



Short communication

Mouse mammary tumor viral *env* sequences are not present in the human genome but are present in breast tumors and normal breast tissues

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ARTICLE INFO

Keywords:

Mouse mammary tumor virus
Breast cancer
The UCSC Genome Browser
The Cancer Genome Atlas

ABSTRACT

In 1936, John Joseph Bittner identified mouse mammary tumor virus (MMTV), a milk transmitted beta retrovirus, a form of single-stranded positive-sense RNA virus. A retrovirus inserts a copy of its genome into the DNA of a host cell, thus altering the cell's genome. In the current analysis, we searched for MMTV sequences within the human genome. To compare the MMTV genome to the human genome, we used BLAT, the Blast-Like Alignment Tool of the UCSC Genome Browser. BLAT can align a user sequence of 25 bases or more to the genome. 60 MMTV sequences were in the human genome. Of 56 sequences from the MMTV POL gene, 36 POL sequences were from the same part of the gene, beginning at viral nucleotide 4800 but of different lengths. 8 viral sequences began at nucleotide ~3430 of the POL gene. Four viral sequences were from GAGdUTPase, encoded by the MMTV PRO gene. Deoxyuridine 5'-triphosphate nucleotidohydrolase (dUTPase) is an enzyme present in several major retroviral families. In MMTV dUTPase may be essential for viral replication. Since BLAT identified no MMTV envelope (*env*) sequence in the human genome, the *env* sequences from breast tumors and normal breast tissue found in other studies may have come from an MMTV infection. However, no one is certain how MMTV could enter human cells, since the cells do not have a cellular receptor for MMTV, as do mouse cells.

Breast cancer is the most common form of cancer in women. The cause of sporadic cases is usually difficult to ascertain. A minority, about 30%, are related to a gene.

An infectious origin is sometimes inferred, since 16% of all human cancer can be attributed to a micro-organism. Among the viruses that might be related to breast cancer are papillomaviruses, herpes viruses and retroviruses. The mouse mammary tumor virus (MMTV), especially, has always been a prime suspect (Gannon et al., 2018; Lawson et al., 2018).

In 1936, John Joseph Bittner identified MMTV, a milk transmitted beta retrovirus, a form of single-stranded positive-sense RNA virus. A retrovirus inserts a copy of its genome into the DNA of a host cell, thus altering the cell's genome.

MMTV is a lentivirus (lente-, Latin for "slow"), a genus of retroviruses that cause chronic, lethal diseases with long incubation periods in humans and other mammals. The best known lentivirus is the Human Immunodeficiency Virus (HIV). Lentiviruses can become endogenous, integrating their genome into the host germline genome. The virus or part thereof is then inherited by the host's offspring. In the current analysis, we searched for MMTV sequences within the entire human genome.

We utilized the UCSC Genome Browser, an on-line genome browser at the University of California, Santa Cruz (UCSC). The browser is an interactive website offering access to genome sequence data from a variety of vertebrate and invertebrate species and major model organisms, integrated with a large collection of aligned annotations. The graphical viewer is optimized to support fast interactive performance and is an open-source, web-based tool suite built on top of a MySQL database for rapid visualization, examination, and querying of data at many levels. The Genome Browser Database, browsing tools, downloadable data files, and documentation are all accessible on the UCSC Genome Bioinformatics website (<https://genome.ucsc.edu>) (Kuhn et al., 2013).

To compare the MMTV genome to the human genome, we used BLAT, the Blast-Like Alignment Tool of the UCSC Genome Browser (Kuhn et al., 2013). BLAT can align a user sequence of 25 bases or more to the genome. Because some level of mismatch is tolerated, cross-species alignments may be performed provided the species have not diverged too far from each other; this capability allowed comparison of the MMTV genome to the human genome. BLAT calculates a percent identity score to indicate differences between sequences without a perfect match (i.e. without 100% identity). The differences include

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<https://doi.org/10.1016/j.virusres.2019.03.011>

Received 7 February 2019; Received in revised form 12 March 2019; Accepted 14 March 2019

Available online 03 April 2019

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Table 1

60 MMTV sequences BLAT identified in the human genome. The viral sequences are of approximately three varieties. Four are from GAGdUTPase. 8 begin at viral nucleotide ~3430 of the POL gene. 48 begin at viral nucleotide ~4800 of the POL gene.

VIRAL SEQ			Human				Viral	Sequence	MMTV
Size	Identity	Chromosome	Gene	Strand	Start	End	Start	End	Gene
253	64.5%	6q22.31		+	121365109	121365361	3084	3336	GAGdUTPase
253	64.1%	11q14.3		-	92681138	92681390	3084	3336	GAGdUTPase
49	91.9%	11p12		-	43188209	43188291	3084	3166	GAGdUTPase
197	67.6%	8p11.1		-	43553754	43553977	3230	3453	GAGdUTPase
56	91.1%	4q22.1		-	88326156	88326406	3434	3684	POL
65	92.4%	11q12.1		-	56096830	56097083	3434	3687	POL
254	57.1%	17q21.31		-	41406291	41406544	3434	3687	POL
25	96.0%	19q13.41	ZNF578	-	52979141	52979165	3434	3458	POL
65	90.8%	Xq22.1		-	100441118	100441371	3434	3687	POL
20	100.0%	6 qbl hap6	HLA-DRB1	-	3763979	3763998	3440	3459	POL
44	86.4%	11q22.1		-	101087161	101087204	3620	3663	POL
21	100.0%	19p12		-	20687696	20687716	3643	3663	POL
98	75.6%	1q25.2		-	178525196	178525383	4797	4992	POL
72	84.8%	3p12.3		+	75605430	75605727	4799	5097	POL
297	66.0%	1q23.3	CD48	+	160666454	160666750	4800	5097	POL
298	66.5%	1q22	BC041646	-	155599516	155599813	4800	5097	POL
104	83.7%	1p36.21		+	13684991	13685276	4800	5085	POL
82	83.0%	1p22.2		-	89553867	89553948	4800	4881	POL
298	66.8%	3q12.3		+	101416506	101416803	4800	5097	POL
220	70.0%	5p13.1		+	40109055	40109621	4800	5354	POL
199	69.9%	6p11.2		+	57626420	57626705	4800	5085	POL
41	85.4%	6q14.3		-	87209196	87209236	4800	4840	POL
286	65.8%	8q24.3		-	146250053	146250338	4800	5085	POL
199	71.9%	8q11.1		-	47179713	47179998	4800	5085	POL
286	66.8%	9q34.11	CCBL1	+	131616161	131616446	4800	5085	POL
110	84.6%	10q24.2	ABCC2	-	101582566	101582864	4800	5097	POL
298	66.8%	11q22.1		+	101571611	101571908	4800	5097	POL
286	63.3%	15q21.3		+	55182155	55182440	4800	5085	POL
110	75.5%	19q13.12		-	36065731	36066011	4800	5097	POL
286	64.0%	22q11.23		+	23885809	23886094	4800	5085	POL
269	67.0%	Xq28		-	153840065	153840351	4800	5085	POL
105	78.1%	7p12.3		+	48182602	48183141	4801	5352	POL
225	63.2%	1q21.3	GOLPH3L	+	150629956	150630587	4802	5370	POL
56	78.6%	2q11.2	MRPL30	-	99889556	99889611	4802	4857	POL
113	78.8%	3q25.1		+	151422866	151423419	4802	5357	POL
191	62.9%	3q13.11		+	102932546	102932736	4802	4992	POL
191	64.4%	4q35.1		-	185967894	185968084	4802	4992	POL
191	62.4%	4q21.3	MAPK10	+	87386270	87386460	4802	4992	POL
24	95.9%	4q13.3		+	74233739	74233762	4802	4825	POL
128	78.2%	7p12.3		-	46079431	46079992	4802	5359	POL
94	74.5%	8q24.23		-	137922224	137922413	4802	4992	POL
214	66.4%	17q11.2		+	29963846	29964402	4802	5359	POL
229	66.0%	17q11.2		+	26026606	26027172	4802	5359	POL
234	68.9%	19p13.2	ZNF433	+	12136441	12137033	4802	5385	POL
191	63.9%	19p13.2		+	9569541	9569731	4802	4992	POL
191	62.9%	19p12		-	21851294	21851484	4802	4992	POL
45	95.6%	19q13.41		-	53254794	53254985	4802	4992	POL
269	56.9%	Yq11.223		-	26164973	26165241	4808	5076	POL
250	60.4%	4q21.23		-	86047722	86047976	4829	5085	POL
274	62.5%	5p14.3		-	18783631	18784154	4829	5353	POL
30	93.4%	Xq28		+	148806315	148806344	4829	4858	POL
267	65.6%	5p13.3		-	30490099	30490365	4831	5097	POL
159	66.1%	Yp11.2		-	8984533	8985051	4847	5359	POL
56	82.2%	1q32.3		-	213200478	213200890	4955	5359	POL
56	82.2%	1q21.3	NUP210L	+	154024314	154024721	4955	5354	POL
57	80.8%	14q21.1		-	42777950	42778368	4955	5359	POL
40	92.5%	5q22.3		-	114373450	114373842	4976	5359	POL
29	89.7%	1q24.1	FMO9P	-	166577918	166577946	5057	5085	POL
28	92.9%	7p14.1		+	38202294	38202321	5057	5084	POL
29	96.6%	Yp11.2	TBL1Y	-	6829855	6829884	5057	5085	POL

mismatches and gaps (Bhagwat et al., 2012). The MMTV sequence we analyzed with BLAT was FASTA Mouse mammary tumor virus, complete genome, NCBI Reference Sequence: NC_001503.1.

Because of the genetic basis for breast cancer (Shiovitz and Korde, 2015), we used cBioportal to access data in The Cancer Genome Atlas (TCGA). cBioPortal for Cancer Genomics provides visualization, analysis and download of large-scale cancer genomics data sets (<http://www.cbioportal.org>). The Cancer Genome Atlas is a project, begun in

2005, to catalog genetic mutations responsible for cancer, using genome sequencing and bioinformatics. We used the KM curve plotting tool in the UCSC Xena Browser to evaluate survival (<https://xenabrowser.net>). UCSC Xena allows users to explore functional genomic data sets for correlations between genomic and/or phenotypic variables.

60 MMTV sequences BLAT identified in the human genome are listed in Table 1. The viral sequences are of three groups, but of variable

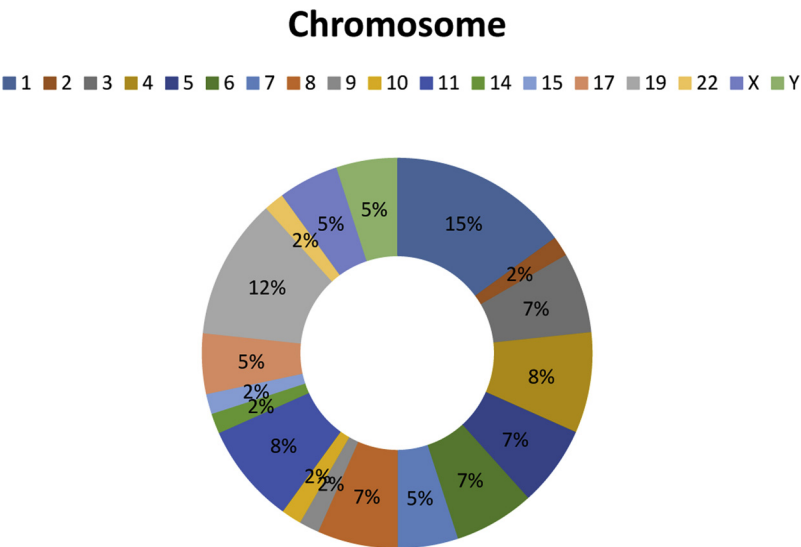


Fig. 1. Distribution of MMTV sequences in the human genome by chromosome. The largest percentage of sequences (15%) is within chromosome 1. Chromosome 3 had 7% and chromosome 11 had 8%, chromosome 19 12%.

length.

- Of 56 sequences from the MMTV POL gene, 36 POL sequences were from the same part of the gene, beginning at viral nucleotide 4800 but of different lengths.
- 8 viral sequences began at nucleotide ~3430 of the POL gene.
- Four viral sequences were from GAGdUTPase, encoded by the MMTV PRO gene. Deoxyuridine 5'-triphosphate nucleotidohydrolase (dUTPase) is an enzyme present in several major retroviral families. In MMTV dUTPase may be essential for viral replication (Hizi and Herzig, 2015).

Distribution of MMTV sequences in the human genome by chromosome is shown in Fig. 1. Most of the sequences (15%) are within chromosome 1. Next was chromosome 19 (12%). Chromosome 3 had 7% of MMTV sequences and chromosome 11 had 8%. No sequence was from the MMTV *env* (envelope) gene. Moreover, BLAT did not identify ENV sequences in the baboon genome, bonobo genome, chimpanzee genome, gorilla genome, or green monkey genome.

The 297 BP MMTV POL gene sequence in an intronic region of the human CD48 gene is shown in the UCSC genome browser (Fig. 2). Increased RNA expression of the sequence is associated with increased survival (Fig. 3).

MMTV sequences BLAT identified in the human genome were in

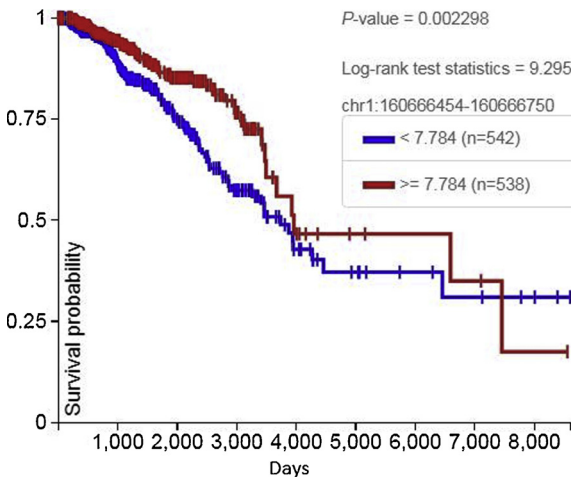


Fig. 3. Increased RNA expression of the 297 BP MMTV POL gene sequence in an intronic region of the human CD48 gene is associated with increased overall survival.

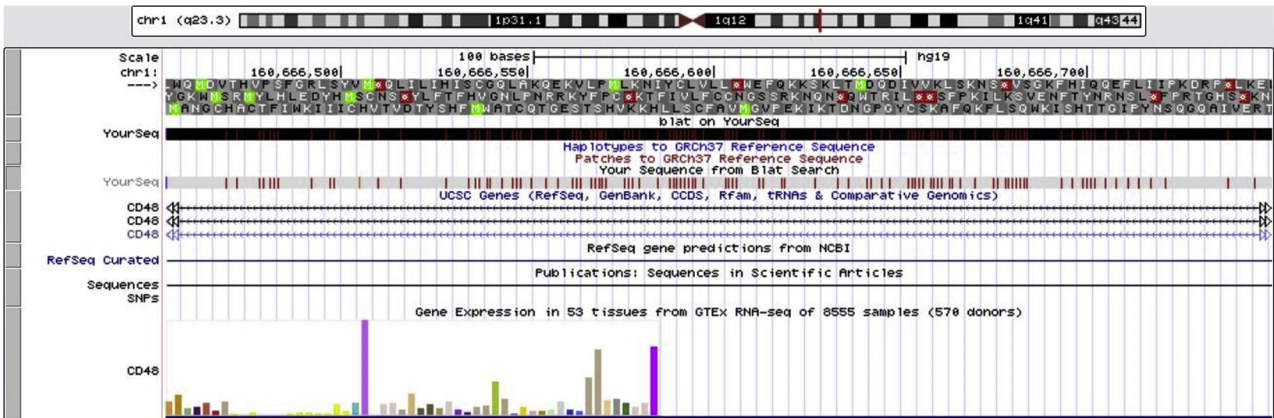


Fig. 2. The 297 BP MMTV POL gene sequence in an intronic region of the human CD48 gene is shown in the UCSC genome browser. Red: Genome and MMTV sequence have different bases at this position. Green: The query sequence appears to have a polyA tail that is not aligned to the genome.

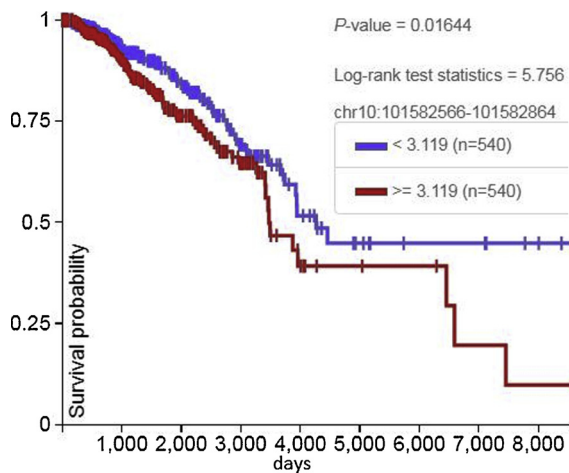


Fig. 4. Increased RNA expression of the 110 BP MMTV POL gene sequence in an intronic region of the human ABCC2 gene is associated with diminished overall survival.

intronic segments of these genes:

- CD48 (1q23.3). The CD48 molecule is a glycosyl-phosphatidyl-inositol (GPI)-anchored cell-surface protein of the CD2 family of molecules (Elishmereni and Levi-Schaffer, 2011). In breast cancer patients, CD48 expression is a favorable sign (Fig. 2).
- HLA-DRB1 (chr 6qbl hap6). HLA-DRB1 has a key function in the immune system by presenting peptides derived from extracellular proteins. In breast cancer HLA-DRB1 may represent a protective allele (Chaudhuri et al., 2000) (RefSeq Summary NM_002124)
- ABCC2 (MRP2, cMOAT) (chr 10q24.2). ABC proteins transport various molecules across extra- and intra-cellular membranes and belong to the MRP subfamily, involved in multi-drug resistance. ABCC2 is localized in the nuclear envelope of breast carcinoma cells and increased expression correlates with poor clinical outcome (Fig. 4) (Maciejczyk et al., 2012).
- MAPK10 (chr 4q21.3) The protein encoded by this gene is a member of the MAP kinase family. MAP kinases act as integration points for multiple biochemical signals, and thus are involved in a wide variety of cellular processes, including proliferation, differentiation, transcription regulation and development (RefSeq Summary NM_138980). A breast cancer susceptibility locus has recently been identified on chr 4q.21 (Hamdi et al., 2016).
- MRPL30 (chr 2q11.2) Mammalian mitochondrial ribosomal proteins are encoded by nuclear genes and help in protein synthesis within mitochondria. (RefSeq Summary NR_028356)
- TBL1Y (chr Yp11.2) This gene is highly similar to TBL1X gene in nucleotide sequence and protein sequence, but the TBL1X gene is located on chromosome X and TBL1Y is on chromosome Y, and therefore would be unrelated to female breast cancer.
- GOLPH3L (chr 1q21.3) The Golgi complex plays a key role in the sorting and modification of proteins exported from the endoplasmic reticulum. GOLPH3L is associated with poor prognosis of patients with epithelial ovarian cancer and may be an independent prognostic factor (Feng et al., 2015).
- NUP210L (chr 1q21.3) Homo sapiens nucleoporin 210 kDa-like (NUP210L), transcript variant 1, mRNA. Chromosome 1q21.3 amplification is a trackable biomarker and actionable target for breast cancer recurrence (Goh et al., 2017).
- ZNF578 (chr 19q13.41) Homo sapiens zinc finger protein 578 (ZNF578), mRNA. A polymorphism at 19q13.41 predicts breast cancer survival after endocrine treatment (Khan et al., 2015).
- TheZNF433 (chr 19p13.2) Human zinc finger protein may be a susceptibility gene for multiple sclerosis (Nischwitz et al., 2010).

High-resolution 19p13.2-13.3 allelotyping of breast carcinomas demonstrates frequent loss of heterozygosity (Yang et al., 2004).

- FMO9P (chr 1q24.1). Chr 1q24.1-2 has been found amplified in the JIMTI breast cancer cell line (Jonsson et al., 2007).

8 percent of DNA in the human genome comes from human endogenous retroviruses (HERV), and some human diseases have been attributed to this DNA. HERV sequences have occasionally been adopted by the human body to serve a useful purpose, such as in the placenta, where they may safeguard fetal-maternal tolerance (Kurth and Bannert, 2010). Some HERV sequences have oncogenic properties; yet treating cancer cells with methyltransferase inhibitors increases HERV RNA and DNA. Like infectious agents, the HERV-derived nucleic acids in the cytoplasm activate innate immune responses that produce tumor cell apoptosis (Bannert et al., 2018; Wildschutte et al., 2016).

Mouse mammary tumor virus (MMTV)-like elements have been identified in the genomes of pikas (*Ochotona* sp.), herbivorous smaller relatives of rabbits and hares. Lemos de Matos et al. found a nearly complete MMTV-like virus (Pika-BERV) in the American pika genome, which was estimated to have invaded the host genome around 3–7 million years ago, coinciding with the divergence time of American pikas from Asian pikas (Lemos de Matos et al., 2015).

Foley has analyzed the molecular phylogeny of lentiviruses and constructed phylogenetic trees of the POL and GAG genes. Foley reported that the protein-coding regions of the lentiviral genome are conserved to varying degrees, with GAG and POL being more conserved overall than TAT or ENV (Foley, 2000).

MMTV POL-Related Sequences have been reported in human DNA (Deen and Sweet, 1986). Similar MMTV-related sequences are present in normal breast tissue. The tissue sequences are over 90% homologous to the nucleotide sequence of the MMTV POL gene. In one study, no significant difference was found when comparing DNA from normal and tumor tissue (Moyret et al., 1992); and MMTV is not associated with neuroendocrine human breast cancers (Lawson et al., 2017).

By using a DNA fragment primarily encoding the POL region of the Syrian hamster intracisternal A particle (IAP; type A retrovirus) gene as a probe, human endogenous retrovirus genes, tentatively termed HERV-K genes, were cloned from a fetal human liver gene library. Typical HERV-K genes were 9.1 or 9.4 kb in length. By filter hybridization, the number of HERV-K genes was estimated to be approximately 50 copies per haploid human genome. The cloned mouse mammary tumor virus (type B) gene was found to hybridize with both the HERV-K and IAP genes to essentially the same extent (Ono, 1986; Ono et al., 1986). The 56 MMTV POL sequences we report here (Table 1) were considerably shorter, 20–298 BP, and correspond to only small sections of the MMTV genome, not the entire genome, as do the HERV-K genes.

As noted above, four MMTV viral sequences in the human genome were from GAGdUTPase, encoded by the MMTV PRO gene. During the replication of retroviruses, large numbers of Gag molecules must be generated to serve as precursors to the structural proteins of the virions. The enzymes encoded by the PRO and POL genes are, in most cases, needed in smaller numbers to carry out catalytic functions (Hughes and Varmus, 1999).

Whether MMTV or a related virus infects humans is controversial. MMTV DNA sequences have been detected inconsistently and serologic methods have varied widely. One study showed no MMTV-specific antibodies in 92 US women with breast cancer (Goedert et al., 2006). A second study could not confirm the presence of MMTV in human breast cancer patients (Perzova et al., 2017). Other studies have revealed antibodies (Nartey et al., 2017).

Yet MMTV-like *env* sequences (envelope protein sequences, also called HMTV sequences to denote their source) were found in 9 of 25 breast cancer specimens (36%). Among 25 non-cancerous breast biopsies of the same patients taken 1 to 11 years earlier, six contained MMTV-like sequences (24%). Five of the six were among the nine virally-associated breast cancers. In two pairs of specimens, benign and

malignant, *env* sequences were 97% identical (Nartey et al., 2017).

Since BLAT identified no MMTV *env* sequence in the human genome, the *env* sequences may have come from an MMTV infection. However, no one is certain how MMTV could enter human cells, since the cells do not have a cellular receptor for MMTV, as do mouse cells (Brower, 2009).

As noted above (Fig. 1) the largest percentage of the MMTV sequences (15%) is within chromosome 1. Next was chromosome 19 (12%). Chromosome 3 had 7% of MMTV sequences and chromosome 11 had 8%. In one study, loss of heterozygosity (LOH) was observed in 30 chromosomal loci of primary breast tumors and 48 chromosomal loci of metastatic lesions. In metastatic lesions, incidence of LOH was highest on chromosome 19, followed by chromosomes 14, 3, and 11 (Li et al., 2014).

In sum, MMTV *env* sequences are not present in the human genome but are present in breast tumors and normal breast tissues. This finding suggests that MMTV infection may be related to human breast cancer. More evidence of causation is still needed.

Funding sources

None.

Conflicts of interest

None.

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