

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/102518/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Wu, Hao, Zhou, Dai-Zhan, Berki, Dorottya, Geisz, Andrea, Zou, Wen-Bin, Sun, Xiao-Tian, Hu, Liang-Hao, Zhao, Zhen-Hua, Zhao, An-Jing, He, Lin, Cooper, David, Férec, Claude, Chen, Jian-Min, Li, Zhao-Shen, Sahin-Tóth, Miklós and Liao, Zhuan 2017. No significant enrichment of rare functionally defective CPA1 variants in a large Chinese idiopathic chronic pancreatitis cohort. *Human Mutation* 38 (8), pp. 959-963. 10.1002/humu.23254

Publishers page: <http://dx.doi.org/10.1002/humu.23254>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



No Significant Enrichment of Rare Functionally Defective *CPAI* Variants in a Large Chinese Idiopathic Chronic Pancreatitis Cohort

Formatted: Font: Italic

Hao Wu,^{1,2,3,4#} Dai-Zhan Zhou,^{5#} Dorottya Berki,⁶ Andrea Geisz,⁶ Wen-Bin Zou,^{1,2,3,4} Xiao-Tian Sun,^{1,2} Liang-Hao Hu,^{1,2} Zhen-Hua Zhao,^{1,2} An-Jing Zhao,^{1,2} Lin He,⁵ David N. Cooper,⁷ Claude Férec,^{3,4,8,9} Jian-Min Chen,^{3,4,8†} Zhao-Shen Li,^{1,2†*} Miklós Sahin-Tóth,^{6†} and Zhuan Liao^{1,2†*}

¹Department of Gastroenterology, Changhai Hospital, the Second Military Medical University, Shanghai, China; ²Shanghai Institute of Pancreatic Diseases, Shanghai, China; ³Institut National de la Santé et de la Recherche Médicale (INSERM), U1078, Brest, France; ⁴Etablissement Français du Sang (EFS) – Bretagne, Brest, France; ⁵Key Laboratory of Developmental Genetics and Neuropsychiatric Diseases (Ministry of Education), Bio-X Institutes, Shanghai Jiao Tong University, Shanghai, China; ⁶Center for Exocrine Disorders, Department of Molecular and Cell Biology, Boston University Henry M. Goldman School of Dental Medicine, Boston, Massachusetts 02118; ⁷Institute of Medical Genetics, School of Medicine, Cardiff University, Cardiff, United Kingdom; ⁸Faculté de Médecine et des Sciences de la Santé, Université de Bretagne Occidentale (UBO), Brest, France; ⁹Laboratoire de Génétique Moléculaire et d'Histocompatibilité, Centre Hospitalier Universitaire (CHU) Brest, Hôpital Morvan, Brest, France

[#]Authors share co-first authorship.

[†]Authors share co-senior authorship.

*Correspondence to: Zhuan Liao, MD or Zhao-Shen Li, MD, Department of Gastroenterology, Changhai Hospital, the Second Military Medical University, 168 Changhai

Road, Shanghai 200433, China. E-mail: jiaozhuan@smmu.edu.cn or
zhaoshenli@hotmail.com

Field Code Changed

Field Code Changed

Disclosure statement: The authors declare no conflict of interest.

Contract Grant Sponsors: HW is a joint PhD student between the Changhai Hospital and INSERM U1078 who was in receipt of a one-year scholarship from the China Scholarship Council (No. 201503170355). WBZ was a joint PhD student between Changhai Hospital and INSERM U1078 and received a 1-year scholarship (2015) from the China Scholarship Council (No. 201403170271). Support for this study came from the National Natural Science Foundation of China (Grant Nos. 81470884 and 81422010; to ZL), the Shuguang Program of Shanghai Education Development Foundation and Shanghai Municipal Education Commission (Grant No. 15SG33; to ZL), the Chang Jiang Scholars Program of Ministry of Education, People's Republic of China (Grant No. Q2015190; to ZL); the Conseil Régional de Bretagne, the Association des Pancréatites Chroniques Héritaires, the Association de Transfusion Sanguine et de Biogénétique Gaetan Saleun, the Institut National de la Santé et de la Recherche Médicale (INSERM), France. Work in the laboratory of MST was supported by National Institutes of Health grants R01 DK058088, R01 DK082412 and R01 DK095753.

ABSTRACT: Rare functionally defective carboxypeptidase A1 (CPA1) variants have been reported to predispose to nonalcoholic chronic pancreatitis, mainly the idiopathic subtype. However, independent replication has so far been lacking, particularly in Asian cohorts where initial studies employed small sample sizes. Herein we performed targeted next-generation sequencing of the *CPA1* gene in 1112 Han Chinese idiopathic chronic pancreatitis (ICP) patients – the largest ICP cohort so far analyzed in a single population – and 1580 controls. Sanger sequencing was used to validate called variants, and the CPA1 activity and secretion of all newly found variants were measured. A total of 18 rare *CPA1* variants were characterized, 11 of which have not been previously described. However, no significant association was noted with ICP irrespective of whether all rare variants [20/1112 (1.8%) in patients vs. 24/1580 (1.52%) in controls; $P=0.573$] or functionally impaired variants [3/1112 (0.27%) in patients vs. 2/1580 (0.13%) in controls; $P=0.410$] were considered.

KEY WORDS: *CPA1* gene; idiopathic chronic pancreatitis; missense mutations; next-generation sequencing; rare variants

Since the identification of a gain-of-function missense mutation in the *PRSSI* gene (encoding cationic trypsinogen; MIM# 276000) as a cause of autosomal dominant hereditary pancreatitis (MIM# 167800) 20 years ago [Whitcomb et al., 1996], heritable variants in multiple genes have been reported to cause, predispose to, or protect against several forms of chronic pancreatitis (see [Fjeld et al., 2015] and references therein). Some of these genetic associations have been consistently replicated in independent studies, and the underlying pathogenic mechanisms elucidated. In particular, findings from the analysis of four genes abundantly expressed in pancreatic acinar cells – *PRSSI* [Le Maréchal et al., 2006; Whitcomb et al. 1996; Whitcomb et al., 2012], *PRSS2* (encoding anionic trypsinogen; MIM# 601564) [Witt et al., 2006], *SPINK1* (encoding pancreatic secretory trypsin inhibitor; MIM# 167790) [Witt et al., 2000] and *CTRC* (encoding chymotrypsin C, which specifically degrades all human trypsinogen/trypsin isoforms [Szmola and Sahin-Tóth 2007]; MIM# 601405) [Masson et al., 2008; Rosendahl et al., 2008] – have established the importance of a balance between the activation and inactivation of trypsinogen within the pancreas, thereby defining a trypsin-dependent pathway as a key component of the pathogenesis of chronic pancreatitis.

Procarboxypeptidase A1, the inactive form of the digestive enzyme carboxypeptidase A1 (CPA1; MIM# 114850), is the second most abundantly synthesized protein after trypsinogen in the pancreatic juice [Scheele et al., 1981]. In addition, procarboxypeptidase A1 is a component of the pancreatic zymogen activation cascade which, if prematurely activated within the pancreas, could potentially lead to pancreatic autodigestion [Chen and Férec, 2009]. Recently, a candidate gene approach [Witt et al., 2013] identified an

overrepresentation of functionally impaired *CPAI* variants (defined as exhibiting enzymatic activity <20% of the wild-type in the conditioned medium of transfected cells) in German patients with nonalcoholic chronic pancreatitis (NACP) as compared to controls. Functionally impaired *CPAI* variants were also found to be significantly overrepresented in NACP patients

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

as compared to controls in a European replication cohort (mainly French, Czech and Polish) and two small Asian cohorts, albeit with much lower odds ratios (OR) and much higher *P* values (see [Table 1](#)). It should be noted that (i) the NACP patients were mainly subjects with idiopathic chronic pancreatitis (ICP) along with a few cases with a family history of chronic pancreatitis and (ii) the <20% cut-off value for defining functionally defective *CPA1* variants was set relative to p.Thr124Ile, a low-frequency variant (defined as having a minor allele frequency of 0.5%-5% in the control population as previously described [[Manolio et al., 2009](#); [Tennessen et al., 2012](#)]) that was present with equal frequency in both German NACP patients and controls, and which exhibited 23% of the activity of the wild-type CPA1 enzyme [[Witt et al. 2013](#)]. Additionally, it is important to mention two other findings in the German discovery population. First, the association between defective *CPA1* variants and NACP was strongest in those German patients aged ≤ 10 years, in whom the detection frequency was nearly 10% (22/228), with the corresponding OR reaching 84.0. Second, defective *CPA1* variants were found in only 2/465 (0.4%) German patients with alcohol-related chronic pancreatitis, suggesting only a very minor role in this disease subtype [[Witt et al. 2013](#)].

In the previous study, most of the functionally impaired *CPA1* variants were found only in patients. For those variants that were found in both patients and controls, or only in controls, their minor allele frequencies in the control population(s) were invariably <0.5% [[Witt et al. 2013](#)]. Therefore, all the functionally impaired *CPA1* variants naturally fell into the category of rare variants [[Manolio et al. 2009](#); [Tennessen et al. 2012](#)]. Biochemical studies revealed no detectable impact of CPA1 on trypsinogen activation, trypsin activity, or the degradation of trypsin and trypsinogen by CTRC, suggesting a trypsin-independent pathogenic mechanism underlying the functionally impaired CPA1 variants [[Witt et al. 2013](#)]. Importantly, the defective CPA1 variants were often characterized by significantly decreased secretion, intracellular retention and degradation, implying involvement of misfolding-induced

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

endoplasmic reticulum stress, as previously observed in a subset of rare *PRSSI* and *CTRC* variants [Beer et al., 2013; Kereszturi et al., 2009; Németh et al., 2016; Schnúr et al., 2014]. Indeed, expression of the *CPAI* p.Asn256Lys variant, which was found in 7 NACP patients but not in controls, resulted in endoplasmic reticulum (ER) stress in AR42J rat acinar cells [Witt et al. 2013]. More recently, a novel *CPAI* variant, p.Ser282Pro, found in two Polish families with hereditary pancreatitis, has been shown to induce ER stress to a comparable degree as the p.Asn256Lys variant [Kujko et al., 2017].

Given the remarkable differences in the occurrence and distribution of rare functional *CPAI* variants among the different populations, and the small sizes of the two Asian cohorts analyzed to date (Table 1), further independent replication in larger studies is clearly warranted [MacArthur et al., 2014]. Herein we report the targeted sequencing of the *CPAI* gene in a large cohort of Han Chinese ICP patients. All 1112 Chinese ICP patients (776 males and 336 females) were of Han origin. A clinical diagnosis of ICP was made as previously described [Zou et al., 2016] (see also Supp. Methods). The 1580 healthy controls were unrelated Han Chinese blood donors. Informed consent was obtained from each patient and the study was approved by the Changhai Hospital's Ethics Committee.

We designed a total of 16 target-specific primer pairs (Supp. Figure S1) for the coding sequence and exon/intron boundaries of the *CPAI* gene (human GRCh37/hg19 <https://genome.ucsc.edu/>; NM_001868.3) using Primer3 (<http://simgene.com/Primer3>) [Untergasser et al., 2012]. The primers were synthesized with common adaptor sequences at their 5' ends as previously described [Forsheew et al., 2012]. The 16 primer pairs were divided into two multiplex primer pools. Pre-amplification of the tagged-*CPAI* amplicons, generation of a barcoded DNA library for multiplex high-throughput sequencing, quantification and clean-up of the DNA library and sequencing were performed essentially as previously described [Forsheew et al. 2012]. The raw paired 150 bp-long reads were aligned to the human

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

reference genome (build hg19) using the Burrows-Wheeler Aligner (BWA version 0.5.9). The Genome Analysis Toolkit (GATK, version 3.1) was then used to perform local realignment and to recalibrate base quality scores, yielding a cleaned BAM file for each individual. The raw single nucleotide variants and small insertions or deletions were filtered based upon the variant quality score recalibration module in GATK. Had we added the step “QD < 2.0” to the SNV (single nucleotide variants) filtration process, most of the mutations located at the target-specific primer regions would have been missed, leading to false negative results. To avoid such a situation, the raw SNVs were simply filtered by the VariantFiltration module in GATK using the following steps: (i) $MQ < 40.0$, (ii) $MQRankSum < -12.5$ and (iii) $ReadPosRankSum < -8.0$; and the raw INDELs were only filtered by the VariantFiltration module in GATK using the following arguments: (i) $ReadPosRankSum < -20.0$ and (ii) $FS > 200.0$. This approach was bound to generate false positive findings, which were then excluded by manual inspection of each called variant using the Integrative Genomics Viewer followed by validation by Sanger sequencing. Given that all the previously reported functionally defective *CPA1* variants [Witt et al. 2013] fell into the category of rare variants, we only included variants for analysis which were absent or occurred with a minor allele frequency of <0.5% in the public database of the 1000 Genomes Project (<http://www.1000genomes.org/>) [Auton et al., 2015; Sudmant et al., 2015]. In case of SNVs, only those that occurred within canonical splice sites or were predicted to result in a premature stop codon or missense mutations were included for analysis. The types of variant under consideration followed the earlier report [Witt et al. 2013], and included (i) small deletions or insertions that occurred within the canonical splice sites and coding sequence and (ii) single nucleotide substitutions that altered either canonical splice sites or else resulted in missense or nonsense mutations. All called rare variants were subjected to validation by

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Sanger sequencing. Sequences of the primers used to amplify the fragments of interest are provided in [Supp. Figure S2](#).

Under the conditions of our targeted sequencing approach, we initially discovered 30 rare *CPAI* variants in 60 subjects. The various exons harboring these variants were then PCR amplified from the 60 carriers; subsequent Sanger sequencing of the resulting PCR products confirmed the presence of 18 variants in 44 subjects. The 18 validated variants spanned all ten exons of the *CPAI* gene, were all detected in the heterozygous state and were all single nucleotide substitutions that were predicted to result in missense mutations. Nearly two thirds ($N = 11$) of the 18 variants had not been previously described ([Table 2](#)). It is possible that some rare variants were missed by this method. However, this is unlikely to be a major issue for two reasons. First, we found variants in all 10 exons of the *CPAI* gene. Second, to avoid false negative results, we used rather relaxed parameters for variant calling, as evidenced by the high false positive rate. As indicated, false positive variants were eliminated by an independent PCR followed by Sanger sequencing.

The 18 rare *CPAI* variants were present in 20 (1.80%) of the 1112 Chinese ICP patients and in 24 (1.52%) of the 1580 controls ([Table 2](#)), indicating no significant difference between the two groups ($P = 0.573$, 2-tailed Fisher's exact test); [Supp. Table S1](#)). For comparison, we tested the association of all rare variants and NACP in the context of each previously published NACP cohort [[Witt et al. 2013](#)]: no association was observed in the European replication cohort whereas a positive association was observed in each of the German, Indian and Japanese NACP cohorts ([Supp. Table S1](#)). We then investigated whether there might be an association between rare functionally defective *CPAI* variants and ICP in the Chinese cohort. To this end, we functionally characterized all 11 newly found rare variants in terms of their CPAI activity and secretion as previously described [[Witt et al. 2013](#)] (for detailed description, see [Supp. Methods](#)). The activities and secretion levels determined for the new

Field Code Changed

Field Code Changed

CPA1 variants relative to the wild-type values are summarized in Table 2 (Miklos: a Supp. Figure showing a gel photo here?). Also shown are the CPA1 activity and secretion data for the 7 known variants taken from Witt et al. [Witt et al. 2013]. We designated CPA1 variants functionally defective if the carboxypeptidase activity in the conditioned medium measured after activation with trypsin and chymotrypsin C was lower than 20% of the wild-type value in accordance with [Witt et al. 2013]. This reduced activity could be the result of decreased secretion, impaired catalytic activity or degradation by the activating proteases. Functionally defective *CPA1* variants were found in 3 (p.Gly225Ser \times 1, p.His306Tyr \times 1 and p.Glu380Lys \times 1) of the 1,112 (0.27%) Chinese ICP patients and in 2 (p.Glu100Lys \times 1, and p.Arg240Gln \times 1) of the 1,580 (0.13%) controls (Table 2), again displaying no significant difference ($P = 0.68$; Table 1). As mentioned earlier, the association between defective *CPA1* variants and NACP was at its strongest for the German patients aged ≤ 10 years, the corresponding detection frequency was nearly 10% [Witt et al. 2013]. The Chinese ICP cohort contained only 61 patients aged ≤ 10 years, but none of these individuals was found to harbor a functionally defective variant.

There is one additional point to make. Functionally impaired *CPA1* missense variants have previously been reported to occur predominantly in the second half of the 419-amino acid-protein [Witt et al. 2013]. Consistent with this finding, four of five such variants found in the Chinese subjects were also located in the second half of the protein (Table 2). Evaluation of all the functionally impaired *CPA1* missense variants in the context of the CPA1 structure (<http://www.uniprot.org/uniprot/P15085>) revealed that p.Arg237His, p.His306Tyr and p.Glu380Lys affected substrate binding or catalytic sites whereas p.Cys271Arg affected a disulfide bond-forming residue (Supp. Figure S3). It should be noted that all five variants occurred in the second half of the CPA1 protein sequence.

Field Code Changed

Field Code Changed

Field Code Changed

In summary, this is the first study to attempt to replicate the recently reported association of rare functional *CPA1* variants with chronic pancreatitis [Witt et al. 2013] in the context of a large ICP cohort. This is also the largest ICP cohort to date used for the sequencing of the entire coding region and exon/intron boundaries of the *CPA1* gene in a single population. Often, the OR of an association observed in a discovery cohort is much higher than in subsequent replication cohorts [Dumas-Mallet et al., 2016]; this was indeed the case for the rare functional *CPA1* variants in the German, European replication and Asian cohorts (Table 1). However, no significant association with ICP was noted in our Chinese cohort, irrespective of whether all rare variants or functionally-deficient variants were considered. Differences in phenotype definition and ethnicity-specific disease risk factors as well as population stratification may account for the inconsistent findings between studies. For example, although both the present study and the previous study focused on non-alcoholic patients (Table 1), differences between the cohorts regarding alcohol consumption (even if not in causative dosage), smoking and age could conceivably have contributed to the observed differences in disease association. Additionally, given that the proposed disease mechanism is provoked ER stress [Witt et al. 2013], the possibility that CPA1 activity might not be the best proxy marker for the functional effect of the disease-associated *CPA1* variants remains to be excluded.

Field Code Changed

Field Code Changed

REFERENCES

- Auton A, Brooks LD, Durbin RM, Garrison EP, Kang HM, Korbel JO, Marchini JL, McCarthy S, McVean GA, Abecasis GR. 2015. A global reference for human genetic variation. *Nature* 526:68-74.
- Beer S, Zhou J, Szabó A, Keiles S, Chandak GR, Witt H, Sahin-Tóth M. 2013. Comprehensive functional analysis of chymotrypsin C (*CTRC*) variants reveals distinct loss-of-function mechanisms associated with pancreatitis risk. *Gut* 62:1616-1624.
- Chen JM, Férec C. Chronic pancreatitis: genetics and pathogenesis. *Annu Rev Genomics Hum Genet* 2009;10:63-87.
- den Dunnen JT, Dalgleish R, Maglott DR, Hart RK, Greenblatt MS, McGowan-Jordan J, Roux AF, Smith T, Antonarakis SE, Taschner PE. 2016. HGVS recommendations for the description of sequence variants: 2016 update. *Hum Mutat* 37:564-569.
- Fjeld K, Weiss FU, Lasher D, Rosendahl J, Chen JM, Johansson BB, Kirsten H, Ruffert C, Masson E, Steine SJ, Bugert P, Cnop M, Grützmann R, Mayerle J, Mössner J, Ringdal M, Schulz HU, Sendler M, Simon P, Sztromwasser P, Torsvik J, Scholz M, Tjora E, Férec C, Witt H, Lerch MM, Njølstad PR, Johansson S, Molven A. 2015. A recombined allele of the lipase gene *CEL* and its pseudogene *CELP* confers susceptibility to chronic pancreatitis. *Nat Genet* 47:518-522.
- Forshew T, Murtaza M, Parkinson C, Gale D, Tsui DW, Kaper F, Dawson SJ, Piskorz AM, Jimenez-Linan M, Bentley D, Hadfield J, May AP, [Caldas C](#), [Brenton JD](#), [Rosenfeld N](#). 2012. Noninvasive identification and monitoring of cancer mutations by targeted deep sequencing of plasma DNA. *Sci Transl Med* 4:136ra168.
- Kereszturi E, Szmola R, Kukor Z, Simon P, Weiss FU, Lerch MM, Sahin-Tóth M. 2009. Hereditary pancreatitis caused by mutation-induced misfolding of human cationic trypsinogen: a novel disease mechanism. *Hum Mutat* 30:575-582.
- Kujko A, Berki D, Oracz G, Wejnarska K, Antoniuk J, Wertheim-Tysarowska K, Kolodziejczyk E, Bal J, Sahin-Toth M, Rygiel A. 2017. A novel p.Ser282Pro *CPA1* variant is associated with autosomal dominant hereditary pancreatitis. *Gut* in press.
- Le Maréchal C, Masson E, Chen JM, Morel F, Ruszniewski P, Levy P, Férec C. 2006. Hereditary pancreatitis caused by triplication of the trypsinogen locus. *Nat Genet* 38:1372-1374.
- MacArthur DG, Manolio TA, Dimmock DP, Rehm HL, Shendure J, Abecasis GR, Adams DR, Altman RB, Antonarakis SE, Ashley EA, Barrett JC, Biesecker LG, [Conrad DF](#), [Cooper GM](#), [Cox NJ](#), [Daly MJ](#), [Gerstein MB](#), [Goldstein DB](#), [Hirschhorn JN](#), [Leal SM](#), [Pennacchio LA](#), [Stamatoyannopoulos JA](#), [Sunyaev SR](#), [Valle D](#), [Voight BF](#), [Winckler W](#), [Gunter C](#). 2014. Guidelines for investigating causality of sequence variants in human disease. *Nature* 508:469-476.
- Manolio TA, Collins FS, Cox NJ, Goldstein DB, Hindorff LA, Hunter DJ, McCarthy MI, Ramos EM, Cardon LR, Chakravarti A, Cho JH, Guttacher AE, [Kong A](#), [Kruglyak L](#), [Mardis E](#), [Rotimi CN](#), [Slatkin M](#), [Valle D](#), [Whittemore AS](#), [Boehnke M](#), [Clark AG](#), [Eichler EE](#), [Gibson G](#), [Haines JL](#), [Mackay TF](#), [McCarroll SA](#), [Visscher PM](#). 2009. Finding the missing heritability of complex diseases. *Nature* 461:747-753.
- Masson E, Chen JM, Scotet V, Le Maréchal C, Férec C. 2008. Association of rare chymotrypsinogen C (*CTRC*) gene variations in patients with idiopathic chronic pancreatitis. *Hum Genet* 123:83-91.
- Németh BC, Patai ÁV, Sahin-Tóth M, Hegyi P. 2016. Misfolding cationic trypsinogen variant p.L104P causes hereditary pancreatitis. *Gut*: doi: 10.1136/gutjnl-2016-313451.
- Rosendahl J, Witt H, Szmola R, Bhatia E, Ozsvári B, Landt O, Schulz HU, Gress TM, Pfützner R, Lohr M, Kovacs P, Bluher M, [Stumvoll M](#), [Choudhuri G](#), [Hegyi P](#), [te Morsche RH](#), [Drenth JP](#), [Trüningner K](#), [Macek M Jr](#), [Puhl G](#), [Witt U](#), [Schmidt H](#), [Büning C](#), [Ockenga J](#), [Kage A](#), [Groneberg DA](#), [Nickel R](#), [Berg T](#), [Wiedenmann B](#), [Bödeker H](#), [Keim V](#), [Mössner J](#), [Teich N](#), [Sahin-Tóth M](#). 2008. Chymotrypsin C (*CTRC*) variants that diminish activity or secretion are associated with chronic pancreatitis. *Nat Genet* 40:78-82.

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Field Code Changed

Field Code Changed

Formatted: English (United States)

Formatted: English (United States)

Field Code Changed

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

Formatted: English (United States)

- Scheele G, Barteld D, Bieger W. 1981. Characterization of human exocrine pancreatic proteins by two-dimensional isoelectric focusing/sodium dodecyl sulfate gel electrophoresis. Gastroenterology 80:461-473.
- Schnúr A, Beer S, Witt H, Hegyi P, Sahin-Tóth M. 2014. Functional effects of 13 rare PRSS1 variants presumed to cause chronic pancreatitis. Gut 63:337-343.
- Sudmant PH, Rausch T, Gardner EJ, Handsaker RE, Abyzov A, Huddleston J, Zhang Y, Ye K, Jun G, Hsi-Yang Fritz M, Konkel MK, Malhotra A, Stütz AM, Shi X, Paolo Casale F, Chen J, Hormozdiari F, Dayama G, Chen K, Malig M, Chaisson MJ, Walter K, Meiers S, Kashin S, Garrison E, Auton A, Lam HY, Jasmine Mu X, Alkan C, Antaki D, Bae T, Cerveira E, Chines P, Chong Z, Clarke L, Dal E, Ding L, Emery S, Fan X, Guiral M, Kahveci F, Kidd JM, Kong Y, Lameijer EW, McCarthy S, Flicek P, Gibbs RA, Marth G, Mason CE, Menelaou A, Muzny DM, Nelson BJ, Noor A, Parrish NF, Pendleton MA, Quitadamo A, Raeder B, Schadt EE, Romanovitch M, Schlattl A, Sebra R, Shabalin AA, Untergasser A, Walker JA, Wang M, Yu F, Zhang C, Zhang J, Zheng-Bradley X, Zhou W, Zichner T, Sebait J, Batzer MA, McCarroll SA; 1000 Genomes Project Consortium, Mills RF, Gerstein MB, Bashir A, Stegle O, Devine SE, Lee C, Eichler EE, Korbel JO. 2015. An integrated map of structural variation in 2,504 human genomes. Nature 526:75-81.
- Szmola R, Sahin-Tóth M. 2007. Chymotrypsin C (caldecrin) promotes degradation of human cationic trypsin: identity with Rinderknecht's enzyme Y. Proc Natl Acad Sci U S A 104:11227-11232.
- Tennessen JA, Biggam AW, O'Connor TD, Fu W, Kenny EE, Gravel S, McGee S, Do R, Liu X, Jun G, Kang HM, Jordan D, Leal SM, Gabriel S, Rieder MJ, Abecasis G, Altshuler D, Nickerson DA, Boerwinkle E, Sunyaev S, Bustamante CD, Bamshad MJ, Akey JM; Broad GO.; Seattle GO.; NHLBI Exome Sequencing Project. 2012. Evolution and functional impact of rare coding variation from deep sequencing of human exomes. Science 337:64-69.
- Untergasser A, Cutcutache I, Koressaar T, Ye J, Fairclough BC, Remm M, Rozen SG. 2012. Primer3--new capabilities and interfaces. Nucleic Acids Res 40:e115.
- Whitcomb DC, Gorry MC, Preston RA, Furey W, Sossenheimer MJ, Ulrich CD, Martin SP, Gates LK, Jr., Amann ST, Toskes PP, Liddle R, McGrath K, Uomo G, Post JC, Ehrlich GD. 1996. Hereditary pancreatitis is caused by a mutation in the cationic trypsinogen gene. Nat Genet 14:141-145.
- Whitcomb DC, LaRusch J, Krasinskas AM, Klei L, Smith JP, Brand RE, Neoptolemos JP, Lerch MM, Tector M, Sandhu BS, Guda NM, Orlichenko L, Alzheimer's Disease Genetics Consortium, Alkaade S, Amann ST, Anderson MA, Baillie J, Banks PA, Conwell D, Coté GA, Cotton PB, DiSario J, Farrer LA, Forsmark CE, Johnstone M, Gardner TB, Gelrud A, Greenhalf W, Haines JL, Hartman DJ, Hawes RA, Lawrence C, Lewis M, Mayerle J, Mayeux R, Melhem NM, Money ME, Munirai T, Papachristou GI, Pericak-Vance MA, Romagnuolo J, Schellenberg GD, Sherman S, Simon P, Singh VP, Slivka A, Stolz D, Sutton R, Weiss FU, Wilcox CM, Zarnescu NO, Wisniewski SR, O'Connell MR, Kienholz ML, Roeder K, Barmada MM, Yadav D, Devlin B. 2012. Common genetic variants in the CLDN2 and PRSS1-PRSS2 loci alter risk for alcohol-related and sporadic pancreatitis. Nat Genet 44:1349-1354.
- Witt H, Luck W, Hennies HC, Classen M, Kage A, Lass U, Landt O, Becker M. 2000. Mutations in the gene encoding the serine protease inhibitor, Kazal type 1 are associated with chronic pancreatitis. Nat Genet 25:213-216.
- Witt H, Sahin-Tóth M, Landt O, Chen JM, Kahne T, Drenth JP, Kukur Z, Szepessy E, Halangk W, Dahm S, Rohde K, Schulz HU, Le Maréchal C, Akar N, Ammann RW, Truninger K, Bargetzi M, Bhatia S, Castellani C, Cavestro GM, Cerny M, Destro-Bisol G, Spedini G, Fibiger H, Jansen JB, Koudova M, Rausova E, Macek M Jr, Malats N, Reel FX, Menzel HJ, Moral P, Galavotti R, Pignatti PF, Rickards O, Spicak J, Zarnescu NO, Böck W, Gress TM, Friess H, Ockenga J, Schmidt H, Pfützer R, Löhr M, Simon P, Weiss FU, Lerch MM, Teich N, Keim V, Berg T, Wiedenmann B, Luck W, Groneberg DA, Becker M, Keil T, Kage A, Bernardova J, Braun M, Güldner C, Halangk J, Rosendahl J, Witt U, Treiber M, Nickel R, Férec C. 2006. A degradation-sensitive anionic trypsinogen (PRSS2) variant protects against chronic pancreatitis. Nat Genet 38:668-673.

Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Field Code Changed	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Field Code Changed	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...
Formatted	...
Formatted	...
Formatted	...
Field Code Changed	...
Formatted	...

- Witt H, Beer S, Rosendahl J, Chen JM, Chandak GR, Masamune A, Bence M, Szmola R, Oracz G, Macek M, Jr., Bhatia E, Steigenberger S, [Lasher D](#), [Bühler F](#), [Delaporte C](#), [Tebbing J](#), [Ludwig M](#), [Pilsak C](#), [Saum K](#), [Bugert P](#), [Masson E](#), [Paliwal S](#), [Bhaskar S](#), [Sobczynska-Tomaszewska A](#), [Bak D](#), [Balasckak I](#), [Choudhuri G](#), [Nageshwar Reddy D](#), [Rao GV](#), [Thomas V](#), [Kume K](#), [Nakano E](#), [Kakuta Y](#), [Shimosegawa T](#), [Durko L](#), [Szabó A](#), [Schnúr A](#), [Hegyi P](#), [Rakonczay Z Jr](#), [Pfützer R](#), [Schneider A](#), [Groneberg DA](#), [Braun M](#), [Schmidt H](#), [Witt U](#), [Friess H](#), [Algül H](#), [Landt O](#), [Schuelke M](#), [Krüger R](#), [Wiedenmann B](#), [Schmidt F](#), [Zimmer KP](#), [Kovacs P](#), [Stumvoll M](#), [Blüher M](#), [Müller T](#), [Janecke A](#), [Teich N](#), [Grützmann R](#), [Schulz HU](#), [Mössner J](#), [Keim V](#), [Löhr M](#), [Férec C](#), [Sahin-Tóth M](#). 2013. Variants in *CPA1* are strongly associated with early onset chronic pancreatitis. *Nat Genet* 45:1216-1220.
- Zou WB, Boulling A, Masamune A, Issarapu P, Masson E, Wu H, Sun XT, Hu LH, Zhou DZ, He L, Fichou Y, Nakano E, Hamada S, Kakuta Y, Kume K, Isayama H, Paliwal S, Mani KR, Bhaskar S, Cooper DN, Férec C, Shimosegawa T, Chandak GR, Chen JM, Li ZS, Liao Z. 2016. No association between *CEL-HYB* hybrid allele and chronic pancreatitis in Asian populations. *Gastroenterology* 150:1558-1560.e5.