Nardilysin promotes hepatocellular carcinoma through activation of signal transducer and activator of transcription 3

Authors
Kasai, Yosuke; Toriguchi, Kan; Hatano, Etsuro; Nishi, Kiyoto; Ohno, Mikiko; Yoh, Tomoaki; Fukuyama, Keita; Nishio, Takahiro; Okuno, Masayuki; Iwaisako, Keiko; Seo, Satoru; Taura, Kojiro; Kurokawa, Masato; Kunichika, Makoto; Uemoto, Shinji; Nishi, Eiichiro

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Nardilysin (NRDC) is a metalloendopeptidase of the M16 family. We previously showed that NRDC activates inflammatory cytokine signaling, including interleukin-6-signal transducer and activator of transcription 3 (STAT3) signaling. NRDC has been implicated in the promotion of breast, gastric and esophageal cancer, as well as the development of liver fibrosis. In this study, we investigated the role of NRDC in the promotion of hepatocellular carcinoma (HCC), both clinically and experimentally. We found that NRDC expression was upregulated threefold in HCC tissue compared to the adjacent non-tumor liver tissue, which was confirmed by immunohistochemistry and western blotting. We also found that high serum NRDC was associated with large tumor size (>3 cm, \( P = 0.016 \)) and poor prognosis after hepatectomy (median survival time 32.0 vs 73.9 months, \( P = 0.003 \)) in patients with hepatitis C (\( n = 120 \)). Diethylnitrosamine-induced hepatocarcinogenesis was suppressed in heterozygous NRDC-deficient mice compared to their wild-type littermates. Gene silencing of NRDC with miRNA diminished the growth of Huh-7 and Hep3B spheroids compared to control spheroids. The effect of a STAT3 inhibitor (S3I-201) on the growth of Huh-7 spheroids was reduced in NRDC-depleted cells relative to controls. Our results show that NRDC is a promising prognostic marker for HCC in patients with hepatitis C, and that NRDC promotes tumor growth through activation of STAT3.

Hepatocellular carcinoma (HCC) is one of the most common cancers and the third leading cause of cancer-related deaths worldwide.\(^1\) Low-grade inflammation, induced by chronic hepatitis B and C and steatohepatitis, is the established pathogen of HCC,\(^2\) but much remains to be learned about how HCC initiates and progresses. The long-term prognosis of HCC, even after curative surgical resection or percutaneous ablation therapy, is unsatisfactory because of the high incidence of recurrence, with a 3-year and 5-year recurrence rate of more than 50 and 70%, respectively.\(^3\)\(^-\)\(^5\) Although sorafenib, a multi-kinase inhibitor, has been established as the standard therapy for advanced HCC,\(^5\) even with such treatment, the prognosis for advanced HCC remains dismal, with a median survival time of less than 1 year.\(^6\) Identification of novel therapeutic targets for HCC is urgently needed.

Nardilysin (N-arginine dibasic convertase = NRDC) is a metalloendopeptidase of the M16 family. We first identified NRDC as a specific binding protein of the heparin-binding
Nardilsyn (NRDC) is upregulated in hepatocellular carcinoma (HCC) tissue and serum NRDC is a prognostic marker for HCC patients with hepatitis C. (a) Immunohistochemistry for an anti-human NRDC mouse monoclonal antibody (#102). Scale bar represents 500 μm. (b,c) Western blotting for an anti-human NRDC mouse monoclonal antibody (#23) for tumor (T) and the adjacent non-tumor liver tissue (NT). The expression level of NRDC is quantified by densitometry and normalized to β-actin. The expression levels of NT and T are converted to logarithms, which are compared using the paired t-test for each patient (n = 27). (d) Comparison of serum NRDC in healthy volunteers (n = 112) and HCC patients (n = 220). Data are expressed as a scatter plot and a box-and-whisker plot. The box, horizontal bar in the box, and whisker represent the interquartile range, median, and quartile to the outermost value within a 1.5 × interquartile range, respectively. Wilcoxon’s test is used for statistical comparison. (e) Scatter plot of histological NRDC expression (tumor to non-tumor ratio) and serum NRDC in each patient (n = 27). Linear correlation is examined using Pearson’s correlation analysis. (f–h) Kaplan–Meier curves of overall survival (f), recurrence-free survival (g) and survival after recurrence (h) related to the serum NRDC in patients with hepatitis C. The cutoff value is determined as 844.6 pg/mL by receiver operating characteristic analysis for the outcome of death within 3 years of surgery among patients with hepatitis C. Cumulative survival rates are compared using the log-rank test.
epidermal growth factor-like growth factor (HB-EGF) \(^{(7)}\). Thereafter, we showed that NRDC enhances ectodomain shedding of HB-EGF and other membrane proteins, including tumor necrosis factor-alpha (TNF-\(\alpha\)) \(^{(8-10)}\). In addition to its functions at the cell surface, nuclear functions of NRDC as a transcriptional co-regulator have been identified \(^{(11-13)}\). NRDC has been implicated in the promotion of breast \(^{(14)}\), gastric \(^{(10)}\), and esophageal cancer \(^{(15)}\). In gastric cancer, we demonstrated that NRDC promotes cancer cell proliferation through activation of an interleukin-6-signal transducer and activator of transcription 3 (STAT3) pathway that was induced by the enhancement of TNF-\(\alpha\) shedding. We reported that NRDC also promotes liver fibrosis in mice via TNF-\(\alpha\) signaling \(^{(16)}\).

In the present study, we investigated the role of NRDC in the promotion of HCC, both clinically and experimentally, and explored whether NRDC might be a prognostic marker and therapeutic target for HCC.

Materials and Methods

Patients and clinical samples. For measurement of serum NRDC, preoperative serum samples were obtained from 220 of 685 patients who underwent hepatectomy for HCC between 1996 and 2006 at the Department of Surgery, Kyoto University Hospital. As a control group, serum samples were obtained from 112 healthy volunteers who had been shown not to have any...
malignant disorder. Serum NRDC was measured using an ELISA, as previously described. (10) Kaplan–Meier analysis was used to assess the prognostic impact of serum NRDC on overall survival, recurrence-free survival, and survival after recurrence. Resected specimens were either preserved as separate fresh-frozen blocks of the tumor and adjacent non-tumor liver tissue, or fixed in 10% formalin (Wako, Osaka, Japan) and embedded in paraffin for immunohistochemistry. Written informed consent was obtained from all patients. This study was performed in accordance with the Declaration of Helsinki and the Japanese Ethical Guidelines for Epidemiological Research, and was approved by the Kyoto University Graduate School and Faculty of Medicine Ethics Committee (Approval code: E1840 and R0571).

**Cohort study from The Cancer Genome Atlas database.** Hepatocellular carcinoma data from The Cancer Genome Atlas (TCGA) was downloaded from the Broad Institute’s Firehose pipeline using the RTCGAToolbox. (17) We integrated clinical data and upper quartile normalized RNAseqv2 data from cancer tissue. The breakpoint of log2-transformed upper quartile fragments per kilobase of exon per million reads mapped (FPKM-UQ) of the NRDC gene was determined using the classification and regression tree (CART) technique. (18) For analysis of the TCGA database, R and the Bioconductor survival, (19) party, (18) MASS, (20) stringr (21) and RTCGAToolbox packages were used.

**Mice and the hepatocarcinogenesis model.** Heterozygous NRDC-deficient mice (Nrdc +/−) (Accession No. CDB0466K, http://www.clst.riken.jp/arg/mutant%20mice%20list.html) on a C57BL/6 background were used along with wild-type littermates. (22) Mice were maintained in filter-topped cages and fed an autoclaved diet of regular Chow and tap water according to the guidelines of the Institutional Animal Care and Use Committee of Kyoto University. In the diethylnitrosamine (DEN, Sigma-Aldrich, St. Louis, MO, USA)-induced hepatocarcinogenesis model, DEN (25 mg/kg) was injected intraperitoneally into mice once on day 14 after birth. (22) Mice were killed at 36 weeks of age and liver tissue was collected and rapidly fixed in 10% formalin for immunohistochemical analysis.

**Cell lines, reagents, and stable knockdown of nardilysin and STAT3.** Human HCC cell lines, Huh-7 and Hep3B, were cultured in DMEM (Thermo Fisher, Scientific, Waltham, MA, USA) supplemented with 10% FBS and 1% penicillin/streptomycin under 5% CO2 at 95% humidity and 37 °C. Mouse cell lines, reagents, and stable knockdown of nardilysin and STAT3. Human HCC cell lines, Huh-7 and Hep3B, were cultured in DMEM (Thermo Fisher, Scientific, Waltham, MA, USA) supplemented with 10% FBS immediately after cell seeding into 96-well ultra-low attachment microplates. Equivalent amounts of DMSO were used as the control for S3I-201. The effect of S3I-201 on spheroid growth was evaluated after 7 days of treatment.

**Immunohistochemistry.** Immunohistochemistry was performed as previously described. (10) Four-μm thick sections were incubated with the indicated primary antibody (4°C overnight); anti-human NRDC mouse monoclonal antibody (#102, established in our laboratory) for human liver specimens, dilution 1:500, anti-mouse NRDC rat monoclonal antibody (#135, established in our laboratory) for mouse liver specimens, dilution 1:200, and Ki67 (DakoCytomation, Glostrup, Denmark) for mouse liver specimens, dilution 1:100. Human specimens were incubated with Mouse EnVision Polymer (DAKO) at room temperature for 1 h. Mouse specimens were incubated with biotinylated secondary antibody for 1–2 h and then with the avidin–biotin–peroxidase complex (Vectastain ABC Kit, Vector Laboratories, Burlingame, CA, USA) at room temperature for 30 min.

**Western blotting.** Western blotting was performed as previously described. (13) Twenty μg of tissue lysate, or 10 μg of cell lysate isolated from spheroids, was electrophoresed on a 10% SDS-polyacrylamide gel (SDS from Wako; acrylamide from Bio-Rad, Hercules, CA, USA) and transferred to a nitrocellulose membrane (GE Healthcare, Buckinghamshire, UK). The targets of the primary antibodies are listed in Table S1. The blot was observed with EZ-Capture II software (ATTO, Tokyo, Japan) after being visualized by ECL Prime (GE Healthcare, Little Chalfont, Buckinghamshire, UK).

| Table 1. Demographics of patients with hepatitis C |  |
|---|---|---|---|
| | NRDC-low | NRDC-high | P-value |
| Age ≤365 | 33/22 | 41/24 | 0.730 |
| Sex | Male | 43/12 | 53/12 | 0.647 |
| HBs-antigen (+) | 3 (5.5%) | 1 (1.5%) | 0.228 |
| Child-Pugh A/B | 50/5 | 60/5 | 0.783 |
| Liver cirrhosis | 22 (40.0%) | 27 (41.5%) | 0.864 |
| a-fetoprotein | 16/39 | 17/48 | 0.720 |
| Vascular invasion >3 cm | 34/21 | 33/32 | 0.224 |
| Tumor size ≤3 cm | 29 (52.7%) | 48 (73.9%) | 0.016 |
| Vascular invasion + | 25 (45.5%) | 36 (55.4%) | 0.278 |
| Extrahepatic metastasis + | 0 (0%) | 4 (6.2%) | 0.025 |
| Poor differentiation | 13 (23.6%) | 17 (27.0%) | 0.677 |

The cutoff value is 844.6 ng/mL. Liver cirrhosis is confirmed by pathological examination of the resected specimens. Differentiation was unknown in 2 patients because of tumor necrosis. HBs-antigen: hepatitis B surface antigen.

| Table 2. Cox proportional hazard model for overall survival for patients with hepatitis C |  |
|---|---|---|---|
| | HR | 95% CI | P-value |
| Multiple tumor | 1.56 | 1.00–2.43 | 0.049 |
| Vascular invasion + | 1.94 | 1.25–3.04 | 0.003 |
| Liver cirrhosis | 2.05 | 1.31–3.22 | 0.002 |
| Serum NRDC ≥844.6 ng/mL | 1.92 | 1.23–3.03 | 0.004 |

Patients with 30-day mortality or extrahepatic metastasis are excluded from this analysis. Because large tumor size (>3 cm) is correlated with high serum NRDC, tumor size is not included in this multivariate analysis as an independent variable. CI, confidence interval; HR, hazard ratio; NRDC, nardilysin.
Healthcare). Analysis of densitometry was performed using Image J software.

**Statistical analysis.** Continuous variables were expressed as the median or the mean plus/minus the standard error, and compared using Wilcoxon’s test, or the paired or unpaired t-test, as appropriate. Categorical variables were compared using the χ²-test. The optimal cutoff value of serum NRDC that defined the prognosis of HCC was determined according to receiver operating characteristic analysis for the outcome of death within 3 years of surgery. Cumulative survival rates were calculated using the Kaplan–Meier method and compared using the log-rank test. Multivariate analysis for overall survival was performed using the Cox proportional hazard model. A two-tailed P-value < 0.05 was considered to be significant. Statistical analyses were performed using JMP software version 10 (SAS Institute, Cary, NC, USA).

**Results**

Nardilysin is upregulated in hepatocellular carcinoma tissue and serum nardilysin is a prognostic marker for hepatocellular carcinoma patients with hepatitis C. Immunohistochemistry using an anti-NRDC antibody revealed that NRDC expression was higher in HCC compared to the adjacent non-tumor liver tissue (Fig. 1a). This finding was confirmed by western blot analysis, which showed that NRDC expression was upregulated threefold in HCC compared to the adjacent non-tumor liver tissue (Fig. 2b,c). Serum NRDC was 1.7 times higher in HCC patients compared to healthy volunteers (median 934.1 vs 539.8 pg/mL, respectively, P < 0.001, Fig. 1d), and correlated modestly, but positively, with the tumor to non-tumor ratio of histological NRDC expression (Fig. 1e). These results suggest that the systemic concentration of NRDC reflects the amount of NRDC in cancer tissues. Serum NRDC did not correlate with tumor multiplicity, vascular invasion or background liver cirrhosis, but did correlate with tumor size and extrahepatic metastasis (Tables 1 and S2). Overall survival for all patients was not associated with serum NRDC (Fig. S1a). However, among patients with hepatitis C (n = 120), overall survival was significantly shorter in patients with high serum NRDC than in those with low serum NRDC (median survival time 32.0 vs 73.9 months, respectively, P = 0.003, Fig. 1f). Interestingly, survival after...
lates positively with tumor cell proliferation. (Fig. 2c). These results indicate that NRDC expression correlated even in Nrdc the liver tumor compared to the adjacent non-tumor tissue, size (Fig. 2a). As in human HCC, NRDC was upregulated in assessed by macroscopic tumor number and maximum tumor expression in HCC was associated with poor prognosis (Fig. S2a,b). These findings strongly suggest that NRDC is a prognostic marker for HCC in patients with hepatitis C.

Diethylnitrosamine-induced hepatocarcinogenesis is suppressed in nardilysin-deficient mice. To determine the involvement of NRDC in the pathogenesis of HCC, DEN-induced hepatocarcinogenesis, a well-established mouse model of HCC, was examined in NRDC-deficient mice. As homozygous deficient mice show multiple phenotypes, including growth retardation and hypothermia, we used heterozygous deficient (Nrdc +/−) mice for our experiments. Hepatocarcinogenesis was suppressed in Nrdc +/− mice compared to Nrdc +/+ mice, as assessed by macroscopic tumor number and maximum tumor size (Fig. 2a). As in human HCC, NRDC was upregulated in the liver tumor compared to the adjacent non-tumor tissue, even in Nrdc +/− mice (Fig. 2b). The proportion of Ki67-positive proliferating cells was significantly lower in the livers of Nrdc +/− mice compared to the livers of Nrdc +/+ mice (Fig. 2c). These results indicate that NRDC expression correlates positively with tumor cell proliferation.

Gene knockdown of nardilysin suppresses spheroid growth and STAT3 phosphorylation in hepatocellular carcinoma cells. To explore the function of NRDC in HCC cells, NRDC was stably knocked down using miRNA in Huh-7 and Hep3B cells from which spheroids were developed, as described in the Methods. Three-dimensional multicellular spheroid growth assays then demonstrated that gene silencing of NRDC suppressed Huh-7 and Hep3B spheroid growth (Fig. 3a,b). Of note, phosphorylation of STAT3 at tyrosine 705 was significantly decreased in spheroids of NRDC-knockdown Huh-7 cells (Fig. 3c). STAT3 is one of the key promoters of HCC, and we previously showed that NRDC induces STAT3 phosphorylation in gastric cancer cells. To confirm the role of STAT3 in spheroid growth, we established Huh-7 cells stably transduced with a lentiviral vector expressing miRNA against STAT3. Knockdown of STAT3 decreased STAT3 phosphorylation (Fig. 4a) and suppressed spheroid growth (Fig. 4b). Furthermore, a small molecule STAT3 inhibitor (S3I-201) was less effective in affecting spheroid growth in NRDC knockdown than control cells (Fig. 4c), which indicates that NRDC regulates spheroid growth via STAT3 activation.

Discussion
In this study, we investigated whether NRDC contributes to the promotion of HCC, both clinically and experimentally, and explored the potential of NRDC as a prognostic marker and therapeutic target for HCC. Our results show that: (i) NRDC is upregulated in HCC tissue; (ii) high serum NRDC is associated with increased tumor size and poor prognosis among patients with hepatitis C; (iii) DEN-induced hepatocarcinogenesis is suppressed in NRDC-deficient mice; and (iv) NRDC promotes the growth of HCC spheroids through activation of STAT3.

Our results suggest that NRDC could be a useful prognostic marker for HCC in patients with hepatitis C because of its ability to predict survival time after recurrence; this capacity of NRDC is unlike that of other markers which predict overall survival or recurrence after curative treatment for HCC. Survival time after recurrence depends on the pattern of recurrence, including the tumor number and size for intrahepatic recurrence and the presence or absence of extrahepatic spread. It also depends on the efficacy of the curative treatment for recurrence, rather than recurrence-free survival, differed significantly between patients with high serum NRDC levels and those with low serum NRDC (median survival time 27.8 vs 49.0 months, respectively; \( P = 0.023 \), Figs 1g,h and S1b,c). In multivariate analysis among patients with hepatitis C, high serum NRDC was an independent prognostic factor for overall survival (Table 2). Thus, high expression of NRDC in cancer tissues correlates with poor prognosis for HCC patients with hepatitis C. Consistent with our observations, survival analysis using the TCGA database showed that high NRDC gene expression is one of the key promoters of HCC, and we previously showed that NRDC induces STAT3 phosphorylation in gastric cancer cells. To confirm the role of STAT3 in spheroid growth, we established Huh-7 cells stably transduced with a lentiviral vector expressing miRNA against STAT3. Knockdown of STAT3 decreased STAT3 phosphorylation (Fig. 4a) and suppressed spheroid growth (Fig. 4b). Furthermore, a small molecule STAT3 inhibitor (S3I-201) was less effective in affecting spheroid growth in NRDC knockdown than control cells (Fig. 4c), which indicates that NRDC regulates spheroid growth via STAT3 activation.

**Fig. 4.** Effect of STAT3 inhibition on spheroid growth. (a) Western blotting of spheroid-derived protein from Huh-7 cells. (b) Spheroid growth assay for Huh-7 cells. Seeding density is 1000 cells. Representative data from three independent experiments are shown. Data are expressed as the mean plus/minus the standard error of six wells, which are compared using the unpaired t-test \( ( * P < 0.05; ** P < 0.01; *** P < 0.001 ) \). Scale bar represents 100 μm. (c) Spheroid growth inhibition with S3I-201. One-thousand Huh-7 cells were incubated with 36 μm of S3I-201 (STAT3 inhibitor) or equivalent amounts of DMSO for 7 days in 96-well ultra-low attachment plates. Data are expressed as the mean plus/minus the standard error of five independent experiments, which are compared using the unpaired t-test \( ( ** P < 0.01; NS, not significant ) \). Scale bar represents 100 μm.
recurrent lesions. Preclinical studies have shown that NRDC promotes tumor growth, at least in part, through activation of STAT3, suggesting that NRDC could be a therapeutic target for HCC.

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Disclosure Statement

The authors have no conflict of interest to declare.

References

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Fig S1. Kaplan–Meier curves of overall survival (a), recurrence-free survival (b) and survival after recurrence (c) related to the serum nardilysin (NRDC) for all patients.

Fig S2. Survival analysis related to the nardilysin (NRDC) gene expression level in hepatocellular carcinoma (HCC) tissue obtained from The Cancer Genome Atlas (TCGA) RNA-seq database.

Table S1. List of primary antibodies for western blotting.

Table S2. Demographics of all patients.