Two modes of microsatellite instability in human cancer: differential connection of defective DNA mismatch repair to dinucleotide repeat instability

Shinya Oda*, Yoshihiko Maehara¹, Yoichi Ikeda¹, Eiji Oki¹, Akinori Egashira¹,², Yoshikazu Okamura, Ikuo Takahashi¹, Yoshihiro Kakeji¹, Yasushi Sumiyoshi¹, Kaname Miyashita, Yu Yamada, Yan Zhao¹, Hiroyoshi Hattori, Ken-ichi Taguchi, Tatsuo Ikeuchi³, Teruhisa Tsuzuki², Mutsuo Sekiguchi⁴, Peter Karran⁵ and Mitsuaki A. Yoshida⁶

Institute for Clinical Research, National Kyushu Cancer Center, Fukuoka 811-1395, Japan, ¹Department of Surgery and Science and ²Department of Medical Biophysics and Radiation Biology, Graduate School of Medical Sciences, Kyushu University, Fukuoka 812-8582, Japan, ³Division of Genetics, Tokyo Medical and Dental University, Tokyo 113-8510, Japan, ⁴Biomolecular Engineering Research Institute, Suita, Osaka 565-0874, Japan, ⁵Mammalian DNA Repair Laboratory, Cancer Research UK, London Research Institute, Clare Hall Laboratories, South Mimms, Herts EN6 3LD, UK and ⁶Biological Dose Section, Department of Dose Assessment, Research Center for Radiation Emergency Medicine, National Institute of Radiological Science, Chiba 263-8555, Japan

Received January 13, 2005; Revised and Accepted February 24, 2005

ABSTRACT

Microsatellite instability (MSI) is associated with defective DNA mismatch repair in various human malignancies. Using a unique fluorescent technique, we have observed two distinct modes of dinucleotide microsatellite alterations in human colorectal cancer. Type A alterations are defined as length changes of ≤6 bp. Type B changes are more drastic and involve modifications of ≥8 bp. We show here that defective mismatch repair is necessary and sufficient for Type A changes. These changes were observed in cell lines and in tumours from mismatch repair gene-knockout mice. No Type B instability was seen in these cells or tumours. In a panel of human colorectal tumours, both Type A MSI and Type B instability were observed. Both types of MSI were associated with hMSH2 or hMLH1 mismatch repair gene alterations. Intriguingly, p53 mutations, which are generally regarded as uncommon in human tumours of the MSI+ phenotype, were frequently associated with Type A instability, whereas none was found in tumours with Type B instability, reflecting the prevailing viewpoint. Inspection of published data reveals that the microsatellite instability that has been observed in various malignancies, including those associated with Hereditary Non-Polyposis Colorectal Cancer (HNPCC), is predominantly Type B. Our findings indicate that Type B instability is not a simple reflection of a repair defect. We suggest that there are at least two qualitatively distinct modes of dinucleotide MSI in human colorectal cancer, and that different molecular mechanisms may underlie these modes of MSI. The relationship between MSI and defective mismatch repair may be more complex than hitherto suspected.

INTRODUCTION

Microsatellites are repetitive DNA sequences comprising short reiterated motifs dispersed throughout the eukaryotic genome (1). Microsatellite lengths are highly polymorphic in human populations, but appear stable during the life span of the individual. Somatic instability of microsatellite sequences has initially been reported in human colorectal cancer (2,3), and particularly in the familial cancer-prone syndrome, hereditary non-polyposis colorectal cancer (HNPCC) (4,5). In 1993, mutations in one of the genes encoding proteins essential for DNA mismatch repair (MMR) were found in
HNPCC individuals (6,7). MMR is an important editing system. It counteracts the base mismatches and strand misalignments that occur during DNA replication and recombination (8). Repetitive sequences such as those comprising microsatellites are particularly prone to polymerase slippage and, consequently, strand misalignment. If these errors remain uncorrected, the mutations are fixed during subsequent replication as addition or deletion of one (or more) repeat units. The phenomenon of unstable microsatellites, i.e. microsatellite instability (MSI), in which tumour cells accumulate this type of repeat length alterations in microsatellites, is considered to reflect MMR deficiency. The MSI phenotype is frequently associated with various human malignancies (9). As defective MMR is regarded as a risk factor for familial predisposition or second malignancies, analyses of microsatellite instability have been prevalent, particularly in the field of oncology. However, the reported frequency for MSI tumours in each malignancy differs widely in the literature (9).

Although analysis of MSI is now commonplace, a designation of MSI may sometimes be a difficult decision. The 1997 National Cancer Institute (NCI) workshop, ‘Microsatellite Instability and RER Phenotypes in Cancer Detection and Familial Predisposition’, suggested that the variety of microsatellites used was a major cause of discrepancies among data from various laboratories, and recommended a panel of five microsatellites as ‘working reference panel’ (10). We believe that, in addition to selection of targets for analysis, methodological problems also account for some of the variability in results. Changes in microsatellite lengths are sometimes minor—as small as loss or gain of a single repeat unit. In addition, cells carrying changes in microsatellite sequences are not always major in a given sample. However, in an assay system using the conventional sequencing gel electrophoresis and autoradiography, it appears difficult to resolve microsatellite PCR products precisely and quantitatively. PCR itself has an intrinsic variability. The most widely used thermostable DNA polymerase (Taq) has a terminal deoxynucleotidyl transferase (TDT) activity, which adds one additional base to PCR products without specificity and/or fidelity. TDT activity of Taq polymerase was variably expressed, depending on the conditions used. This property, in addition to intrinsic strand misalignment during amplification of microsatellite repeats, increases the complexity of PCR products. In the conventional microsatellite analysis, intrinsic caution and the desire to avoid scoring false-positives may have led to an underestimate of the frequency of minor, more subtle microsatellite changes, such as alterations of limited numbers of repeat units. We have applied our fluorescent technique for microsatellite instability analysis (11) to address these problems. Here, we report that relatively subtle alterations in microsatellites are indeed generally associated with MMR deficiency. In contrast, most HNPCC tumours display much more extensive microsatellite changes. Our findings suggest that there are previously unrecognized aspects of microsatellite instability in human cancer.

**MATERIALS AND METHODS**

**Cells and tissue specimens**

Msh2−/− mouse embryonic fibroblast (MEF) cell line, RH95021 (12) and Mlh1−/− MEF cell line, MC2, were kindly provided by Dr Hein te Riele, Amsterdam Cancer Center and Dr Michael Liskay, University of Oregon, respectively. Cells were cultured in DMEM supplemented with 10% fetal calf serum, penicillin (100 U/ml) and streptomycin (100 μg/ml). Samples of cancer tissues and the corresponding normal mucosa were obtained from 79 patients with colorectal carcinoma who underwent surgery in the Department of Surgery and Science, Kyushu University Hospital from 1996 to 1999. Written informed consent for studies using the tissues was obtained from each patient. Ethical approval was obtained from the IRB of Kyushu University. Specimens, taken immediately after resection, were placed in liquid nitrogen. High molecular weight DNA was extracted and subjected to microsatellite analyses.

**Microsatellite instability**

Microsatellite analysis using fluorescence-labelled primers and an automated DNA sequencer has been described in detail (11). Briefly, five human dinucleotide microsatellites, D2S123, D5S107, D10S197, D11S904 and D13S175, in genomic DNA from tissue specimens were amplified by PCR. 5′ primers were labelled with the fluorescent compound, ROX (6-carboxy-x-rhodamine) or HEX (6-carboxy-2',4',7',4,7-hexachloro-fluorescein). PCR reactions were done using TaKaRa Taq (TaKaRa Co. Ltd., Tokyo, Japan). T4 DNA polymerase was added to the PCR products, followed by incubation at 37°C for 10 min. To compare electrophoretic profiles between two samples, 1.2 μl of ROX-labelled product and 0.3 μl of HEX-labelled product were mixed. Samples were denatured and loaded onto the ABI 373A sequencer (Applied Biosystems, Foster City, CA, USA). The data were processed using the GeneScan software (Applied Biosystems). For mice, three dinucleotide microsatellites, D1Mit62, D6Mit59 and D7Mit91, were analysed.

**DNA sequencing**

All the exons and exon-intron junctions of hMSH2 and hMLH1 were amplified by PCR using Taq polymerase with 3′ exonuclease activity. TaKaRa Ex Taq (TaKaRa Co. Ltd., Tokyo, Japan). Primer sequences are the same as reported by Kolodner et al. (13,14), except that the additional sequence complementary for M13 universal primer was deleted, and that one-step PCR was mainly employed. PCR products were used as a template for cycle sequencing reactions using BigDye terminator cycle sequencing kit (Applied Biosystems, Foster City, CA, USA). Mutations found in one PCR product were verified by reverse sequencing and finally confirmed in two independently amplified PCR products. Sequencing analyses of p53 gene (exon 5–9) were performed using p53 primers (Nippon Gene, Tokyo, Japan).

**Immunohistochemistry**

Tissue specimens were fixed in buffered 10% paraformaldehyde and embedded in paraffin. Prior to the assay, the specimens were sectioned at 4 μm and deparaffinized using xylene. Immunohistochemistry was performed using the streptavidin–biotin–peroxidase complex method (Histofine SAB kit, Nichirei, Tokyo, Japan) using an automated stainer (VENTANA Discovery System, Ventana Medical Systems Inc., Tucson, AZ, USA). At least, two independent antibodies...
were used to confirm the status of negative staining. Sections prepared from Msh2- and Mlh1-knockout mice were also used as negative controls. Antibodies used were as follows: anti-MSH2: NA27 and NA26 (Oncogene Research Products, Cambridge, MA, USA), anti-MLH1: PM-13291A (Phar Mingen, Hamburg, Germany), NA28 (Oncogene Research Products) and sc-581 (Santa Cruz Biotechnology Inc., Santa Cruz, CA, USA).

RESULTS
Two modes of dinucleotide microsatellite instability in human cancer

We have established a sensitive fluorescent technique for microsatellite analysis (11). Application of this technique to human cancers revealed a number of previously unrecognized aspects of MSI. In particular, we observed two distinct patterns of alterations at dinucleotide microsatellites in human malignancies (15–17). Examples are shown in Figure 1. In some cases, length changes are relatively small and affect ≤6 bp (Type A, Figure 1A–D). In the other, more dramatic changes involving ≥8 bp are observed (Type B) (Figure 1E–H). Because Type B alterations involve large differences in microsatellite length, it can sometimes appear as if a ‘third’ allele is present in addition to the parental alleles (Figure 1E–H). Throughout the analyses using this technique, results were highly reproducible in several independent experiments. Neither additional peaks nor changes in the ratio between peaks were noted.

Microsatellite instability observed in mismatch repair gene-knockout mice

To analyse MSI in a defined genetic background, we used the Msh2+/− MEF cell line RH95021 (12). Alterations in the lengths of three dinucleotide microsatellites were analysed in RH95021 subclones. The majority of subclones (14/21) exhibited the same configuration at the D6Mit59 locus (exemplified by clone a, Figure 2A). In clones that deviated from this predominant pattern (Figure 2A, clones b–d), the microsatellite length was altered by ≤4 bp. In other words, the microsatellite changes were invariably Type A. A similar pattern of small-scale microsatellite changes was observed at

Figure 1. Type A and Type B microsatellite instability observed in human colorectal cancer. Using genomic DNA samples prepared from cancer and the corresponding normal mucosa, microsatellite sequences, indicated at the right top of each panel, were amplified by PCR with primers differentially labelled with fluorescence, then mixed and run on a same lane in an automated DNA sequencer. The amount of each DNA fragment was quantitatively detected and its size was estimated with accuracy of 1 bp, by standardization with size markers run in each lane. Results representative for each mode of microsatellite instability are shown: red lines, cancer; green lines, normal mucosa; Type A, (A) (IC678), (B) (IC8710), (C) (IC721) and (D) (IC793); Type B, (E) (IC790), (F) (IC733), (G) (IC690) and (H) (NoTa). Patient codes in the parentheses correspond to those used in Table 1.
Figure 2. Microsatellite changes in Msh2−/− mouse embryonic fibroblast (MEF) cells and in tumours that arose in Msh2-knockout mice. (A) More than 20 subclones were isolated from RH95021 (Msh2−/−) MEF cells and microsatellite changes were compared among these subclones. The majority exhibited the same configuration (clone a) and a few deviated from this predominant pattern (clone b–d). In each clone, the pattern of clone A has been superimposed with green lines, to facilitate comparison. Results obtained in D6Mit59 microsatellite are shown. (B) RH95021 cells were continuously cultured and sampled at different passages. Results obtained in D6Mit59 microsatellite at passage 1, 20, 30 and 81 are shown. In passage 81, the initial profile at passage 1 has been superimposed with a green line. (C) Tumours that arose in vivo in Msh2-knockout mice were analysed. Representative results obtained in D7Mit91 (tumours a and b) and D6Mit59 (tumours c and d) microsatellites are shown: red lines, tumour; green lines, the corresponding normal tissue.

Table 1. hMSH2 and hMLH1 alterations found in tumours exhibiting Type A and Type B MSI

<table>
<thead>
<tr>
<th>PATIENT</th>
<th>MSI A/B</th>
<th>NUCLEAR EXPRESSION</th>
<th>exon</th>
<th>hMSH2</th>
<th>hMLH1</th>
<th>SEQUENCE</th>
<th>SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC869</td>
<td>A</td>
<td>P</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC678</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC692</td>
<td>A</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC721</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC724</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC759</td>
<td>A</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC793</td>
<td>A</td>
<td>P</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC807</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC806</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC815</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC874</td>
<td>A</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC826</td>
<td>A</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC832</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC833</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC850</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC851</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC853</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC698</td>
<td>B</td>
<td>P</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC733</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC735</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC649</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC662</td>
<td>B</td>
<td>P</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC673</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC674</td>
<td>B</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MSI, microsatellite instability; P, positive nuclear staining in immunohistochemistry; N, negative; *, determined by immunoblotting; Closed circle, base substitution with amino acid change; open triangle, possible polymorphism; Open rectangle, base substitution without amino acid change.
two other dinucleotide microsatellites, D1Mit62 and D7Mit91 (data not shown). To investigate whether Type B variations might simply reflect the accumulation of numerous smaller alterations over many generations, RH95021 cells were continuously cultured, and sampled periodically at different passages. As shown in Figure 2B, even after undergoing 81 population doublings (2^81 corresponds to 10^24), there was no detectable appearance of shorter or longer D6Mit59 alleles. Similar patterns were observed at the two other microsatellite loci (data not shown). Thus, there was no evidence of the accumulation of changes consistent with Type B instability at any of the three microsatellites in these MMR-defective MEFs. Similar data were obtained using a second MMR-deficient MEF cell line, MC2, which derived from an Mlh1−/− mouse (data not shown).

We also examined microsatellite instability in lymphomas and adenocarcinomas that arose in various organs of Msh2−/− mice. Among 16 tumours that were analysed at the three microsatellite loci, each contained alterations at one or more locus. In all cases, changes were limited to ≤6 bp (examples are shown in Figure 2C) and no Type B alteration was observed. Intriguingly, an examination of published microsatellite changes in cells of MMR gene-knockout mice clearly indicates that most changes are of Type A (12,18,19).

Analysis of microsatellites in MEFs and tumours from MMR-defective animals therefore indicates that Type A MSI is a direct consequence of defective MMR. The absence of more extensive microsatellite length changes may indicate further that an Msh2 or Mlh1 defect is insufficient for the development of Type B instability.

Mismatch repair gene inactivation is associated with both Type A and Type B MSI in human colorectal cancer

HNPCC patients inherit mutations in MMR genes (6,7). More than 90% of HNPCC tumours are MSI+ (20). The MSI+ phenotype is also frequent among sporadic colorectal carcinomas (2–4,6,21). Inspection of published data derived from the conventional microsatellite analysis reveals that microsatellite changes thus far reported in various tumours, including those in HNPCC individuals, are largely Type B (2–4,20–22). We considered the possibility that the more subtle Type A MSI might have remained undetected in some cases. Using our fluorescent assay with a panel of five dinucleotide repeat microsatellites, we found that the frequencies of Type A and Type B MSI among 79 colorectal carcinomas were 30% and 17%, respectively. In agreement with previous observations that Type B instability is common in HNPCC colon tumours, the IC690 tumour and the colorectal carcinoma cell line, NoTa (Table 1), both of which were derived from patients who fulfilled the Amsterdam Criteria II for HNPCC (23), exhibited Type B instability (Figure 1G and H). Our finding that 17% of colorectal tumours display Type B MSI is consistent with the generally reported figure of around 20% for MSI among colorectal carcinomas (20,24,25). The observation that a further 30% of tumours displayed Type A MSI suggests that the frequency of MSI, at least in colorectal carcinomas, has previously been underestimated.

The relationship between MSI and defective MMR in our set of colorectal tumours was investigated further. hMSH2 and hMLH1 MMR genes of 12 tumours with Type A and 9 with Type B MSI were sequenced. The same genes in the NoTa cell line were also sequenced (Figure 3A and Table 1). Sequence alterations causing amino acid substitutions were identified in 5 of the 21 tumours. Four of these (80%) were associated with Type A MSI. In addition, one patient with Type A MSI (IC793) in whom no mutation was identified was negative for immunohistochemical staining of hMLH1 (Figure 3B, panel b). This is consistent with a possible epigenetic hMLH1 gene silencing (26–28). In one other Type A case (IC669) and one Type B case (IC690), there was an abnormal intracellular distribution of hMLH1 which remained predominantly cytoplasmic (Figure 3B, panels c and d). Among the 10 tumours displaying Type B MSI, there was an example of base substitutions causing amino acid change in hMLH1. In this case, IC690, the failure of hMLH1 to localize to the nucleus was associated with the codon 226 mutation in exon 8 (Figure 3A, panels c and d).
Table 2. p53 mutations found in 79 colorectal carcinomas

<table>
<thead>
<tr>
<th>No.</th>
<th>Patient</th>
<th>EX05</th>
<th>EX06</th>
<th>EX07</th>
<th>EX08</th>
<th>EX09</th>
<th>Codon change</th>
<th>Base substitution</th>
<th>(type)</th>
<th>AA change</th>
<th>MSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IC628</td>
<td></td>
<td>196</td>
<td></td>
<td></td>
<td>273</td>
<td>CGT → CAT</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → His</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>IC630</td>
<td></td>
<td>196</td>
<td></td>
<td></td>
<td>306</td>
<td>CGA → TGA</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → stop</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>IC634</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>273</td>
<td>CAT → CGT</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>His → Arg</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>IC668</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>193</td>
<td>CGC → CAC</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → His</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>IC669</td>
<td>175</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TGC → AGC</td>
<td>A:T → T:A</td>
<td>TV</td>
<td>Cys → Ser</td>
<td>N</td>
</tr>
<tr>
<td>6</td>
<td>IC673</td>
<td>176</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GAG → AAG</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Glu → Lys</td>
<td>N</td>
</tr>
<tr>
<td>7</td>
<td>IC674</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>285</td>
<td>ATC → ACC</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>Ile → Thr</td>
<td>A</td>
</tr>
<tr>
<td>8</td>
<td>IC680</td>
<td>ND</td>
<td>255</td>
<td></td>
<td></td>
<td>273</td>
<td>CAT → CTT</td>
<td>A:T → T:A</td>
<td>TV</td>
<td>His → Leu</td>
<td>A</td>
</tr>
<tr>
<td>9</td>
<td>IC693</td>
<td>179</td>
<td></td>
<td></td>
<td></td>
<td>273</td>
<td>CGT → CAT</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → His</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>IC694</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>239</td>
<td>AAC → GAC</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>Asn → Asp</td>
<td>N</td>
</tr>
<tr>
<td>11</td>
<td>IC711</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>175</td>
<td>CGC → CAC</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → His</td>
<td>A</td>
</tr>
<tr>
<td>12</td>
<td>IC721</td>
<td>175</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CCT → CTT</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Pro → Leu</td>
<td>A</td>
</tr>
<tr>
<td>13</td>
<td>IC748</td>
<td>190</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CGA → CCA</td>
<td>G:C → C:G</td>
<td>TV</td>
<td>Arg → Pro</td>
<td>N</td>
</tr>
<tr>
<td>14</td>
<td>IC754</td>
<td>196</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CCC → CAC</td>
<td>G:C → T:A</td>
<td>TV</td>
<td>Pro → His</td>
<td>N</td>
</tr>
<tr>
<td>15</td>
<td>IC763</td>
<td>151</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CGC → CAC</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → His</td>
<td>N</td>
</tr>
<tr>
<td>16</td>
<td>IC772</td>
<td>175</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CAT → GTG</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>His → Arg</td>
<td>A</td>
</tr>
<tr>
<td>17</td>
<td>IC778</td>
<td>175</td>
<td>ND</td>
<td>214</td>
<td></td>
<td>273</td>
<td>CAT → CTT</td>
<td>A:T → C:G</td>
<td>TV</td>
<td>Tyr → Asp</td>
<td>A</td>
</tr>
<tr>
<td>18</td>
<td>IC784</td>
<td>205</td>
<td></td>
<td></td>
<td></td>
<td>273</td>
<td>CCT → CTT</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Pro → Leu</td>
<td>N</td>
</tr>
<tr>
<td>19</td>
<td>IC808</td>
<td>190</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CAT → GTG</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>His → Arg</td>
<td>A</td>
</tr>
<tr>
<td>20</td>
<td>IC812</td>
<td></td>
<td></td>
<td></td>
<td>248</td>
<td>273</td>
<td>CGG → CAG</td>
<td>G:C → A:T</td>
<td>TS</td>
<td>Arg → Gln</td>
<td>N</td>
</tr>
<tr>
<td>21</td>
<td>IC816</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CAT → GTG</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>Arg → His</td>
<td>A</td>
</tr>
<tr>
<td>22</td>
<td>IC819</td>
<td>248</td>
<td></td>
<td></td>
<td></td>
<td>273</td>
<td>CAT → GTG</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>Arg → His</td>
<td>A</td>
</tr>
<tr>
<td>23</td>
<td>IC860</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CAT → GTG</td>
<td>A:T → G:C</td>
<td>TS</td>
<td>Arg → His</td>
<td>A</td>
</tr>
</tbody>
</table>

MSI, microsatellite instability; N, negative; A, Type A MSI; TS, transition; TV, transversion; ND, not determined. Bold codon numbers indicate the acknowledged hot-spots for mutation.

Table 3. p53 mutation highly correlates with Type A MSI

<table>
<thead>
<tr>
<th>p53</th>
<th>MSI Type A</th>
<th>MSI Type B</th>
<th>MSI Negative</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild type</td>
<td>13</td>
<td>14</td>
<td>29</td>
<td>56</td>
</tr>
<tr>
<td>Mutant</td>
<td>12</td>
<td>0</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>Subtotal</td>
<td>25</td>
<td>14</td>
<td>40</td>
<td>79</td>
</tr>
</tbody>
</table>

p = 0.006. MSI: Microsatellite instability.

DISCUSSION

The fluorescent technique we used here allows the unequivocal designation of Type A and Type B MSI, and has revealed a previously unrecognized complexity in the relationship between dinucleotide MSI and defective DNA MMR in human cancer. Type A MSI (changes ≤ 6 bp) is clearly linked with MMR inactivation in both mice and humans, which implies that Type A MSI is a direct consequence of defective MMR. Since we found no evidence of Type B instability (changes ≥ 8 bp) in MMR-defective animals, it is possible that changes in addition to repair deficiency contribute to, or are responsible for, Type B MSI. One important finding of this study is that Type A instability is frequent among human tumours. Type A MSI predominated in our large panel of colorectal carcinomas. We suggest that, because the changes associated with Type A instability are more subtle, the frequency of MSI among colorectal tumours may have been considerably underestimated. Our findings also reveal a hitherto unrecognized association between defective MMR and p53 mutation. Significantly, Type A MSI was strongly associated with p53 mutation in human colorectal tumours. Since Type A instability is unequivocally associated with MMR deficiency, this novel finding implies that, in contrast to prevailing opinion, p53 mutations are common in MMR-defective tumours, at least in human colorectal cancer.

Established guidelines for classification of MSI utilize hot-spots for mutation.

p53 mutation is strongly associated with Type A MSI in human colorectal cancer

One view of the involvement of MMR defects in cancer development is that the ‘microsatellite mutator phenotype (MMP)’ (29,30) in mismatch repair-defective cells offers an alternative to chromosomal instability as a mechanism for genetic instability in cancer (31). On this model, MSI and chromosomal instability represent mutually exclusive pathways of tumour development. This reasoning is based partly in the observation that p53 mutations, commonly associated with chromosomal instability, are infrequent among MSI+ tumours (2,32–34). To examine the relationship between Type A/B instability and p53 mutation, we sequenced the p53 gene in our panel of 79 colorectal tumours. p53 mutations resulting in an amino acid substitution were detected in 23 tumours (29.1%). The mutations were predominantly transitions in acknowledged hot spots; codons 175, 248 and 273 (Table 2). Of the p53 mutations that were found in MSI+ tumours, all were associated with Type A MSI (Tables 2 and 3). No p53 mutations were detected among the 14 Type B tumours. Among Type A tumours, the frequency of p53 mutation approached 50% (12/25). These findings confirm that p53 mutations are rare in tumours with Type B MSI. More importantly, they suggest that, in contrast to prevailing opinion, defective MMR is significantly associated with p53 mutation, at least in human colorectal cancer.
markers, i.e. MSI-H and -L (10). However, qualitative differences in microsatellite changes are not widely discussed. In one of the earliest report of the MSI phenomenon, however, Thibodeau et al. divided microsatellite changes into two categories; Type I and II mutations (3). The former was defined a ‘significant increase (expansion) or decrease (deletion) in the apparent fragment size’ and the latter as a ‘single 2 bp change’. This distinction has received little attention since then. Our data indicate that Type A MSI, which appears similar to their Type II mutation, is more frequent than hitherto suspected, and suggest that it represents the bona fide MMR-deficient phenotype. On the other hand, Type I mutations may correspond to our Type B instability. The problem is that mutations in MMR genes have been reported in tumours displaying this type of instability. More than 90% of HNPCC tumours are MSI (20), and this type of MSI can be categorized as Type B/Type I (2–4,20–22). However, the frequencies of mutation in the two major MMR genes, hMSH2 and hMLH1, in HNPCC kindred are not high in some reports (35–40). Among the panel of tumours displaying Type B MSI, we found a base substitution mutation in hMLH1 and one case with a possible hMLH1 silencing. This incidence of MMR gene inactivation in the Type B group is not unduly low, compared with the reported frequencies in the literature (25,36,41–43). The relationship between Type B MSI and defective MMR is probably more complex than hitherto suspected.

Type B MSI may involve molecular abnormalities in addition to defective MMR. We suggest that whereas Type A MSI probably reflects the uncorrected DNA polymerase slippage events that accumulate in MMR-defective cells, inappropriate processing of damage by recombinational DNA repair may contribute to Type B MSI. This hypothesis may be supported partly by our observation that there was no evidence of the emergence of Type B instability in MMR gene-knockout animals. It is known that microsatellite alterations occur via several independent mechanisms, including recombination (44–46), and MMR counteracts incorrect strand alignment during homologous recombination (47). The drastic microsatellite changes in Type B MSI may be more consistent with dynamic events, such as recombination, than with replication slippage. In this context, defective MMR might be a promoting, and consequently highly coincidental, but insuffi- cient factor for Type B changes. Connection between MSI and the recombinational repair pathway in tumours, particularly in HNPCC, may warrant attention.

Type A MSI is also strongly associated with p53 mutation in human colorectal tumours. This observation may be compatible with several recent reports (36,48,49) that have shown a connection between p53 mutation and the MSI-L phenotype, since in colorectal cancer Type A MSI tends to be observed in a limited number of markers and, consequently, categorized as MSI-L. This finding may also provide an insight to the mechanism of genetic instability in tumours. Genetic instability in tumours has been regarded as deriving from two mutually exclusive pathways, chromosomal instability (CIN)—frequently associated with mutations in various oncogenes or tumour suppressor genes such as p53—and ‘microsatellite mutator phenotype (MMP)’ (29,30), in which p53 mutations are rare and, instead, mutations are found in mono- nucleotide repeats within genes of a different variety. Several recent reports suggest that there might be an oversimplification in this distinction (50–53). From our observations, dinucleotide MSI in tumours can be divided into two modes, Type A and Type B, and Type A instability is the direct consequence of defective MMR. A close association of Type A MSI with p53 mutation may suggest a hitherto unrecognized causal relationship between p53 mutation and defective MMR. p53 mutations may derive from a state with an elevated mutation rate, i.e. MMR-deficient phenotype, as initially suspected. Thus, our observations suggest added complexities to the relationship between MMR defects and MSI, and also shed light on previously unrecognized fundamental processes in the molecular mechanisms of genetic instability underlying tumour development.

ACKNOWLEDGEMENTS

We are extremely grateful to Drs H. te Riele and M Liskay for providing the RH95021 and MC2 cell lines, respectively. The expert assistance in DNA sequencing by Y. Baba, K. Miyamoto, Y. Ikematsu and K. Funatsu is also gratefully acknowledged. This study was supported by a Grant-in-aid for Cancer Research from the Ministry of Health, Labour and Welfare, and grants from the Ministry of Education, Science, Sports and Culture of Japan. The Open Access publication of this article was also supported in part by these grants.

Conflict of interest statement. None declared.

REFERENCES


