An influenza A(H1N1)pdm09 virus carrying a G147R substitution in combination with an H275Y substitution in the neuraminidase protein, which confers cross-resistance to oseltamivir and peramivir, was detected from an immunocompromised inpatient in Japan, March 2016. This dual H275Y/G147R mutant virus exhibited enhanced cross-resistance to both drugs compared with the single H275Y mutant virus and reduced susceptibility to zanamivir, although it showed normal inhibition by laninamivir.

Detection of a dual H275Y/G147R mutant influenza A(H1N1)pdm09 virus

In the context of our nationwide monitoring for antiviral-resistant viruses, we previously reported that a large community cluster of influenza A(H1N1)pdm09 virus exhibiting cross-resistance to oseltamivir and peramivir had occurred in Hokkaido, Japan between November 2013 and February 2014 [1,2]. Of a total of 2,531 A(H1N1)pdm09 viruses investigated in the 2013/14 influenza season, 105 (4.1%) were shown to harbour the H275Y substitution in the neuraminidase (NA) protein. In the 2015/16 season (Figure 1), we screened 1,938 A(H1N1)pdm09 viruses by allelic discrimination [3] and detected 39 (2.0%) H275Y mutant viruses.

No epidemiological links were identified among the patients infected with the H275Y mutant viruses except for five nosocomial infections. Among 34 sporadic cases, 11 (32%) cases had no exposure to NA inhibitors before the specimen collection. This is consistent with our previous study that 19 (32%) of 59 sporadic cases had no exposure to NA inhibitors in the 2013/14 season [2]. One H275Y mutant virus with an additional G147R substitution in the NA protein was detected from a sporadic case treated with peramivir in March 2016. Both substitutions were confirmed in the corresponding clinical specimen. Deep sequencing analysis of the specimen using MiSeq (Illumina, California, United States) revealed that the G147R substitution was detected in 21% of mixed sequence populations with 147G wild type, in contrast to H275Y, which was detected at a rate of 100%. The results suggested that the H275Y mutant virus had acquired the additional G147R substitution in the patient during peramivir administration. The NA H275Y mutation of the A(H1N1)pdm09 and the former seasonal A(H1N1) viruses confers cross-resistance to oseltamivir and peramivir [4] and the NA G147R is linked to slightly reduced susceptibility of the highly pathogenic avian A(H5N1) virus to oseltamivir and zanamivir [5]. Searching the EpiFlu Database of the Global Initiative on Sharing All Influenza Data (GISAID) yielded 18,172 A(H1N1)pdm09 viruses, of which nine were G147R mutant viruses (Table). No dual H275Y/G147R substitution appears to have been previously reported however.

Clinical course of the patient infected with the dual H275Y/G147R mutant virus

The patient, a woman in her early 50s with malignant lymphoma who was receiving chemotherapy, was hospitalised with myelosuppression in late February 2016. She received prophylaxis with laninamivir (40 mg) on the same day because her husband had been diagnosed as having influenza A virus infection. Three days later, she had onset of illness and tested positive for influenza A. At this time, peramivir was administered intravenously at a dosage of 600 mg daily for three intermittent periods of 5 days because of persistent influenza A virus infection. She developed left lower
After isolation in MDCK cells, A/Hiroshima/13/2016 possessed the H275Y and G147R substitutions in 100% population, respectively, although the G147R mutation was detected at a rate of 21% in the specimen. We could not obtain a specimen from the husband.

Antiviral susceptibility of the dual H275Y/G147R mutant virus

After isolation in MDCK cells, A/Hiroshima/13/2016 possessed the H275Y and G147R substitutions in 100% population, respectively, although the G147R mutation was detected at a rate of 21% in the specimen. We compared the susceptibilities of the dual H275Y/G147R mutant virus and single H275Y mutant viruses isolated during the same influenza season to four NA inhibitors approved in Japan: laninamivir, oseltamivir, peramivir and zanamivir (Figure 2).

Osel tamivir carboxylate, peramivir and zanamivir were purchased from Sequoia Research Products (Pangbourne, UK) and laninamivir was kindly provided by Daiichi Sankyo Co., Ltd. (Tokyo, Japan). The susceptibilities of the viruses to NA inhibitors were determined by fluorescent NA inhibition assay with the NA-Fluor Influenza Neuraminidase Assay Kit (Applied Biosystems, California, United States). Results were expressed as the drug concentrations required to inhibit NA activity by 50% (IC$_{50}$). To interpret the NA inhibitor susceptibility, we used the World Health Organization criteria, which are based on the fold change of IC$_{50}$ values compared with the median IC$_{50}$ values of the same subtype/lineage [6]. For influenza A viruses, normal (<10-fold increase of IC$_{50}$ value), reduced (10–100-fold increase) or highly reduced (>100-fold increase) inhibition were defined.

The IC$_{50}$ values of the viruses to laninamivir, oseltamivir, peramivir and zanamivir are shown in Figure 2. The median IC$_{50}$ values of 19 single H275Y mutant viruses to oseltamivir and peramivir were 920- and 260-fold higher, respectively, than those of the 236 wild-type viruses. The dual H275Y/G147R mutant virus exhibited 2,600- and 1,400-fold higher IC$_{50}$ values compared with those for the single H275Y mutant viruses. Furthermore, the IC$_{50}$ value of the dual mutant virus to zanamivir was ca fivefold higher than the median IC$_{50}$ values of the wild type and the single H275Y mutant viruses, although the dual mutant virus showed normal inhibition by laninamivir.

**Discussion**

The first widespread community cluster of the H275Y mutant A(H1N1)pdm09 virus was detected in Newcastle, Australia in 2011 [7]. The H275Y substitution in the NA protein would destabilise the mutant virus. However, two additional V241I and N369K substitutions in the NA of H275Y mutant viruses were reported to increase their replication and transmission fitness, contributing to efficient transmission [8,9]. Almost all recently circulating A(H1N1)pdm09 viruses possess these permissive substitutions, suggesting an increased risk for H275Y mutant viruses to emerge and spread globally [10]. Indeed, during the 2013/14 influenza season, the H275Y mutant viruses from a large community cluster in Hokkaido, Japan carried these permissive substitutions. Following this finding, we subsequently increased nationwide monitoring for the H275Y mutant viruses in the 2015/16 season and detected an H275Y mutant with V241I and N369K and an additional G147R substitution in the NA protein from an immunocompromised inpatient. The IC$_{50}$ fold changes of a number of NA inhibitors for the dual H275Y/G147R mutant virus compared with those for the single H275Y viruses showed clearly the synergistic effect of this dual substitution (Figure 2).

Hooper et al. reported that the G147R substitution in the NA protein has been detected in A(H1N1)pdm09, in the former seasonal A(H1N1) as well as in the A(H5N1) viruses where it conferred receptor-binding activity to the NA proteins of these viruses, similar to a D151G substitution in the NA protein from an immunocompromised inpatient. The IC$_{50}$ fold changes of a number of NA inhibitors for the dual H275Y/G147R mutant virus compared with those for the single H275Y viruses showed clearly the synergistic effect of this dual substitution (Figure 2).

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the D151G substitution emerged during propagation of virus in MDCK cell culture [11,12].

Residue 147 is located in a 150-loop that includes residues 147 to 152 adjacent to the NA active site as shown in Figure 3 [13]. A previous study reported it as having an essential role in the conformation of the 150-loop [14]. Our structural analysis of the NA protein of the dual H275Y/G147R mutant virus using Molecular Operating Environment, MOE, (Chemical Computing Group Inc., Quebec, Canada) [15] suggests that the G147R substitution may alter the stability of the 150-loop because the side chain of arginine is larger than that of glycine (Figure 3), negatively affecting the binding affinity to NA inhibitors.

The G147R substitution of N1 NA has been shown to slightly decrease enzymatic activity but not to affect the viral replication fitness [12]. These results, together with the findings of recent H275Y mutant viruses carrying permissive substitutions, V241I and N369K, suggest that the dual H275Y/G147R mutant virus had the

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**Figure 2**

Susceptibility to neuraminidase inhibitors of influenza A(H1N1)pdm09 viruses with H275Y and G147R substitutions detected in Japan, September 2015–April 2016 (n = 256)

<table>
<thead>
<tr>
<th></th>
<th>Wild type</th>
<th>H275Y</th>
<th>H275Y/G147R</th>
</tr>
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<tbody>
<tr>
<td><strong>Oseltamivir</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Log IC50 (nM)</td>
<td>0.01</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
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<td><strong>Peramivir</strong></td>
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<tr>
<td>Log IC50 (nM)</td>
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<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.400</td>
<td></td>
</tr>
<tr>
<td><strong>Zanamivir</strong></td>
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<tr>
<td>Log IC50 (nM)</td>
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<td>1.0</td>
<td>2.8</td>
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IC50: 50% inhibitory concentration.

The IC50 values of the viruses to laninamivir, oseltamivir, peramivir and zanamivir were determined by fluorescent neuraminidase inhibition assay. Box-and-whisker plots of the IC50 values (medians and interquartile ranges) are shown. The numbers at the bottom of each box-and-whisker plot indicate the fold change in IC50 values compared with the median IC50 values of 275H wild-type viruses.
potential to replicate efficiently. In this study, we found that the dual H275Y/G147R mutant virus grew well in cell culture. Furthermore, the patient infected with the dual H275Y/G147R mutant virus developed pneumonia without isolation of bacterial pathogens, suggesting viral pneumonia with this dual mutant virus.

Immunocompromised patients are at great risk for emergence of the antiviral resistant virus because of the selective pressure from prolonged exposure to antiviral drugs [16]. A high rate and prolonged shedding of the H275Y mutant A(H1N1)pdm09 virus in immunocompromised patients treated with oseltamivir and/or peramivir were reported previously [17]. As a specimen from the husband of the patient was unavailable, we cannot rule out that the patient was infected with a virus readily carrying the G147R substitution. Results of this study nevertheless suggest that this substitution likely occurred in the patient during peramivir treatment. On the other hand, whether the H275Y mutation had already occurred or not before infection remains unclear. Other additional substitutions, I223R and S247N, in the NA protein of H275Y mutant A(H1N1)pdm09 viruses have been reported and showed a synergistic effect with the H275Y substitution on the reduction of NA inhibitor susceptibility [18,19]. Although the frequencies of these dual substitutions were low, the surveillance of antiviral-resistant viruses should be continued to protect public health and support clinical management, particularly for high risk populations.

The Influenza Virus Surveillance Group of Japan

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**Figure 3**

Three-dimensional structure of the neuraminidase protein of influenza A(H1N1)pdm09 virus with the H275Y and G147R substitutions

A. H275Y

B. H275Y/G147R

Structure models of the neuraminidase proteins of the single H275Y (A) and the dual H275Y/G147R (B) mutant viruses were constructed by homology modelling. The crystal structure of the A(H1N1)pdm09 neuraminidase protein (PDB ID: 4B7R) was used as the modelling template.

A 150-loop in the neuraminidase protein is shown in green.
Oshibe (Hyogo Prefectural Institute of Public Health and Consumer Sciences), Ai Mori (Kobe Institute of Health), Daichi Sugimoto (Nara Prefecture Institute of Health), Yuki Matsui (Wakayama Prefectural Research Center of Environment and Public Health), Hidenobu Ekawa (Wakayama City Institute of Public Health), Nobuyuki Kato (Tottori Prefectural Institute of Public Health and Environmental Science), Tetsuo Mita (Shimane Prefectural Institute of Public Health and Environmental Science), Yasuhiro Matsuoka (Okayama Prefectural Institute for Environmental Science and Public Health), Shinichi Takao (Center for Public Health and Environment, Hiroshima Prefecture), Yuki Terajima (Kagawa Prefectural Research Institute for Environmental Sciences and Public Health), Kaori Nishizawa (Kumamoto City Environmental Research Center), Miki Kato (Oita Prefectural Institute of Health and Environment), Miho Miura (Miyazaki Prefectural Institute for Public Health and Environment), Yuka Iwamoto (Kagoshima Prefectural Institute for Environmental Research and Public Health), and Kuba Yumani (Okinawa Prefectural Institute of Health and Environment).

Acknowledgements

We thank Rie Ogawa, Hideka Miura, Hiromi Sugawara, Aya Sato and Miki Akimoto for technical assistance and Drs. Masato Tashiro and Yoko Matsuzaki for fruitful discussions. We acknowledge the authors, originating and submitting laboratories of the sequences from GISAID’s EpiFlu Database on which this research is based (see Table). All submitters of data may be contacted directly via the GISAID website www.gisaid.org.

This study was supported, in part, by Grant-in-Aid for Emerging and Reemerging Infectious Diseases from the Ministry of Health, Labour and Welfare, Japan and by JSPS KAKENHI grant 26460816.

Conflict of interest

None declared.

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GISAID: Global Initiative on Sharing All Influenza Data; NA: neuraminidase.
Authors' contributions

Designed the analyses: ET, SF, SW, TO. Analysed and interpreted data: ET, SF, MS, KN, NK, TK, YS, TS, SW, TO. The members of the Influenza Virus Surveillance Group of Japan. Drafted the article: ET. Revised the article: SW, TO.

References


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