whether the bacterial community is an important risk factor for both adenoma and carcinoma. To accomplish this we first assessed whether the diversity changes throughout disease (control to adenoma to carcinoma) and if it results in an increased relative risk (RR) for adenoma or carcinoma. Next, we assessed how typical CRC associated genera (*Fusobacterium*, *Parvimonas*, *Peptostreptococcus*, or *Porphyromonas*) affect the relative risk of adenoma or carcinoma. Third, using Random Forest models, we analyzed whether the full community or only the CRC associated genera resulted in better model classification based on the area under the curve (AUC). Since the changes in community were subtle for adenoma we also examined what effect size and sample size the studies that were used were adequately powered for.

Our analysis found a continuous decrease in Shannon diversity as disease became more severe which correlated with a significantly increased RR for carcinoma. Using only CRC-associated genera, the RR for carcinoma was higher relative to what was

55 observed for the Shannon diversity RR. Conversely, we demonstrate that the AUC of the
56 classification models increased when the full community was incorporated as opposed
57 to only CRC-associated genera. Although we analyzed data sets which sampled large
58 numbers of individuals, our results indicate the individual studies were underpowered for
59 detecting effect size differences of 10% or below between the case and control groups.

Results

Lower Community Diversity is Associated with Increased RR of Carcinomas: Using power transformed and Z-score normalized α -diversity metrics, both evenness and Shannon diversity in feces, but not tissue, were lower in those with carcinoma [Figure 1]. Using linear mixed-effect models to control for study and variable region, there was a significant decrease from control to adenoma to carcinoma for both evenness (P-value = 0.025) and Shannon diversity (P-value = 0.043). However, in tissue, this effect was not observed in tissue when resampling of the same individual was also controlled for (P-value > 0.05). Within fecal samples, a decrease in Shannon diversity and evenness resulted in a significantly increased RR for carcinoma (P-value = 0.01 and 0.0011, respectively) [Figure 2]. Although these values were significant, the effect size was relatively small for both metrics (Shannon RR = 1.31 and evenness RR = 1.34) [Figure 2]. Only a decrease in evenness had an increased RR for adenoma (P-value = 0.032) [Figure 2A & S1] but this effect size was even smaller than what was observed for carcinoma (RR = 1.16).

Using the Bray-Curtis distance metric, there was a significant difference across studies in the bacterial community of fecal samples between carcinoma and controls, but not adenoma and controls [Table S1 & S2]. For studies with unmatched tissue samples a similar trend was observed [Table S3 & S4] while studies with matched tissue samples had no differences [Table S3 & S4].

Carcinoma-Associated Genera Minimally Impacts RR of Adenoma: The majority of CRC-associated genera for both feces and tissue had a significantly increased RR for carcinoma but not for adenoma [Figure 3]. In fecal samples the RR due to CRC associated genera was greater than either the RR associated with evenness or Shannon diversity [Figure 2 & 3]. Additionally, the RR of carcinoma continuously increased as individuals tested positive for more CRC associated genera [Figure 3B & 3D]. The RR effect size was

greater for stool (RR range = 1.61 - 2.74) than for tissue (RR range = 1.21 - 1.81). This decrease may be explained by the fact that the tissue analysis included matched samples.

There were two significant measures for increased RR of adenoma when investigating CRC-associated genera in stool: 1) Having a higher than median value of *Porphyromonas* (P-value = 0.023) and 2) whether samples were positive for three CRC associated genera (P-value = 0.022) [Figure 3A]. With tissue, there were three significant measures for an increased RR of adenoma: 1) being positive for one CRC-associated genera (P-value = 0.032), 2) being positive for two CRC associated genera (P-value = 0.008), and 3) being positive for four CRC associated genera (P-value = 0.039) [Figure 3C].

Using the Whole Community Instead of Only CRC-Associated Genera Increases

Model AUC: For both fecal and tissue (matched and unmatched) samples, the AUC decreases when only OTUs from the CRC-associated genera are used [Figure 4 & 5]. This decrease is observed in both adenoma and carcinoma groups [Figure 4 & 5]. The genus models generally performed similar to the OTU-based models with the full genera models performing better than the CRC-associated genera models [Figure S2-S3]. Both genus models were similarly predictive in their ability to detect adenomas or carcinomas, with carcinoma having a higher AUC than adenoma [Figure S4-S5]. Of note, matched tissue samples for those with carcinoma had an AUC that was more similar to the adenoma models [Figure S4A, S5B, & S6] than carcinoma models [Figure S4B & S5A].

A Majority of Studies are Underpowered for Detecting Small Effect Size Differences:

When assessing the power of each study at different effect sizes the majority of studies for both adenoma and carcinoma have an 80% power to detect a 30% difference [Figure 6A & B]. No single study that was analyzed had the standard 80% power to detect an effect size difference that was equal to or below 10% [Figure 6A & B]. In order to achieve adequate power for small effect sizes, studies would need to recruit over 1000 individuals for each arm [Figure 6C].

Discussion

Our study identifies clear differences in diversity both at the community level and within individual genera that are present in individuals with CRC versus those without the disease. Although there was a step-wise decrease in diversity from control to adenoma to carcinoma, this did not translate into large effect sizes for the relative risk of either of these two conditions. Even though CRC-associated genera increase the RR of carcinoma, they do not consistently increase the relative risk of adenoma. This information suggests that these specific genera are important in carcinoma genesis but may not be the primary members of the microbial community contributing to the formation of an adenoma. Additionally, our data show that by using the whole community, our models perform better than when only the CRC-associated genera are included. CRC-associated genera are clearly important to carcinoma pathogenesis but accounting for the community in which these microbes exist can drastically increase the ability of models to make predictions. These observations suggest that small localized changes within the community may be occurring that are important in early disease progression of CRC and that this process may not directly involve CRC-associated genera.

The data presented herein supports the driver-passenger model of the microbial role in CRC, as summarized by Flynn [2], when applied to carcinoma but not necessarily adenoma. Both the drastically increased RR of CRC-associated genera versus diversity for carcinoma and increasing RR with more CRC-associated genera positivity are highly supportive of this model. It is also possible that in a driver-passenger scenario, simply having the driver present or only identifying the passenger is a good enough proxy that the event is occurring. This would account for the observation that there is no constant additive effect on RR for increasing positivity. Additionally, the initial establishment of the driver within the system appears to be dependent on the current community. This is supported by our finding that when adding the community context to our models in addition to the

CRC-associated genera, the model AUC increases.

With regards to carcinoma, our results support the driver-passenger model within the framework of the transition from adenoma to carcinoma. Conversely, using the present data, we can only theorize observations related to adenoma development fit this model. The changes that occur at this timepoint are small and possibly focal to the adenoma itself. The stepwise decrease in diversity suggests that the adenoma community is not normal but has changed subtly. Although there appears to be localized changes that do depend on the driver-passenger model, as supported by an increased RR for one, two, and four positive CRC-associated genera in tissue [Figure 3C], there may be other processes at play that ultimately exacerbate the condition from a subtle localized change to a change in the global community. The poor performance of the Random Forest models for classifying adenoma based only on the microbiota would suggest that this is the case. It is possible to hypothesize that at early stages of the disease, the host interacts with these subtle changes and catalyzes what ultimately leads to a thoroughly dysfunctional community.

Although there are still questions that need to be answered regarding the microbiota and carcinoma, a clearer framework for their relationship is beginning to develop as to how this occurs. From our observations many changes in carcinoma could easily result in effect sizes that are 30% or more between the case and control and most studies analyzed have sufficient power to detect these types of changes [Figure 6]. Conversely, the role of the microbiota in adenoma is less clear and part of the reason this may be is because many studies are not powered effectively to observe the small changes reported here. None of the studies analyzed were properly powered to detect a 10% or lower change between case and controls. This small effect size range may well be the scope in which differences consistently occur in adenoma due to the subtle changes in community that occur between control and adenoma. Future studies investigating adenoma and the microbiota need to take these factors into consideration if we are to work out the role of the microbiota in

163 adenoma formation.

164 **Conclusion**

165 By aggregating together a large collection of studies from both feces and tissue, we are
166 able to provide evidence in support of the importance of the bacterial community in both
167 adenoma and carcinoma. We are also able to provide support for the driver-passenger
168 model in the context of carcinoma. However, within the context of adenoma, it is less clear
169 that this relationship exists. These observations highlight the importance of power and
170 sample number considerations when undertaking investigations into the microbiota and
171 adenoma due to the subtle changes in the community. Although there are power limitations
172 associated with adenoma, this report highlights the strong influence the microbiota has on
173 CRC development.

Methods

Obtaining Data Sets: Studies used for this meta-analysis were identified through the review articles written by Keku, *et al.* and Vogtmann, *et al.* [26,27]. Additional studies not mentioned in the reviews were obtained based on the authors' knowledge of the literature. Studies that used tissue or feces as their sample source for 16S rRNA gene sequencing analysis were included. Studies using either 454 or Illumina sequencing technology were included. Only data sets that had sequences available for analysis were included. Some studies did not have publically available sequences or did not have metadata in which the authors were able to share. After these filtering steps, the following studies remained: Ahn, *et al.* [21], Baxter, *et al.* [24], Brim, *et al.* [17], Burns, *et al.* [22], Chen, *et al.* [14], Dejea, *et al.* [19], Flemer, *et al.* [13], Geng, *et al.* [25], Hale, *et al.* [12], Kostic, *et al.* [28], Lu, *et al.* [16], Sanapareddy, *et al.* [20], Wang, *et al.* [15], Weir, *et al.* [18], and Zeller, *et al.* [23]. The Zackular [29] study was not included because the 90 individuals analyzed within the study are contained within the larger Baxter study [24]. Additionally, after sequence processing all the case samples for the Kostic study only had 100 sequences remaining and was not used. This left a total of 14 studies for which analysis could be completed.

Data Set Breakdown: In total, there were seven studies with only fecal samples (Ahn, Baxter, Brim, Hale, Wang, Weir, and Zeller), five studies with only tissue samples (Burns, Dejea, Geng, Lu, Sanapareddy), and two studies with both fecal and tissue samples (Chen and Flemer). The total number of individuals that were analyzed after sequence processing for feces was 1737 [Table 1]. The total number of matched and unmatched tissue samples that were analyzed after sequence processing was 492 [Table 2].

Sequence Processing: For the majority of studies raw sequences were downloaded from the Sequence Read Archive (SRA) (<ftp://ftp-trace.ncbi.nih.gov/sra/sra-instant/reads/ByStudy/sra/SRP/>) and metadata was obtained from the by searching the respective

accession number of the study following website: <http://www.ncbi.nlm.nih.gov/Traces/study/>. Of the studies that did not have sequences and metadata on the SRA, data was obtained from DBGap for one study [21] and for four studies was obtained directly from the authors [12,13,18,20]. Each study was processed using the mothur (v1.39.3) software program [30]. Where possible, quality filtering utilized the default methods used in mothur for either 454 or Illumina based sequencing. If it was not possible to use these defaults, the stated quality cut-offs were used instead. Chimeras were identified and removed using VSEARCH [31] before *de novo* OTU clustering at 97% similarity using the OptiClust algorithm [32] was utilized.

Statistical Analysis: All statistical analysis after sequence processing utilized the R (v3.4.2) software package [33]. For the α -diversity analysis, values were power transformed using the rcompanion (v1.10.1) package [34] and then Z-score normalized using the car (v2.1.5) package [35]. Testing for α -diversity differences utilized linear mixed-effect models created using the lme4 (v1.1.14) package [36] to correct for study and variable region effects in feces and study, variable region, and individual effects in tissue. Relative risk was analyzed using both the epiR (v0.9.87) and metafor (v2.0.0) packages [37,38] by assessing how many with and without disease were above and below the overall median value within the specific study. Relative risk significance testing utilized the chi-squared test. β -diversity differences utilized a Bray-Curtis distance matrix and PERMANOVA executed with the vegan (v2.4.4) package [39]. Random Forest models were built using both the caret (v6.0.77) and randomForest (v4.6.12) packages [40,41]. Differences between the obtained AUC versus a random model AUC was assessed using T-tests. Power analysis and estimations were made using the pwr (v1.2.1) and statmod (v1.4.30) packages [42,43]. All figures were created using both ggplot2 (v2.2.1) and gridExtra (v2.3) packages [44,45].

Study Analysis Overview: α -diversity was first assessed for differences between controls, adenoma, and carcinoma. We analyzed the data using linear mixed-effect models

and relative risk. β -diversity was then assessed for each individual study. Next, four specific CRC-associated genera (*Fusobacterium*, *Parvimonas*, *Peptostreptococcus*, and *Porphyromonas*) were assessed for differences in relative risk. We then built Random Forest models based on all genera or the select CRC-associated genera. The models were trained on one study then tested on the remaining studies for every study. The data was split between feces and tissue samples. Within the tissue groups the data was further divided between matched and unmatched tissue samples. Where applicable for each study, predictions for adenoma and carcinoma were tested. This same approach was then applied at the OTU level with the exception that instead of testing on the other studies, a 10-fold cross validation was utilized and 100 different models were created based on random 80/20 splitting of the data to generate a range of expected AUCs. For OTU based models the CRC associated genera included all OTUs that had a taxonomic classification to *Fusobacterium*, *Parvimonas*, *Peptostreptococcus*, or *Porphyromonas*. The power of each study was assessed for an effect size ranging from 1% to 30%. An estimated sample n for these effect sizes was also generated based on 80% power.

Reproducible Methods: The code and analysis can be found here https://github.com/SchlossLab/Size_CRCMetaAnalysis_Microbiome_2017. Unless mentioned otherwise, the accession number for the raw sequences for the studies used in this analysis can be found directly in the respective batch file in the GitHub repository or in the original manuscript.

Declarations

Ethics approval and consent to participate

Ethics approval and informed consent for each of the studies used is mentioned in the respective manuscripts used in this meta-analysis.

Consent for publication

Not applicable.

Availability of data and material

A detailed and reproducible description of how the data were processed and analyzed for each study can be found at https://github.com/SchlossLab/Size_CRCMetaAnalysis_Microbiome_2017. Raw sequences can be downloaded from the SRA in most cases and can be found in the respective studies batch file in the GitHub repository or within the original publication. For instances when sequences are not publicly available, they may be accessed by contacting the corresponding authors from whence the data came.

Competing Interests

All authors declare that they do not have any relevant competing interests to report.

Funding

MAS is supported by a Candian Institute of Health Research fellowship and a University of Michigan Postdoctoral Translational Scholar Program grant.

Authors' contributions

All authors helped to design and conceptualize the study. MAS identified and analyzed the data. MAS and PDS interpreted the data. MAS wrote the first draft of the manuscript and both he and PDS reviewed and revised updated versions. All authors approved the final manuscript.

Acknowledgements

The authors would like to thank all the study participants who were a part of each of the individual studies uitlized. We would also like to thank each of the study authors for making their data available for use. Finally we would like to thank the members of the Schloss lab for valuable feed back and proof reading during the formulation of this manuscript.

References

1. Siegel RL, Miller KD, Jemal A. Cancer statistics, 2016. *CA: a cancer journal for clinicians*. 2016;66:7–30.
2. Flynn KJ, Baxter NT, Schloss PD. Metabolic and Community Synergy of Oral Bacteria in Colorectal Cancer. *mSphere*. 2016;1.
3. Goodwin AC, Destefano Shields CE, Wu S, Huso DL, Wu X, Murray-Stewart TR, et al. Polyamine catabolism contributes to enterotoxigenic *Bacteroides fragilis*-induced colon tumorigenesis. *Proceedings of the National Academy of Sciences of the United States of America*. 2011;108:15354–9.
4. Abed J, Emgård JEM, Zamir G, Faroja M, Almogy G, Grenov A, et al. Fap2 Mediates *Fusobacterium nucleatum* Colorectal Adenocarcinoma Enrichment by Binding to Tumor-Expressed Gal-GalNAc. *Cell Host & Microbe*. 2016;20:215–25.
5. Arthur JC, Perez-Chanona E, Mühlbauer M, Tomkovich S, Uronis JM, Fan T-J, et al. Intestinal inflammation targets cancer-inducing activity of the microbiota. *Science (New York, N.Y.)*. 2012;338:120–3.
6. Kostic AD, Chun E, Robertson L, Glickman JN, Gallini CA, Michaud M, et al. *Fusobacterium nucleatum* potentiates intestinal tumorigenesis and modulates the tumor-immune microenvironment. *Cell Host & Microbe*. 2013;14:207–15.
7. Wu S, Rhee K-J, Albesiano E, Rabizadeh S, Wu X, Yen H-R, et al. A human colonic commensal promotes colon tumorigenesis via activation of T helper type 17 T cell responses. *Nature Medicine*. 2009;15:1016–22.
8. Zackular JP, Baxter NT, Chen GY, Schloss PD. Manipulation of the Gut Microbiota

Reveals Role in Colon Tumorigenesis. *mSphere*. 2016;1.

9. Zackular JP, Baxter NT, Iverson KD, Sadler WD, Petrosino JF, Chen GY, et al. The gut microbiome modulates colon tumorigenesis. *mBio*. 2013;4:e00692–00613.

10. Baxter NT, Zackular JP, Chen GY, Schloss PD. Structure of the gut microbiome following colonization with human feces determines colonic tumor burden. *Microbiome*. 2014;2:20.

11. Shah MS, DeSantis TZ, Weinmaier T, McMurdie PJ, Cope JL, Altrichter A, et al. Leveraging sequence-based faecal microbial community survey data to identify a composite biomarker for colorectal cancer. *Gut*. 2017;

12. Hale VL, Chen J, Johnson S, Harrington SC, Yab TC, Smyrk TC, et al. Shifts in the Fecal Microbiota Associated with Adenomatous Polyps. *Cancer Epidemiology, Biomarkers & Prevention: A Publication of the American Association for Cancer Research, Cosponsored by the American Society of Preventive Oncology*. 2017;26:85–94.

13. Flemer B, Lynch DB, Brown JMR, Jeffery IB, Ryan FJ, Claesson MJ, et al. Tumour-associated and non-tumour-associated microbiota in colorectal cancer. *Gut*. 2017;66:633–43.

14. Chen W, Liu F, Ling Z, Tong X, Xiang C. Human intestinal lumen and mucosa-associated microbiota in patients with colorectal cancer. *PloS One*. 2012;7:e39743.

15. Wang T, Cai G, Qiu Y, Fei N, Zhang M, Pang X, et al. Structural segregation of gut microbiota between colorectal cancer patients and healthy volunteers. *The ISME journal*. 2012;6:320–9.

16. Lu Y, Chen J, Zheng J, Hu G, Wang J, Huang C, et al. Mucosal adherent bacterial dysbiosis in patients with colorectal adenomas. *Scientific Reports*. 2016;6:26337.

17. Brim H, Yooseph S, Zoetendal EG, Lee E, Torralbo M, Laiyemo AO, et al. Microbiome

317 analysis of stool samples from African Americans with colon polyps. PloS One.
318 2013;8:e81352.

319 18. Weir TL, Manter DK, Sheflin AM, Barnett BA, Heuberger AL, Ryan EP. Stool microbiome
320 and metabolome differences between colorectal cancer patients and healthy adults. PloS
321 One. 2013;8:e70803.

322 19. Dejea CM, Wick EC, Hechenbleikner EM, White JR, Mark Welch JL, Rossetti BJ, et al.
323 Microbiota organization is a distinct feature of proximal colorectal cancers. Proceedings of
324 the National Academy of Sciences of the United States of America. 2014;111:18321–6.

325 20. Sanapareddy N, Legge RM, Jovov B, McCoy A, Burcal L, Araujo-Perez F, et al.
326 Increased rectal microbial richness is associated with the presence of colorectal adenomas
327 in humans. The ISME journal. 2012;6:1858–68.

328 21. Ahn J, Sinha R, Pei Z, Dominianni C, Wu J, Shi J, et al. Human gut microbiome and
329 risk for colorectal cancer. Journal of the National Cancer Institute. 2013;105:1907–11.

330 22. Burns MB, Lynch J, Starr TK, Knights D, Blekhman R. Virulence genes are a signature
331 of the microbiome in the colorectal tumor microenvironment. Genome Medicine. 2015;7:55.

332 23. Zeller G, Tap J, Voigt AY, Sunagawa S, Kultima JR, Costea PI, et al. Potential of
333 fecal microbiota for early-stage detection of colorectal cancer. Molecular Systems Biology.
334 2014;10:766.

335 24. Baxter NT, Ruffin MT, Rogers MAM, Schloss PD. Microbiota-based model improves the
336 sensitivity of fecal immunochemical test for detecting colonic lesions. Genome Medicine.
337 2016;8:37.

338 25. Geng J, Fan H, Tang X, Zhai H, Zhang Z. Diversified pattern of the human colorectal

cancer microbiome. Gut Pathogens. 2013;5:2.

26. Keku TO, Dulal S, Deveau A, Jovov B, Han X. The gastrointestinal microbiota and colorectal cancer. American Journal of Physiology - Gastrointestinal and Liver Physiology [Internet]. 2015 [cited 2017 Oct 30];308:G351–63. Available from: <http://ajpgi.physiology.org/lookup/doi/10.1152/ajpgi.00360.2012>

27. Vogtmann E, Goedert JJ. Epidemiologic studies of the human microbiome and cancer. British Journal of Cancer [Internet]. 2016 [cited 2017 Oct 30];114:237–42. Available from: <http://www.nature.com/doifinder/10.1038/bjc.2015.465>

28. Kostic AD, Gevers D, Pedamallu CS, Michaud M, Duke F, Earl AM, et al. Genomic analysis identifies association of Fusobacterium with colorectal carcinoma. Genome Research. 2012;22:292–8.

29. Zackular JP, Rogers MAM, Ruffin MT, Schloss PD. The human gut microbiome as a screening tool for colorectal cancer. Cancer Prevention Research (Philadelphia, Pa.). 2014;7:1112–21.

30. Schloss PD, Westcott SL, Ryabin T, Hall JR, Hartmann M, Hollister EB, et al. Introducing mothur: Open-Source, Platform-Independent, Community-Supported Software for Describing and Comparing Microbial Communities. Appl.Environ.Microbiol. [Internet]. 2009 [cited 12AD Jan 1];75:7537–41. Available from: <http://aem.asm.org/cgi/content/abstract/75/23/7537>

31. Rognes T, Flouri T, Nichols B, Quince C, Mahé F. VSEARCH: A versatile open source tool for metagenomics. PeerJ. 2016;4:e2584.

32. Westcott SL, Schloss PD. OptiClust, an Improved Method for Assigning

361 Amplicon-Based Sequence Data to Operational Taxonomic Units. mSphere. 2017;2.

362 33. R Core Team. R: A language and environment for statistical computing [Internet].
363 Vienna, Austria: R Foundation for Statistical Computing; 2017. Available from: <https://www.R-project.org/>
364

365 34. Mangiafico S. Rcompanion: Functions to support extension education program
366 evaluation [Internet]. 2017. Available from: [https://CRAN.R-project.org/package=](https://CRAN.R-project.org/package=rcompanion)
367 [rcompanion](https://CRAN.R-project.org/package=rcompanion)

368 35. Fox J, Weisberg S. An R companion to applied regression [Internet]. Second. Thousand
369 Oaks CA: Sage; 2011. Available from: [http://socserv.socsci.mcmaster.ca/jfox/Books/](http://socserv.socsci.mcmaster.ca/jfox/Books/Companion)
370 [Companion](http://socserv.socsci.mcmaster.ca/jfox/Books/Companion)

371 36. Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4.
372 Journal of Statistical Software. 2015;67:1–48.

373 37. Telmo Nunes MS with contributions from, Heuer C, Marshall J, Sanchez J, Thornton
374 R, Reiczigel J, et al. EpiR: Tools for the analysis of epidemiological data [Internet]. 2017.
375 Available from: <https://CRAN.R-project.org/package=epiR>

376 38. Viechtbauer W. Conducting meta-analyses in R with the metafor package. Journal of
377 Statistical Software [Internet]. 2010;36:1–48. Available from: [http://www.jstatsoft.org/v36/](http://www.jstatsoft.org/v36/i03/)
378 [i03/](http://www.jstatsoft.org/v36/i03/)

379 39. Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, et al. Vegan:
380 Community ecology package [Internet]. 2017. Available from: [https://CRAN.R-project.org/](https://CRAN.R-project.org/package=vegan)
381 [package=vegan](https://CRAN.R-project.org/package=vegan)

382 40. Jed Wing MKC from, Weston S, Williams A, Keefer C, Engelhardt A, Cooper T,
383 et al. caret: Classification and regression training [Internet]. 2017. Available from:

384 <https://CRAN.R-project.org/package=caret>

385 41. Liaw A, Wiener M. Classification and regression by randomForest. R News [Internet].
386 2002;2:18–22. Available from: <http://CRAN.R-project.org/doc/Rnews/>

387 42. Champely S. Pwr: Basic functions for power analysis [Internet]. 2017. Available from:
388 <https://CRAN.R-project.org/package=pwr>

389 43. Giner G, Smyth GK. Statmod: Probability calculations for the inverse gaussian
390 distribution. R Journal. 2016;8:339–51.

391 44. Wickham H. Ggplot2: Elegant graphics for data analysis [Internet]. Springer-Verlag
392 New York; 2009. Available from: <http://ggplot2.org>

393 45. Auguie B. GridExtra: Miscellaneous functions for “grid” graphics [Internet]. 2017.
394 Available from: <https://CRAN.R-project.org/package=gridExtra>

Table 1: Total Individuals in each Study Included in the Stool Analysis

| Study | Data Stored | 16S Region | Control (n) | Adenoma (n) | Carcinoma (n) |
|--------|-------------|------------|-------------|-------------|---------------|
| Ahn | DBGap | V3-4 | 148 | 0 | 62 |
| Baxter | SRA | V4 | 172 | 198 | 120 |
| Brim | SRA | V1-3 | 6 | 6 | 0 |
| Flemer | Author | V3-4 | 37 | 0 | 43 |
| Hale | Author | V3-5 | 473 | 214 | 17 |
| Wang | SRA | V3 | 56 | 0 | 46 |
| Weir | Author | V4 | 4 | 0 | 7 |
| Zeller | SRA | V4 | 50 | 37 | 41 |

Table 2: Studies with Tissue Samples Included in the Analysis

| Study | Data Stored | 16S Region | Control (n) | Adenoma (n) | Carcinoma (n) |
|-------------|-------------|------------|-------------|-------------|---------------|
| Burns | SRA | V5-6 | 18 | 0 | 16 |
| Chen | SRA | V1-V3 | 9 | 0 | 9 |
| Dejea | SRA | V3-5 | 31 | 0 | 32 |
| Flemer | Author | V3-4 | 103 | 37 | 94 |
| Geng | SRA | V1-2 | 16 | 0 | 16 |
| Lu | SRA | V3-4 | 20 | 20 | 0 |
| Sanapareddy | Author | V1-2 | 38 | 0 | 33 |

Figure 1: α -Diversity Differences between Control, Adenoma, and Carcinoma Across Sampling Site. A) α -diversity metric differences by group in stool samples. B) α -diversity metric differences by group in unmatched tissue samples. C) α -diversity metric differences by group in matched tissue samples. The dashed line represents a Z-score of 0 or no difference from the median.

Figure 2: Relative Risk for Adenoma or Carcinoma based on α -Diversity Metrics in Stool. A) α -metric relative risk for adenoma. B) α -metric relative risk for carcinoma. Colors represent the different variable regions used within the respective study.

Figure 3: CRC-Associated Genera Relative Risk for Adenoma and Carcinoma in Stool and Tissue. A) Adenoma relative risk in stool. B) Carcinoma relative risk in stool. C) Adenoma relative risk in tissue. D) Carcinoma relative risk in tissue. For all panels the relative risk was also compared to whether one, two, three, or four of the CRC-associated genera were present.

Figure 4: OTU Random Forest Model of Stool Across Studies. A) Adenoma random forest model between the full community and CRC-associated genera OTUs only. B) Carcinoma random forest model between the full community and CRC-associated genera OTUs only. The dotted line represents an AUC of 0.5 and the lines represent the range in which the AUC for the 100 different 80/20 runs fell between. The solid red line represents the median AUC of all the studies for either the full community or CRC-associated genera OTUS only model.

Figure 5: OTU Random Forest Model of Tissue Across Studies. A) Adenoma random forest model between the full community and CRC-associated genera OTUs only. B) Carcinoma random forest model between the full community and CRC-associated genera OTUs only. The dotted line represents an AUC of 0.5 and the lines represent the range in which the AUC for the 100 different 80/20 runs fell between. The solid red line represents

the median AUC of all the studies for either the full community or CRC-associated genera
OTUS only model.

Figure 6: Power and Effect Size Analysis of Studies Included. A) Power based on
effect size for studies with adenoma individuals. B) Power based on effect size for studies
with carcinoma individuals. C) The estimated sample number needed for each arm of each
study to detect an effect size of 1-30%. The dotted red lines in A) and B) represent a power
of 0.8.

Figure S1: Relative Risk for Adenoma or Carcinoma based on α -Diversity Metrics in Tissue. A) α -metric relative risk for adenoma. B) α -metric relative risk for carcinoma. Colors represent the different variable regions used within the respective study.

Figure S2: Random Forest Genus Model AUC for each Stool Study. A) AUC of adenoma models using all genera or CRC-associated genera only. B) AUC of carcinoma models using all genera or CRC-associated genera only. The black line represents the median within each group.

Figure S3: Random Forest Genus Model AUC for each Tissue Study. A) AUC of adenoma models using all genera or only CRC-associated genera divided between matched and unmatched tissue. B) AUC of carcinoma models using all genera or CRC-associated genera only. The black line represents the median within each group divided between matched and unmatched tissue.

Figure S4: Random Forest Prediction Success Using Genera for each Stool Study. A) AUC for prediction in adenoma using all genera or CRC associated genera only. B) AUC for prediction in carcinoma using all genera or CRC-associated genera only. The dotted line represents an AUC of 0.5. The x-axis is the data set in which the model was initially trained on.

Figure S5: Random Forest Prediction Success of Carcinoma Using Genera for each Tissue Study. A) AUC for prediction in unmatched tissue for all genera or CRC-associated genera only. B) AUC for prediction in matched tissue using all genera or CRC-associated genera only. The dotted line represents an AUC of 0.5. The x-axis is the data set in which the model was initially trained on.

Figure S6: Random Forest Prediction Success of Adenoma Using Genera for each Tissue Study.