

Clonal expansions in ulcerative colitis identify patients with neoplasia

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Chronic inflammation predisposes to a variety of human cancers. Affected tissues slowly accumulate mutations, some of which affect growth regulation and drive successive waves of clonal evolution, whereas a far greater number are functionally neutral and serve only to passively mark expanding clones. Ulcerative colitis (UC) is an inflammatory bowel disease, in which up to 10% of patients eventually develop colon cancer. Here we have mapped mutations in hypermutable intergenic and intronic polyguanine tracts in patients with UC to delineate the extent of clonal expansions associated with carcinogenesis. We genotyped colon biopsies for length altering mutations at 28 different polyguanine markers. In eight patients without neoplasia, we detected only two mutations in a single individual from among 37 total biopsies. In contrast, for 11 UC patients with neoplasia elsewhere in the colon, we identified 63 mutations in 51 nondysplastic biopsies, and every patient possessed at least one mutant clone. A subset of clones were large and extended over many square centimeters of colon. Of these, some occurred as isolated populations in nondysplastic tissue, considerably distant from neoplastic lesions. Other large clones included regions of cancer, suggesting that the tumor arose within a preexisting clonal field. Our results demonstrate that neutral mutations in polyguanine tracts serve as a unique tool for identifying fields of clonal expansions, which may prove clinically useful for distinguishing a subset of UC patients who are at risk for developing cancer.

field effect | lineage mapping | neoplastic evolution

Cancer is a disease of somatic cellular evolution characterized by successive waves of mutation, selection, and clonal expansion (1–3). In many malignancies, most of this process is thought to occur within a relatively confined location, such as in the well studied adenoma-to-carcinoma sequence of sporadic colorectal cancer (4). However, cancers arising within the context of certain predisposing and preneoplastic conditions, including oral leukoplakia (5), Barrett's esophagus (6), and inflammatory bowel disease (7), among others, appear to evolve more diffusely. The concept of “field effect,” first articulated by Slaughter (8) more than half a century ago, describes the observation that cells within an area surrounding some tumor types display abnormal, yet not fully cancerous properties. More recently, it has been appreciated that clonally derived cell populations bearing a subset of the genetic and epigenetic abnormalities found in the tumor itself frequently form the basis for such fields (9). Recognition that cancer-causing mutations may first emerge as widespread clones within non-neoplastic tissue has motivated efforts to identify the unique genetic changes that precede cancer for use in predicting its future development.

Ulcerative colitis (UC) is a chronic inflammatory disease of the colon that predisposes to colorectal cancer and affects approximately half a million individuals in the United States alone (10). After 8 years of disease, a patient's risk of cancer increases 0.5–1% per year, reaching nearly one in five after 30 years (11). Longstanding UC presents a formidable clinical challenge; although cancer risk is markedly increased relative to an age-matched population, the absolute risk is not sufficiently high to justify the morbidity, cost, and quality of life issues associated with prophylactic colectomy if

management of symptoms is otherwise satisfactory. Because UC-derived dysplasias can be flat and hard to visualize endoscopically, current surveillance measures entail performing colonoscopy every 1 to 2 years to procure 30–60 biopsies for histological assessment in the hope that if cancer or advanced dysplasia exists, it will be found by random sampling (12). This practice is expensive, insufficiently sensitive, and only detects a neoplastic process once it has progressed to a morphologically recognizable stage.

We have previously demonstrated that genetic abnormalities common to UC-associated adenocarcinoma, including *TP53* mutations (13), ploidy abnormalities (14, 15), and chromosomal losses and gains (14, 16) can be found as large clonal fields in normal-appearing UC tissue outside of cancer sites. Some of these clonal lesions predict risk of future histological progression in individuals currently without dysplasia (15). A subset of individuals, however, progress in the absence of any of these markers. Recent cancer genome sequencing studies suggest that the genetic alterations responsible for driving tumorigenesis are highly diverse and unique to every tumor (17–19). Although some genes are commonly mutated in specific cancers, others are mutated infrequently. Widespread clonal evolution could occur in nondysplastic colon before all UC-associated cancers, yet sometimes be undetectable by standard markers when clonal expansions are driven by mutation of unsuspected genes or regulators elsewhere within the (epi)genome.

We hypothesize that the general phenotype of clonal expansion, rather than expansion of specific drivers, might serve as a more sensitive biomarker of prehistological neoplastic processes in UC. During normal mitosis, mutations occur at low frequency throughout the genome of all cells (20), bestowing each cell with a unique fingerprint. While some mutations produce phenotypic changes, the vast majority occur outside of genes and regulatory regions and are likely to be functionally silent “passengers.” Irrespective of the specific mutation driving a clonal expansion, in theory, the progeny of any such event will be distinguishable from nearby cells by virtue of sharing the neutral mutational signature of the founding cell. The challenge to such a detection approach lies in the difficulty of locating these rare passenger mutations within a 6-Gb diploid genome.

Short, repetitive sequences are replicated with significantly lower fidelity than other portions of the genome. Polyguanine tracts, in particular, undergo insertion and deletion mutation with rates on the order of $\approx 10^{-4}$ per cell generation (21). These mutational hotspots serve as likely candidates for bearing lineage-identifying somatic variants. We have recently developed a high-throughput

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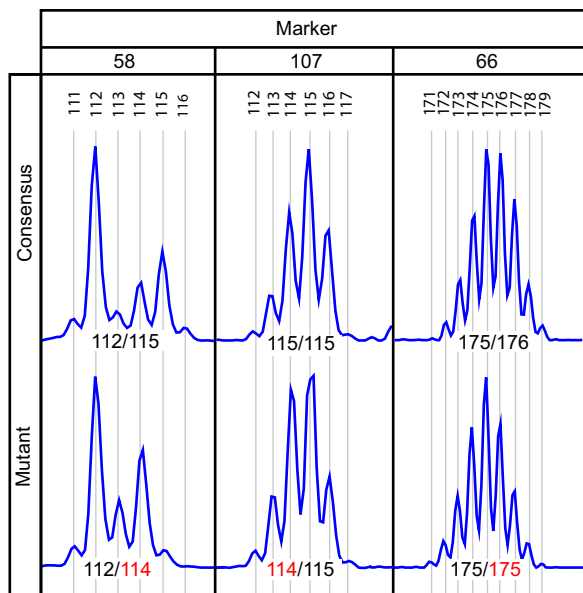


Fig. 1. Example electropherograms showing polyguanine tract genotype variation between a spatially separated pair of UC colon biopsies in three individuals. For each polyguanine marker, the “consensus” genotype is that most commonly observed among biopsies from a single patient. Mutant genotypes are those that differ from the consensus with respect to the length of at least one allele. X-axis indicates product length (bp), y-axis represents signal intensity. Allele lengths are indicated, with mutant alleles in red. Non-indicated peaks are an artifact of PCR amplification (“stutter”).

genomic approach to screen for mitotically acquired mutations at polyguanine sites (22, 23) and have used this to produce cell fate maps of mouse development (22, 24). In the present study, we adapt this technique to identify clonal expansions in UC colon. Our results indicate that the method is highly effective at detecting discrete clones and that the presence of these clones in nondysplastic tissue distinguishes patients who have progressed to advanced histological disease from those who have not. We demonstrate that the cell lineage information encoded in the genome by neutral mutant markers provides a useful tool for studying histologically invisible neoplastic processes and a potentially powerful method of identifying patients at greatest risk for developing cancer.

Results

Polyguanine Tract Genotyping. Microsatellite genotyping by capillary electrophoresis produces an analog signal that reflects the predominant allele lengths within a DNA sample. We have previously identified somatic mutations in polyguanine alleles that are unique to single mouse cells by clonally expanding their genome *in vitro* before analysis (22, 24). Such mutations cannot be detected in bulk-tissue, because rare alleles are obscured by more prevalent ones. Initial experiments in the present study sought to establish the feasibility of detecting polyguanine genotypes in the human colon where clonal expansion has occurred *in vivo*.

Fluorescently labeled PCR primers were designed to flank 35 non-coding polyguanine tracts, arbitrarily selected from throughout the human genome (Fig. S1). The amplified product of each marker displayed either one or two maximal peaks depending on whether the individual was heterozygous or homozygous for repeat length at the locus (22) (Fig. 1). Adjacent submaximal peaks (“stutter”) are an artifact of PCR amplification, resulting from strand slippage leading to insertions and deletions in a subset of amplicon molecules (25). To confirm reproducibility of genotyping based on maximal peak position, a single DNA sample was used to initiate 15 replicate PCRs for each primer set. Genotype assignments made by a blinded observer were 100% concordant among replicates.

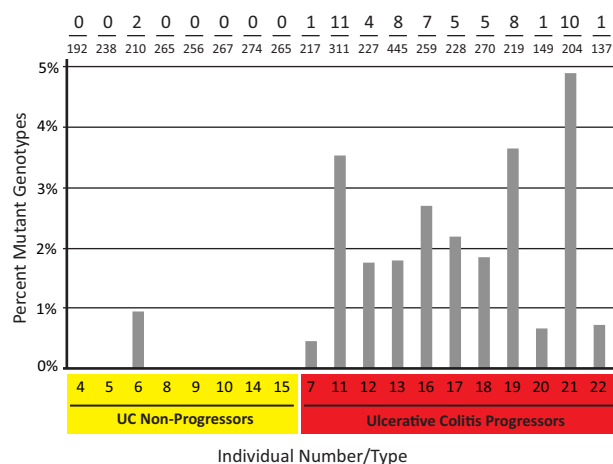


Fig. 2. Frequency of mutant polyguanine genotypes by disease status. An average of 4.6 histologically nondysplastic biopsies were obtained from eight individuals with UC and no histological evidence of cancer or HGD anywhere in the colon (UC Non-Progressors) and 11 with UC and at least one site with adenocarcinoma and/or HGD (UC Progressors). Biopsies were divided into epithelial and stromal fractions, and both fractions were genotyped at 28 polyguanine markers. For each individual, the number of mutant genotypes out of the total number of successful genotypes (*Top*), and the percentage of mutant genotypes (bars) are reported. Genotyping was performed under fully blinded conditions.

To determine the threshold for detection of mutants within a heterogeneous population of mutants and adjacent nonmutant cells, we carried out mixing experiments. For a subset of markers, DNA from two individuals whose germline genotypes differed by a single base pair in one allele were combined in ratios of 20% increments. Electropherograms from these mixtures were then compared to those from the original, unmixed DNAs. The fractional abundance required to reliably identify a simulated mutant clone varied by marker, but consistently fell between 40–60%. Thus, identification of a mutant allele by this technique indicates that a minimum of 40% of harvested cells must share the mutation.

Clonal Expansions in Nondysplastic UC. We next investigated whether polyguanine tract mutations could be used to identify clonally expanded cell populations within UC tissue. Between 44 and 144 biopsies were harvested in an evenly spaced grid along the colon of 19 UC patients (15 after colectomy, four during colonoscopy). Eight individuals with no histological evidence of high-grade dysplasia (HGD) or cancer anywhere in the colon were classified as “Non-Progressors.” Eleven individuals with at least one biopsy with HGD or cancer were classified as “Progressors.” An average of 4.6 non-dysplastic biopsies were arbitrarily selected (average spacing of 20.1 cm) along each colon for genotyping. Of exception were three Non-Progressor and one Progressor cases where genotyped biopsies were limited to the rectum. DNA separately purified from epithelial and stromal cell fractions of an $\approx 9\text{-mm}^2$ portion of each biopsy was genotyped at 28 polyguanine sites and four “Bethesda Panel” markers used to diagnose microsatellite instability (MSI) in DNA mismatch repair (MMR)-deficient states (26). Personnel performing the genotyping were blinded to all clinical information.

Within each patient, the majority of genotypes for a given marker were identical across all samples. Occasionally, however, the allele pattern of a biopsy tissue fraction differed from the predominant, “consensus genotype” identified elsewhere in the colon, indicating that a rare, clonally expanded mutation had been sampled (Fig. 1). A complete listing of genotype calls is provided in Fig. S2. The presence of detectable clones was strongly correlated with progression status (Fig. 2). Of the 63 mutations identified, 97% occurred among Progressors. Whereas 100% of Progressors had at least one

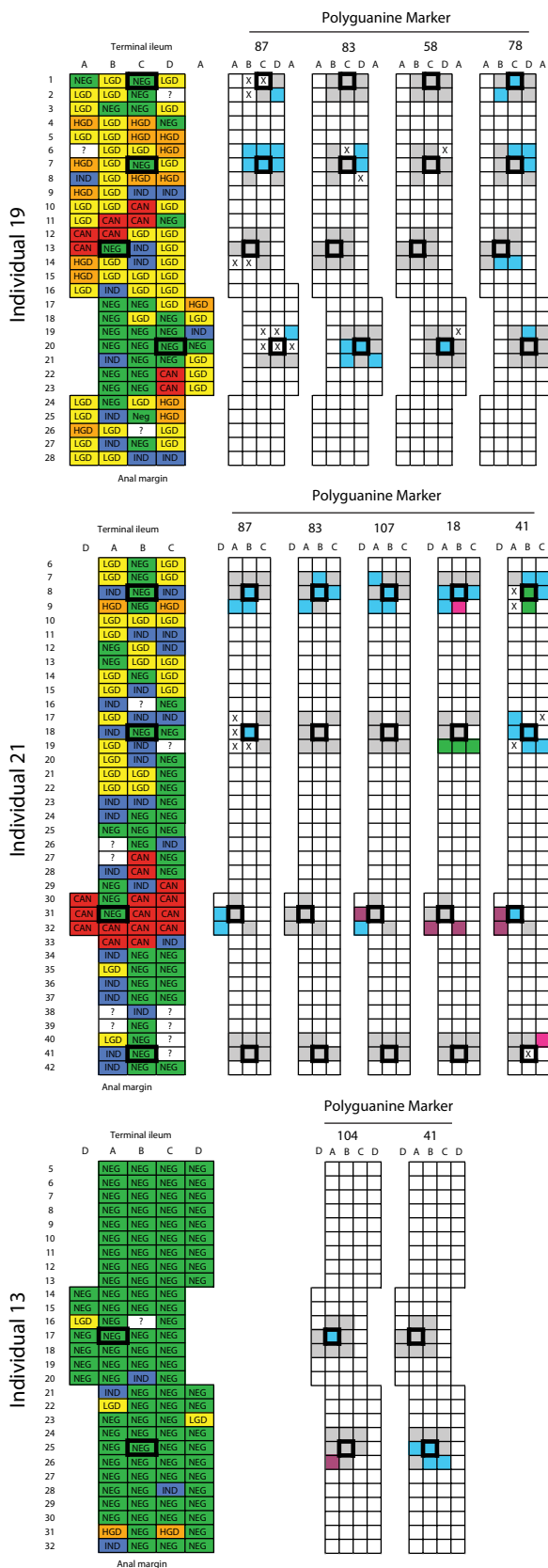


Fig. 3. Clonal patches identified by polyguanine mapping. Longitudinally opened colectomy specimens from three individuals are diagrammed with small boxes representing individual biopsies ($\approx 9 \text{ mm}^2$), taken at evenly spaced intervals within an alphanumeric grid. The histological diagnosis of each biopsy in the colon is indicated at left: NEG, negative for dysplasia; IND,

noncancer dysplasia samples as belonging to the same clone, suggesting that the cancer and dysplasia emerged from a preexisting, nondysplastic clonal field.

Discussion

We have shown that neutral markers of cell lineage can be used to identify clonal expansions in nondysplastic UC colon and effectively distinguish patients who have progressed to histologically advanced disease from those who have not. These clones may occur as fields from which a cancer has arisen or as otherwise invisible populations, more than half a meter from the nearest dysplasia. Our findings reinforce prior evidence that neoplastic evolution in UC is delocalized, multifocal, and involves both epithelium and stroma (7, 13–16, 28, 29). Our results suggest that screening for clonal expansions in UC patients may be able to identify tumorigenic processes before the emergence of histologically recognizable disease.

The presence of large, clonally derived patches in colon represents a divergence from normal cellular homeostasis. The colon is divided into replicative units known as crypts. These invaginated structures contain a small population of stem cells at their base that continually replicate to clonally populate the luminal surfaces with terminally differentiated progeny that are then sloughed off after several days (30). Studies of normal female colons have shown that embryonically originating patches sharing a common inactivated X-chromosome do not exceed 450 crypts in size (31). Spontaneously arising mitochondrial mutations indicate that clonal crypt clusters arise postnatally in normal colon and increase in size with age, yet rarely exceed a dozen units (32). The biopsy portions we genotyped contained $\approx 2,000\text{--}5,000$ crypts. Because at least 40% of cells in a sample must share a mutation for it to be detectable, it can be estimated that clones within isolated mutant biopsies comprise at least 800–2,000 crypts. In our study, only one patch was identified in a single Non-Progressor colon. It is possible that this case may, in fact, represent one of the 10% of the general UC population who would have ultimately progressed to cancer.

Using neutral passenger rather than putative driver mutations as lineage markers of clonal expansions has two primary advantages. First, cancer is a stochastic evolutionary process, and not all tumors necessarily arise through mutation of the same set of drivers (18, 19). Neutral mutations offer an unbiased, generalizable way of identifying clones that is independent of molecular causation. Such an approach integrates all possible bases for an abnormal cell/tissue behavior, including mutation of unknown genetic and epigenetic sites as well as nonheritable influences of local environment. Second, screening for known drivers may limit detectability to relatively late-arising clones. Experimental mutation of many of the best characterized oncogenes and tumor suppressors in otherwise untransformed cells induces growth arrest and senescence (33). It is conceivable that mutation in common tumor drivers seen in UC-derived adenocarcinoma, including *TP53* and *KRAS*, may not be tolerated in the earliest arising clones. Similar arguments mitigate against the utility of randomly arising gross chromosomal abnormalities as early clonal markers.

Functionally, neutral mutations serve as useful markers of clonality but are, nevertheless, imperfect. Detection of a clone requires that members share a common mutation, originating in the founding cell, which distinguishes them from the surrounding population (Fig. 5). While every clone is likely to be uniquely marked relative

indefinite for dysplasia; LGD, low grade dysplasia; HGD, high grade dysplasia; CAN, cancer; ?, no data. The genotypes of biopsies for specific polyguanine markers are indicated at right. Outlined boxes represent biopsies used in the initial study. Empty boxes represent biopsies not genotyped, "X" indicates unsuccessful genotyping. Gray fields indicate biopsies with the consensus genotype for the marker, and different colors represent distinct mutant genotypes within an individual for each marker. Clustering of identical mutant genotypes in adjacent biopsies suggests large, clonally derived patches.

Polyguanine Marker

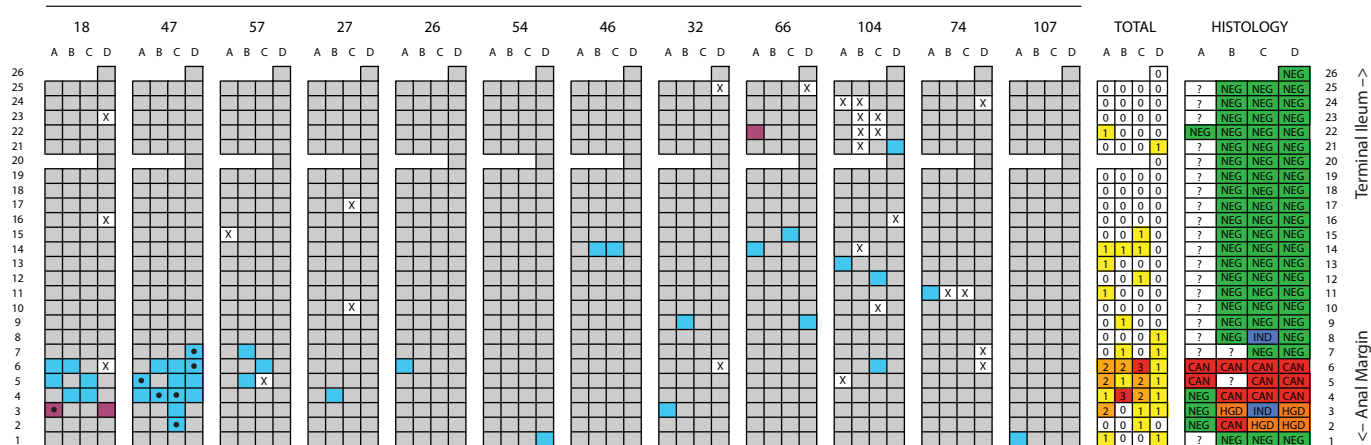


Fig. 4. Polyguanine mapping of a complete UC Progressor colon. A longitudinally opened colectomy specimen is diagrammed with boxes representing evenly spaced biopsies measuring $\approx 9 \text{ mm}^2$ within an alphanumeric grid. The histological diagnosis of each biopsy is indicated at far right: NEG, negative for dysplasia; IND, indefinite dysplasia; HGD, high grade dysplasia; CAN, cancer; ?, no data. Biopsy genotypes for various polyguanine marker are indicated in separate grids. “X” indicates unsuccessful genotyping. Gray fields indicate biopsies with the consensus genotype for the marker, and different colors represent distinct mutant genotypes for each marker. Dots indicate biopsies where a mixture of consensus and mutant genotypes were observed, suggesting a mixed population of cells with different genotypes. The total number of mutant genotypes identified across all markers is reported for each biopsy (heat map). Large, clonally derived patches identified by three markers were observed near the cancer site. Numerous smaller patches were detected throughout the nondysplastic portions of the colon.

to neighboring cells somewhere in the thousands of polyguanine tracts in its genome, there is no guarantee that a mutation will have occurred in the specific subset of tracts being genotyped, so some clones will go undetected. Although we identified clones in two-thirds of Progressor biopsies, the true proportion is likely to be even greater given that we only examined 28 polyguanine tracts.

Although our study relies on microsatellite mutations as lineage markers, we find no evidence for the presence of the extensive MSI that results from deficiencies in MMR (26). No mutations were identified in any of the National Cancer Institute (NCI) Bethesda Panel MSI markers examined, and the low frequency of polyguanine mutations detected (1.4% overall, 2.3% in Progressors) is inconsistent with a vastly increased rate of microsatellite slippage (21). Moreover, whereas MMR-mediated MSI commonly manifests as a “widening” of electropherogram stutter peaks, indicative

of a large number of length variants simultaneously present within a sample (34), the rare polyguanine mutations we identified were predominantly the result of single slipped alleles. While there have been reports of “low-level” MSI in UC-derived adenocarcinomas and occasionally in surrounding nondysplastic tissue (29, 35, 36), microsatellite slippage events are expected to be occasionally witnessed in any clonally derived population (22, 37), and the latter may best explain our findings. Nevertheless, it is possible that a moderately increased rate of slippage may occur in UC. Direct measurement of the per-division mutation rate in UC Progressors relative to normal colon would be challenging given that detection of slippage is necessarily coupled to clonal expansion—something that does not occur in normal colon. Although an increased rate of mutagenesis resulting from inflammation-derived reactive oxygen species (38, 39) or defects in replication fidelity acquired during neoplastic transformation (2) would increase the number of somatic variants and facilitate detection of clones, it is not mandatory to invoke such mechanisms to explain our observations.

A unique aspect of our study is that it exclusively relies on neutral markers of cell lineage to identify clinically relevant clonal expansions in a preneoplastic condition. Several groups have previously used neutral markers to study tumor ancestry and tissue dynamics. In combination with suspected driver mutations, Maley and colleagues used slippage in short tandem repeats to show that risk of cancer progression is related to clonal diversity in Barrett’s esophagus (40). Although the bulk of clones in the study were identified by likely driver mutations, evolutionary statistics suggested that clonal heterogeneity, in and of itself, is an important cancer predictor. Frumkin et al. used microsatellite slippage events to phylogenetically reconstruct the lineage relationship between single cells in a mouse lymphoma (41). Shibata’s group used noncoding microsatellite mutations as a “molecular clock” of somatic division and used this to calculate the number of cell generations between initiation and sampling of human MSI tumors (34). More recently, these investigators have capitalized on the high frequency of epimutations in CpG islands of nontranscribed genes to study the clonal structure of non-MSI tumor development (42). Wright and colleagues have recently used the stainable phenotype of neutral, homoplasmic mutations in a mitochondrially encoded cyclooxygenase gene to study cell lineages in variety of tissues (43). Although the process by which homoplasmy arises is not well understood and

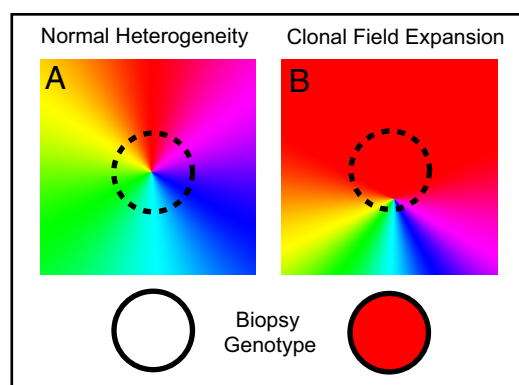


Fig. 5. Model for how mutant genotypes become identifiable as a result of clonal expansion. (A) As cells divide throughout life, they acquire unique somatic mutations at polyguanine tracts. However, because such mutations are rare and independent, for any given locus the majority of cells do not carry a mutation. Consequently, genotyping identifies only the dominant, nonmutated (or “consensus”) genotype in a biopsy, and the individual mutant genotypes carried by single cells or small subclones are not observed. (B) If an individual cell marked by a mutant allele clonally proliferates to populate a relatively large area, a unique genotype can come to dominate the sampled population and mutant alleles become detectable by genotyping.

takes many years to develop in some tissues (32), the ability to directly visualize the individual cells of a clonal population in an unperturbed tissue context makes this a promising technique with the potential to complement our studies.

The experiments we have undertaken expand on our previous studies of field effects in UC. We have shown that neutral markers of cell lineage can identify large clonally derived patches in normal-appearing colon of patients having histologically recognizable disease but not in those without. Although this ability will be of clinical utility in its own right, a more significant possibility is that such patches may be able to identify individual UC patients at greatest risk for developing colon cancer before the emergence of histological changes (i.e., Future Progressors). Our observation that clones may cover an area with both dysplastic and nondysplastic tissue strongly argues that expansions can predate dysplasia. Prospective studies will be needed to determine efficacy as a predictive biomarker of cancer risk.

From a basic science perspective, we have demonstrated that random mutations can be used to define the boundaries of clonal expansions occurring *in vivo* and identify subclones within larger clones. Screening a larger number of polyguanine marker sites will enable detailed phylogenetic reconstruction of the relationship between clones and may allow estimation of the number of rounds of selective outgrowths needed for neoplastic transformation. After using these markers to define clone boundaries, it will be possible to screen for candidate driver mutations and

determine the fraction of expansions that are driven by factors other than genes already known to play a role in UC-mediated carcinogenesis. Our technique should be adaptable to the study of other preneoplastic conditions or cancers. We believe that the general tactic of tracing cell lineage with spontaneously arising neutral markers of all forms holds promise for better understanding the neoplastic process. While there are thousands of polyguanine tracts in the human genome, there are billions other nucleotides and epigenetic sites for which mutation is likely to be functionally silent. When it becomes technically and economically possible to screen the whole genome with future sequencing technologies, a wealth of developmental history from all forms of normal and abnormal cell proliferation will become available. Not only do random mutations form the fundamental basis of evolutionary biology, they provide a powerful tool for studying its role in human disease.

Materials and Methods

Specimen information as well as sample preparation and polyguanine tract genotyping protocols are detailed in *SI Materials and Methods*.

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