MINI-REVIEW

Poly(ADP-Ribose) Polymerases

New Players in the Pathogenesis of Exocrine Pancreatic Diseases

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Accepted for publication
September 25, 2015.

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The poly(ADP-ribose) polymerase (PARP) enzymes were initially characterized as sensors of DNA breaks but are now known to play key roles not only in the DNA damage response but also in regulating numerous molecular processes, such as gene transcription. Furthermore, these polymerases have emerged as key players in the pathogenesis of multiple diseases, providing promising therapeutic targets for pathologies such as cardiovascular disorders, neurodegenerative diseases, and cancer. In recent years, PARPs have been implicated in the pathogenesis of pancreatitis and pancreatic cancer, and PARP inhibition has been proposed as a valuable strategy for treating these two important gastrointestinal tract disorders. For instance, in preclinical mouse models, pancreatitis was significantly attenuated after genetic or pharmacological PARP inactivation, and several clinical trials have demonstrated promising responses to PARP inhibitors in pancreatic cancer patients. In this review, we summarize the current understanding of PARP functions in these two dismal pathologies and discuss the next steps necessary to determine whether PARP inhibitors will finally make the difference in treating pancreatitis and pancreatic cancer successfully. (*Am J Pathol* 2016, 186: 234–241; <http://dx.doi.org/10.1016/j.ajpath.2015.09.021>)

Pancreatitis (acute or chronic) and pancreatic cancer are the most common disorders of the exocrine pancreas. In developed countries, pancreatitis is one of the most frequent gastrointestinal causes for hospital admission, and pancreatic cancer is the fourth cause of cancer-related deaths, highlighting the drastic impact of these pathologies. Although valuable insight into the molecular basis of these disorders has been gained, efficient treatments are still lacking, so that patients are resigned to experience the symptoms of pancreatitis or to be treated with inefficient chemotherapy for pancreatic cancer. However, new therapies for these pancreatic pathologies are in the pipeline, and many research groups are joining efforts toward this direction.

Poly(ADP-ribose) polymerase (PARP) inhibitors have recently been shown to have a great potential as a tool for attenuating the inflammatory response and in cancer

treatment. More important, recent clinical trials with PARP inhibitors have shown high effectiveness against hereditary cancers in individuals with mutations in DNA repair pathways, like *BRCA*.¹ Several clinical studies have been launched in light of these promising results. Herein, we provide a detailed overview on the role of PARP proteins in

Supported by the Spanish Ministry of Economy and Competitiveness/Health Institute Carlos III-European Regional Development Fund (ISCIII-FEDER PI14/00125; P.N.), Thematic cooperative research networks in health of Cancer-European Regional Development Fund (RETIC Cancer RD12/0036/0051/FEDER; P.N.), Generalitat de Catalunya (2014/SGR/143; P.N.), Spanish Ministry of Economy and Competitiveness (SAF2014-53467-R; J.Y.), Fundació La Marató de TV3 (20134130; J.Y.), and Network Center for Biomedical Research on Hepatic and Digestive Diseases-CIBERehd (EHD15G1092; J.Y.).

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Disclosures: None declared.

pancreatitis and pancreatic cancer and discuss the use of PARP inhibitors for treating these two dismal gastrointestinal tract pathologies.

Biochemical and Cellular Biological Properties of the PARP Family of Proteins

PARylation and the PARP Superfamily

Poly(ADP-ribosyl)ation (PARylation) is a post-translational modification of proteins, mediated by members of the PARP family, in which ADP-ribose units from donor NAD⁺ molecules are covalently transferred to acceptor amino acid residues of target proteins.² This protein modification, first detected >50 years ago, is a dynamic process, as indicated by the short half-life of the ADP-ribose polymer (PAR), which is rapidly degraded by the poly(ADP-ribose) glycohydrolase and the poly(ADP-ribose) hydrolase 3 enzymes (Figure 1). The PARP superfamily includes 17 members that share a conserved catalytic domain with the PARP signature motif, a highly conserved sequence that forms the active site. However, only six PARP proteins (PARP-1, PARP-2, PARP-3, PARP-4, PARP-5A, and PARP-5B) can be considered as bona fide PARP proteins, because these contain a conserved glutamate residue that defines the PARP catalytic activity. Several PARP members lack this critical residue for ADP-ribose polymer synthesis and therefore display only mono(ADP-ribosyl) transferase activity. Furthermore, other family members are catalytically inactive or require a specific and as-of-yet undetermined cofactor to trigger ADP-ribosylation.² PARylation plays a critical role in many cellular processes involved in physiological

functions, such as DNA damage detection and repair, modulation of chromatin structure, transcription regulation, control of cell division, mitochondrial function, and cell differentiation.^{2,3} Therefore, ADP-ribose polymer levels and PARylation are finely regulated through the opposite actions of PARPs and poly(ADP-ribose) glycohydrolase to prevent dramatic consequences for cellular physiology.

PARPs in DNA Damage and Repair

PARP-1 and PARP-2 are the best characterized members of the family, and both act as molecular sensors of DNA breaks² (Figure 1). These two enzymes are activated by DNA-strand interruptions, which increase their catalytic activity by >500-fold. PARylation mediated by PARP-1 and PARP-2 causes chromatin decondensation around damaged sites, recruitment of repair machineries, and acceleration of DNA damage repair. PARP-1 and PARP-2 form heterodimers and share nuclear partners, with some redundant functions. This is probably the reason that *Parp-1* and *Parp-2* double-knockout mice have an embryonic lethal phenotype,⁴ whereas mice with a single *Parp1* or *Parp2* gene disruption are viable and fertile.^{5,6} Interestingly, *Parp1* and *Parp2* single-knockout mice are sensitive to both ionizing radiation and alkylating agents.⁴ Together, these data indicate a role of PARP-1 and PARP-2 in the DNA damage response.^{2,7}

PARPs in the Regulation of Gene Transcription and Cell Division

PARP-1 and PARP-2 play key roles in regulating other molecular and cellular processes besides the DNA damage

Figure 1 Biochemistry and biological functions of poly(ADP-ribosyl)ation (PARylation) reaction mediated by poly(ADP-ribose) polymerase (PARP) enzymes. Activated PARPs hydrolyze NAD⁺, releasing nicotinamide, and catalyze the polymerization of ADP-ribose units onto acceptor proteins. The reaction is reversed by the activities of poly(ADP-ribose) glycohydrolase (PARG) and poly(ADP-ribose) hydrolase-3 (ARH3), which hydrolyze poly(ADP-ribose) into ADP-ribose units. Modification of acceptor proteins by PARylation has a critical role in many cellular processes, such as DNA damage repair, regulation of chromatin structure and transcription, control of cell division, mitochondrial metabolism, epithelial-mesenchymal transition (EMT), and angiogenesis.

response (Figure 1). One of the best examples is that of PARP-1 and PARP-2 in gene transcription regulation, which occurs by one of two main mechanisms: through regulation of chromatin structure by PARylating histones and destabilizing nucleosomes or through direct interaction with transcription factors and cofactors, such as NF- κ B or nuclear factor for activated T cell.^{7,8} Another important physiological role of PARPs is the regulation of cell division. PARP-1 and PARP-2, as well as other PARP family members, are associated with components of the mitotic apparatus, like centromeres and centrosomes, thereby controlling microtubule organization during mitosis and chromosome segregation.⁷

PARPs in the Regulation of Angiogenesis, Epithelial-Mesenchymal Transition, Cell Death, and Energy Homeostasis

PARP-1 has also been shown to modulate angiogenesis through its regulation of several factors, such as hypoxia-inducible factor-1 α ⁹ and vascular endothelial growth factor.¹⁰ Furthermore, PARP-1 has also been shown to regulate the epithelial-mesenchymal transition by modulating key inducers of this cellular conversion, like vimentin and Snail.⁹ In addition, different types of cell death processes, such as apoptosis, parthanatos, necroptosis, and autophagy, have been shown to be modulated by PARylation.¹¹ Finally, PARylation plays important roles in mitochondrial respiration regulation and energy homeostasis.³

Taken together, these studies have provided the rationale for evaluating PARP proteins as pharmacological targets in several human diseases, particularly those involving genotoxic and inflammatory stress responses.

PARP Inhibition Attenuates Pancreatitis

Pancreatitis, which can occur in either an acute or a chronic form, is an inflammatory disorder of the pancreas that involves a complex cascade of local and systemic events, resulting in severity that ranges from mild and self-limiting to a severe form.¹² A yet-unknown triggering event converts digestive proenzymes within the pancreas into their active forms, leading to membrane disruption, edema, interstitial hemorrhage, and necrosis, accompanied by an inflammatory response with infiltrating neutrophils and leukocytes that contributes to the progression of both local pancreatic destruction and systemic manifestations.¹² Many of the genes encoding these inflammatory mediators are regulated by NF- κ B,¹³ whose activity is largely regulated by PARP-1.⁷ PARP-1 can be involved in acute and chronic inflammatory disorders by increasing the synthesis of proinflammatory mediators, like inducible nitric oxide synthase, through activation of NF- κ B and activator protein 1 transcription factors.^{7,14} This generates reactive hydroxyl radicals that cause extensive DNA damage, which, in turn,

activates PARP-1. The resulting PARP-1 activation induces necrotic cell death and release of intracellular content, causing tissue damage and exacerbating the inflammatory reaction. Accordingly, the severity of acute pancreatitis and pancreatitis-associated lung injury has been shown to be significantly attenuated in mice lacking *Parp1*, but not in those lacking *Parp2*, compared with wild-type mice.¹⁵ Moreover, administration of PARP inhibitors in animal models of acute pancreatitis markedly decreased acute pancreatitis severity and pulmonary- and kidney-associated injuries.^{15–18} Future clinical trials in pancreatitis will be necessary to define the therapeutic efficacy of PARP inhibitors in a clinical setting.

More important, chronic pancreatitis is one of the major risk factors linked to pancreatic cancer development, thus suggesting that treatment of chronic pancreatitis patients with PARP inhibitors could protect the pancreas against cancer initiation by attenuating pancreatic inflammation and injury.¹⁵

PARP in Pancreatic Cancer

Pancreatic cancer, and in particular pancreatic ductal adenocarcinoma (PDA), which accounts for >90% of pancreatic tumors, is the solid tumor with the worst prognosis. PDA is currently the fourth leading cause of cancer-related deaths in developed countries and, because the outcome for PDA patients has not significantly improved during the past 40 years, is predicted to become the second leading cause of cancer-related death by 2020.¹⁹ Thus, effective treatments are urgently needed. Given the success of PARP inhibition in the treatment of different tumors, several clinical studies have been conducted to explore this therapeutic strategy in PDA (Table 1). The first results on the safety, tolerability, and maximum tolerated doses of olaparib in combination with gemcitabine were recently published.²⁰ Promising—yet not statistically significant—results encourage ongoing clinical trials that consider selected patients with *BRCA* mutations in the absence of a chemotherapeutic backbone (Table 1).²¹

PARP, and in particular PARP-1, is frequently overexpressed in tumors,² where its increased enzymatic activity might protect cancer cells against DNA damage and genetic instability. The involvement of these proteins in cancer is featured by the fact that high PARP levels correlate with poor prognosis in different tumor types.^{2,22} Accordingly, inhibition of PARP activity has emerged as a promising cancer therapy, either in combination with DNA-damaging agents (radiotherapy or chemotherapy) or as a single therapy in tumors harboring specific mutations in DNA-repair pathways, like *BRCA1/2*, to achieve synthetic lethality.²³

Nonetheless, PARP-1 expression and correlation with tumor prognosis and/or progression in PDA remain controversial. On the one hand, and in contrast to other tumors,^{2,22} high nuclear PARP-1 expression levels have

Table 1 Clinical Trials with PARP Inhibitors in Pancreatic Cancer

PARP inhibitor	Code name	Sponsor	Study phase	Status	In combination with	Indications	ClinicalTrials.gov ID
Olaparib	AZD2281	AstraZeneca (London, UK)	1	Completed	Gemcitabine	Pancreatic cancer	NCT00515866
Olaparib	AZD2281	AstraZeneca	2	Ongoing, but not recruiting		Pancreatic cancer with genetic <i>BRCA1/2</i> mutation	NCT01078662
Veliparib	ABT-888	National Cancer Institute (Rockville, MD)	2	Recruiting	Gemcitabine and cisplatin	Locally advanced or metastatic pancreatic cancer	NCT01585805
Veliparib	ABT-888	Georgetown University (Washington, DC) and Abbott Laboratories (Lake Bluff, IL)	2	Recruiting	5-FU, oxaliplatin and leucovorin	Metastatic pancreatic cancer	NCT01489865
Veliparib	ABT-888	National Cancer Institute	1	Ongoing, but not recruiting		Recurrent pancreatic carcinoma	NCT00892736
Rucaparib	AG014699	Clovis Oncology (Boulder, CO)	2	Recruiting		Pancreatic cancer with deleterious <i>BRCA</i> mutation	NCT02042378
Talazoparib	BMN-673	BioMarin (Novato, CA)	1	Ongoing, but not recruiting		Pancreatic cancer	NCT01286987
Talazoparib	BMN-673	National Cancer Institute	Pilot trial	Recruiting		Advanced solid tumors and deleterious <i>BRCA</i> mutations	NCT01989546
Olaparib	AZD-2281	AstraZeneca	3	Recruiting		Germline <i>BRCA</i> mutated pancreatic cancer, not progressing on first-line platinum-based chemotherapy	NCT02184195

PARP inhibitors that have undergone or are currently in clinical trials are listed, with the code number, the clinical trial sponsor, type, and state of the clinical trial, whether PARP inhibitors are being used in combination with chemotherapy, types of tumors included in the clinical trial, and the official ID given by ClinicalTrials (<http://clinicaltrials.gov>).

5-FU, fluorouracil; PARP, poly(ADP-ribose) polymerase.

been correlated with longer survival in PDA patients.²⁴ On the other hand, our recent studies using normal, preneoplastic, and tumor samples from humans and mice support the hypothesis that PARP-1 expression is restricted to acinar cells (both normal and cancer), and that it is undetectable in normal and cancer ductal cells²⁵ (Figure 2). In fact, no significant survival differences were observed in transgenic mice that developed pancreatic cancer under a *Parp1* genetic deletion, as expected. However, more research is needed to explore whether expression of PARP-1 in ductal cancer cells can be up-regulated in PDA patients after radiation or chemotherapy treatments. This information is critical to understand whether PARP inhibitors can be used as a combined therapy with DNA-damaging agents. Recent studies have shown that PARP inhibitors can increase sensitivity to radiotherapy and/or chemotherapy in several human pancreatic cell lines,^{26,27} and some *in vivo* studies using animal models have shown results along the same direction.^{28,29} However, further preclinical data and information from human samples are required before translating these results to the clinic.

Remarkably, beyond the putative use of PARP inhibitors to enhance the cytotoxic effects of radiation or DNA-methylating agents, recent clinical trials have demonstrated that PDA patients with mutations in *BRCA1* or *BRCA2* genes may benefit from single treatments of inhibiting PARP.^{30–32} Moreover, a recent phase 1b study using cisplatin chemotherapy and a PARP-1 inhibitor was successful for 56% of PDA patients with *BRCA* mutations, whereas no response was observed in patients with wild-type *BRCA* tumors.³³ Another interesting study comes from a case report showing a notable clinical outcome of a PDA patient with an advanced, gemcitabine-resistant tumor that later responded to DNA-damaging agents.³⁴ Further genetic studies of cancer cells from this patient revealed a biallelic inactivation of the *PALB2* gene,³⁴ the protein of which links *BRCA1* and *BRCA2* and which is required for DNA damage repair. These data confirm that inactivation of DNA repair genes from the *BRCA* pathway sensitizes tumors to DNA-damaging agents and PARP inhibitors. Interestingly, mutations in *BRCA1* and *BRCA2* are the most common mutations in familial PDA, supporting the use of

Figure 2 Poly(ADP-ribose) polymerase 1 (PARP-1) expression in normal pancreas, acinar-to-ductal metaplasia (ADM), acinar (AC), and pancreatic ductal adenocarcinoma (PDA) tumors in humans, and the *Ela-myc* transgenic mouse model of pancreatic cancer. PARP-1 nuclear expression is detected by immunohistochemistry and shows similar patterns of distribution in both human and mouse. PARP-1 is only expressed in acinar cells and is undetectable in ductal cells (arrows) or islets of Langerhans (arrowhead) in normal, metaplastic, or tumor samples. Scale bar = 100 μ m.

PARP inhibitors as a promising therapy for these patients.³⁵ However, familial PDA is responsible for <10% of cases of pancreatic cancer,³⁶ and most PDA cases are sporadic without known hereditary predisposition. Nonetheless, in the era of genomics, it would be worthwhile to develop screening programs to identify those PDA patients harboring mutations—such as *BRCA* or *PALB2*—who could benefit from PARP inhibition.^{37,38} Furthermore, recent data from other tumors have identified that besides *BRCA* deficiency, defects in other DNA damage repair machineries render cells highly sensitive to PARP inhibition,^{38–40} thereby expanding the subset of patients who could potentially be treated with this strategy. Remarkably, Waddell et al³⁸ recently performed whole-genome sequencing and copy number variation analyses of 100 PDAs and identified a mutational signature of DNA damage repair deficiency, which included not only the *BRCA* genes but also other Fanconi anemia genes, like *PALB2* and *FANCM*, and *XRCC4/6*. These data could help to identify putative responders to platinum-based and PARP inhibition therapy, which would encourage high-throughput efforts to profile PDA patients, with important therapeutic implications. Finally, although rare, the possibility of *de novo*, rather than germline, mutations in any of these DNA repair genes in sporadic PDA should also be considered. Indeed, spontaneous *BRCA* mutations have been demonstrated in sporadic breast cancer.⁴¹ Altogether, these data highlight the need to test the molecular signature of individual PDA patients, to identify targets that would allow a personalized cancer treatment and thereby broaden the population of patients who can benefit from PARP inhibitors.

In addition to the significant contribution that PARP inhibition could have in treating patients with advanced PDAs, our recent data demonstrate that PARP-1 may also play a role during tumor progression, suggesting a potential use for these inhibitors in early stages of tumorigenesis.²⁵ Using a genetically engineered mouse model of PDA that recapitulates tumor progression⁴² and *Parp-1*-deficient mice, we have recently shown that PARP-1 expression induces acinar-to-ductal metaplasia. This event involves reprogramming of acinar cells to a ductal phenotype and is a key step in the development of pancreatic cancer.⁴³ Thus, using PARP-1 inhibitors at early stages of PDA (eg, chronic pancreatitis) may hamper tumor initiation. Indeed, recent data have suggested the use of PARP inhibitors in chemopreventive regimens for high-risk individuals (eg, for homologous repair-deficient tumors).⁴⁴ Still, we must take into account that preventive treatments with PARP inhibitors require further clinical evaluation, because long-term inhibition of PARP-1 may have adverse effects on health or even result in generating PARP-resistant tumors.⁴⁵

Last, but not least, although the endocrine pancreas is out of the scope of this review, a role for PARP activation in the diabetes-associated inflammatory reaction, through a mechanism involving endothelial cells, has been recently reported.⁴⁶ These data are highly relevant because diabetes is a potential cause, as well as a consequence, of pancreatic cancer.

Concluding Remarks

PARP proteins play a critical role in the DNA damage response. Several pathological situations, such as

Figure 3 Use of poly(ADP-ribose) polymerase (PARP) inhibitors in exocrine pancreatic pathologies. Diagram showing the main exocrine pancreatic pathologies and how PARP inhibitors (PARPi) can help in their treatment. Effectiveness of these inhibitors has already been proved in preclinical studies of murine acute pancreatitis^{15–18} and in pancreatic ductal adenocarcinoma (PDA) cell lines and clinical trials, either as a single therapy—in patients with mutations in *BRCA1/2* or *PALB2*—or in combination with DNA-damaging agents (PARPi, continuous green line).^{26,27,30–34} Moreover, on the basis of our results with *Parp-1*^{−/−} mice,^{15,25} we speculate that PARPi can be useful for treating precursor lesions before the onset of a malignant PDA, such as acinar-to-ductal metaplasia (ADM) and chronic pancreatitis (PARPi, discontinuous green line).

inflammation and cancer, can induce the DNA damage response, leading to increased activity of PARPs. Accordingly, PARP inhibition has emerged as a promising novel therapeutic strategy for these pathologies, and several PARP inhibitors have been tested in clinical trials during the past decade, in breast, ovarian, prostate, lung, head and neck, and brain cancers, among others.¹ Results have been promising for tumors with specific genetic alterations, such as *BRCA1/2*-deficient ovary and breast tumors. In pancreatic cancer, PARP inhibitors have demonstrated positive responses in patients with mutations in DNA repair pathways, who account for 5% to 8% of PDA patients. **Figure 3** summarizes the state-of-the-art of PARP inhibition in pancreatitis and pancreatic cancer and speculates about the putative use of these compounds in precursor lesions, like acinar-to-ductal metaplasia or chronic pancreatitis, to hamper further tumor development.

Personalized medicine has recently emerged as a fundamental tool to stratify patients for response classification, which would help to avoid unnecessary treatments and save health care costs. In particular, identifying mutations in those DNA damage repair genes that have been demonstrated to increase the tumor sensitivity to PARP inhibition may be extremely helpful for determining which PDA patients would benefit from PARP inhibitors. These genes include *BRCA1*, *BRCA2*, and *PALB2*, for which positive results have been already demonstrated in clinical trials,^{30,32,33} but should also be expanded to new targets identified in other cancers, such as pentaerythritol tetranitrate

deficiency,³⁹ ataxia-telangiectasia mutated deficiency, and Aurora A overexpression.⁴⁰ Moreover, although not tested, it is tempting to speculate that cancer cells with mutations in other DNA repair genes, such as ligase IV in T-cell lymphoma and *XRCC1* in nonmelanoma skin cancer, may be selectively killed using PARP inhibitors.⁴⁷ Future research and genetic screenings are needed to investigate whether these possibilities would also work in PDA patients.

Finally, despite the encouraging results obtained with PARP inhibitors in cancer clinical trials, there are still many hurdles to overcome: not only do we need to increase our knowledge about the mechanisms of resistance of tumor cells to PARP inhibition, but we also need to develop more specific and effective inhibitors. In this regard, most of the current research has focused on the inhibition of the PARP-1 and PARP-2 enzymes; however, the role(s) of the other PARP members have not been explored. In particular, considering the homology and sequence similarities among PARP proteins, it is likely that current PARP inhibitors may inhibit other members of the PARP family or even other proteins,^{48,49} highlighting the importance of extending our knowledge about the mechanisms of action of these inhibitors as well as the precise functions of the different PARP enzymes in physiology and pathology. Selective inhibitors are required not only to elucidate the specific functions of each PARP member but also to design cleaner therapeutic strategies. Interestingly, new tankyrase selective compounds have emerged as a plausible alternative to the classic nicotinamide-based inhibitors.⁵⁰ Moreover, studies

on PARP structure offer a path toward increasing selectivity as well as the possibility of altering PARP-specific functions by developing agents that target acceptor sites or even noncatalytic domains.⁵⁰

Preclinical and clinical data point to an outstanding potential for PARP inhibitors in cancer treatment, both in combination with radiotherapy and/or chemotherapy or used as single agents to achieve synthetic lethality in BRCA-deficient tumors. In pancreatic cancer in particular, whose dismal prognosis is highly worrying to the scientific community, much effort has been put into PARP-targeting agents, with >10 clinical trials currently registered with encouraging preliminary results. Numerous issues must now be taken into account and deserve further research, such as optimization of dosage regimens, resistance to therapy, long-term therapeutic responses, putative use for pancreatitis treatment as PDA prevention, and careful patient selection, before we will know whether these compounds could finally mark a turning point in its treatment.

Acknowledgments

We thank Albert Flotats-Pozo for his valuable help in graphic design and Veronica A. Raker for help in editing the manuscript.

References

1. Tangutoori S, Baldwin P, Sridhar S: PARP inhibitors: a new era of targeted therapy. *Maturitas* 2015, 81:5–9
2. Yelamos J, Farres J, Llacuna L, Ampurdanes C, Martin-Caballero J: PARP-1 and PARP-2: new players in tumour development. *Am J Cancer Res* 2011, 1:328–346
3. Michels J, Obrist F, Castedo M, Vitale I, Kroemer G: PARP and other prospective targets for poisoning cancer cell metabolism. *Biochem Pharmacol* 2014, 92:164–171
4. Menissier de MJ, Ricoul M, Tartier L, Niedergang C, Huber A, Dantzer F, Schreiber V, Ame JC, Dierich A, LeMeur M, Sabatier L, Chambon P, de Murcia G: Functional interaction between PARP-1 and PARP-2 in chromosome stability and embryonic development in mouse. *EMBO J* 2003, 22:2255–2263
5. Wang ZQ, Auer B, Stingl L, Berghammer H, Haidacher D, Schweiger M, Wagner EF: Mice lacking ADPRT and poly(ADP-ribosylation) develop normally but are susceptible to skin disease. *Genes Dev* 1995, 9:509–520
6. de Murcia JM, Niedergang C, Trucco C, Ricoul M, Dutrillaux B, Mark M, Oliver FJ, Masson M, Dierich A, LeMeur M, Walztinger C, Chambon P, de Murcia G: Requirement of poly(ADP-ribose) polymerase in recovery from DNA damage in mice and in cells. *Proc Natl Acad Sci U S A* 1997, 94:7303–7307
7. Gibson BA, Kraus WL: New insights into the molecular and cellular functions of poly(ADP-ribose) and PARPs. *Nat Rev Mol Cell Biol* 2012, 13:411–424
8. Valdor R, Schreiber V, Saenz L, Martinez T, Munoz-Suano A, Dominguez-Villar M, Ramirez P, Parrilla P, Aguado E, Garcia-Cozar F, Yelamos J: Regulation of NFAT by poly(ADP-ribose) polymerase activity in T cells. *Mol Immunol* 2008, 45:1863–1871
9. Rodriguez MI, Peralta-Leal A, O'Valle F, Rodriguez-Vargas JM, Gonzalez-Flores A, Majuelos-Melguizo J, Lopez L, Serrano S, de Herreros AG, Rodriguez-Manzanique JC, Fernandez R, Del Moral RG, de Almodovar JM, Oliver FJ: PARP-1 regulates metastatic melanoma through modulation of vimentin-induced malignant transformation. *PLoS Genet* 2013, 9:e1003531
10. Pyriochou A, Olah G, Deitch EA, Szabo C, Papapetropoulos A: Inhibition of angiogenesis by the poly(ADP-ribose) polymerase inhibitor PJ-34. *Int J Mol Med* 2008, 22:113–118
11. Aredia F, Scovassi AI: Poly(ADP-ribose): a signaling molecule in different paradigms of cell death. *Biochem Pharmacol* 2014, 92:157–163
12. Lankisch PG, Apte M, Banks PA: Acute pancreatitis. *Lancet* 2015, 386:85–96
13. Pahl HL: Activators and target genes of Rel/NF-kappaB transcription factors. *Oncogene* 1999, 18:6853–6866
14. Andreone TL, O'Connor M, Denenberg A, Hake PW, Zingarelli B: Poly(ADP-ribose) polymerase-1 regulates activation of activator protein-1 in murine fibroblasts. *J Immunol* 2003, 170:2113–2120
15. Mota RA, Sanchez-Bueno F, Saenz L, Hernandez-Espinosa D, Jimeno J, Tornel PL, Martinez-Torrano A, Ramirez P, Parrilla P, Yelamos J: Inhibition of poly(ADP-ribose) polymerase attenuates the severity of acute pancreatitis and associated lung injury. *Lab Invest* 2005, 85:1250–1262
16. Mazzone E, Genovese T, Di PR, Muia C, Crisafulli C, Malleo G, Esposito E, Meli R, Sessa E, Cuzzocrea S: Effects of 3-aminobenzamide, an inhibitor of poly (ADP-ribose) polymerase, in a mouse model of acute pancreatitis induced by cerulein. *Eur J Pharmacol* 2006, 549:149–156
17. Mota R, Sanchez-Bueno F, Berenguer-Pina JJ, Hernandez-Espinosa D, Parrilla P, Yelamos J: Therapeutic treatment with poly(ADP-ribose) polymerase inhibitors attenuates the severity of acute pancreatitis and associated liver and lung injury. *Br J Pharmacol* 2007, 151:998–1005
18. Yu J, Deng W, Wang W, Ding Y, Jin H, Chen C, Chen X, Xiong X, Xu S: Inhibition of poly(ADP-ribose) polymerase attenuates acute kidney injury in sodium taurocholate-induced acute pancreatitis in rats. *Pancreas* 2012, 41:1299–1305
19. Garrido-Laguna I, Hidalgo M: Pancreatic cancer: from state-of-the-art treatments to promising novel therapies. *Nat Rev Clin Oncol* 2015, 12:319–334
20. Bendell J, O'Reilly EM, Middleton MR, Chau I, Hochster H, Fielding A, Burke W, Burris H III: Phase I study of olaparib plus gemcitabine in patients with advanced solid tumours and comparison with gemcitabine alone in patients with locally advanced/metastatic pancreatic cancer. *Ann Oncol* 2015, 26:804–811
21. Kindler HJ, Locker GY, Mann H, Golan T: POLO: a randomized phase III trial of olaparib tablets in patients with metastatic pancreatic cancer (mPC) and a germline BRCA1/2 mutation (gBRCAm) who have not progressed following first-line chemotherapy. *J Clin Oncol* 2015, 33. abstr TPS4149
22. Rojo F, Garcia-Parra J, Zazo S, Tusquets I, Ferrer-Lozano J, Menendez S, Eroles P, Chamizo C, Servitja S, Ramirez-Merino N, Lobo F, Bellosillo B, Corominas JM, Yelamos J, Serrano S, Luch A, Rovira A, Albanell J: Nuclear PARP-1 protein overexpression is associated with poor overall survival in early breast cancer. *Ann Oncol* 2012, 23:1156–1164
23. Ashworth A: A synthetic lethal therapeutic approach: poly(ADP-ribose) polymerase inhibitors for the treatment of cancers deficient in DNA double-strand break repair. *J Clin Oncol* 2008, 26:3785–3790
24. Klauschen F, von Winterfeld M, Stenzinger A, Sinn BV, Budczies J, Kamphues C, Bahra M, Wittschieder D, Weichert W, Striefler J, Riess H, Dietel M, Denkert C: High nuclear poly-(ADP-ribose)-polymerase expression is prognostic of improved survival in pancreatic cancer. *Histopathology* 2012, 61:409–416
25. Martinez-Bosch N, Iglesias M, Munne-Collado J, Martinez-Caceres C, Moreno M, Guerra C, Yelamos J, Navarro P: Parp-1

- genetic ablation in Ela-myc mice unveils novel roles for Parp-1 in pancreatic cancer. *J Pathol* 2014, 234:214–227
26. Lowery MA, Vanoli F, Yu KH, Jasin M, O'Reilly EM, Moynahan ME: Inhibition of poly (ADP-ribose) polymerase-1 (PARP-1) to increase radiosensitivity of human pancreatic cancer (PAC) cell lines proficient in homology-directed repair (HDR). *J Clin Oncol* 2012, 30(Suppl 4): abstract 204
 27. De Soto JA, Mullins R: The use of PARP inhibitors as single agents and as chemosensitizers in sporadic pancreatic cancer. *J Clin Oncol* 2011, 29:e13542
 28. Karnak D, Engelke CG, Parsels LA, Kausar T, Wei D, Robertson JR, Marsh KB, Davis MA, Zhao L, Maybaum J, Lawrence TS, Morgan MA: Combined inhibition of Wee1 and PARP1/2 for radiosensitization in pancreatic cancer. *Clin Cancer Res* 2014, 20: 5085–5096
 29. Lowery MA, Lee A, Tobias E, Sung P, Bhanot U, Shakya R, Ludwig T, O'Reilly EM, Jasin M, Moynahan ME: Evaluation of PARP inhibition as a platinum sparing strategy in Brca2-deficient pancreatic tumors. *J Clin Oncol* 2014, 32:e15237
 30. Fogelman DR, Wolff RA, Kopetz S, Javle M, Bradley C, Mok I, Cabanillas F, Abbruzzese JL: Evidence for the efficacy of Iniparib, a PARP-1 inhibitor, in BRCA2-associated pancreatic cancer. *Anticancer Res* 2011, 31:1417–1420
 31. Leung K, Saif MW: BRCA-associated pancreatic cancer: the evolving management. *JOP* 2013, 14:149–151
 32. Kaufman B, Shapira-Frommer R, Schmutzler RK, Audeh MW, Friedlander M, Balmana J, Mitchell G, Fried G, Stemmer SM, Hubert A, Rosengarten O, Steiner M, Loman N, Bowen K, Fielding A, Domchek SM: Olaparib monotherapy in patients with advanced cancer and a germline BRCA1/2 mutation. *J Clin Oncol* 2015, 33:244–250
 33. O'Reilly EM, Lowery MA, Segal MF, Smith SC, Moore MJ, Kindler HL, Golan T, Segal A, Salo-Mullen EE, Hollywood E, Epstein AS, Capanu M, Moynahan ME, Fusco A, Stadler ZK, Gando RK, Chen AP, Yu KH, Tang LH, Kelsen DP: Phase IB trial of cisplatin (C), gemcitabine (G), and veliparib (V) in patients with known or potential BRCA or PALB2-mutated pancreas adenocarcinoma (PC). *J Clin Oncol* 2014, 32. abstr4023
 34. Villarroel MC, Rajeshkumar NV, Garrido-Laguna I, De Jesus-Acosta A, Jones S, Maitra A, Hruban RH, Eshleman JR, Klein A, Laheru D, Donehower R, Hidalgo M: Personalizing cancer treatment in the age of global genomic analyses: PALB2 gene mutations and the response to DNA damaging agents in pancreatic cancer. *Mol Cancer Ther* 2011, 10:3–8
 35. Bhalla A, Saif MW: PARP-inhibitors in BRCA-associated pancreatic cancer. *JOP* 2014, 15:340–343
 36. Holter S, Borgida A, Dodd A, Grant R, Semotiuk K, Hedley D, Dhani N, Narod S, Akbari M, Moore M, Gallinger S: Germline BRCA mutations in a large clinic-based cohort of patients with pancreatic adenocarcinoma. *J Clin Oncol* 2015, 33:3124–3129
 37. Zhen DB, Rabe KG, Gallinger S, Syngal S, Schwartz AG, Goggins MG, Hruban RH, Cote ML, McWilliams RR, Roberts NJ, Cannon-Albright LA, Li D, Moyes K, Wenstrup RJ, Hartman AR, Seminara D, Klein AP, Petersen GM: BRCA1, BRCA2, PALB2, and CDKN2A mutations in familial pancreatic cancer: a PACGENE study. *Genet Med* 2015, 17:569–577
 38. Waddell N, Pajic M, Patch AM, Chang DK, Kassahn KS, Bailey P, et al: Whole genomes redefine the mutational landscape of pancreatic cancer. *Nature* 2015, 518:495–501
 39. Mendes-Pereira AM, Martin SA, Brough R, McCarthy A, Taylor JR, Kim JS, Waldman T, Lord CJ, Ashworth A: Synthetic lethal targeting of PTEN mutant cells with PARP inhibitors. *EMBO Mol Med* 2009, 1: 315–322
 40. Weston VJ, Oldreive CE, Skowronska A, Oscier DG, Pratt G, Dyer MJ, Smith G, Powell JE, Rudzki Z, Kearns P, Moss PA, Taylor AM, Stankovic T: The PARP inhibitor olaparib induces significant killing of ATM-deficient lymphoid tumor cells in vitro and in vivo. *Blood* 2010, 116:4578–4587
 41. Rios J, Puhalla S: PARP inhibitors in breast cancer: BRCA and beyond. *Oncology (Williston Park)* 2011, 25:1014–1025
 42. Sandgren EP, Quaife CJ, Paulovich AG, Palmiter RD, Brinster RL: Pancreatic tumor pathogenesis reflects the causative genetic lesion. *Proc Natl Acad Sci U S A* 1991, 88:93–97
 43. Maitra A, Hruban RH: Pancreatic cancer. *Annu Rev Pathol* 2008, 3: 157–188
 44. To C, Kim EH, Royce DB, Williams CR, Collins RM, Risingsong R, Sporn MB, Liby KT: The PARP inhibitors, veliparib and olaparib, are effective chemopreventive agents for delaying mammary tumor development in BRCA1-deficient mice. *Cancer Prev Res (Phila)* 2014, 7:698–707
 45. Chand SN, Blanco FF, Jimbo M, Tsangaris TN, Cristofanilli M, Yeo CJ, Winter JM, Pishvaian MJ, Brody JR: PARP inhibitors for chemoprevention: letter. *Cancer Prev Res (Phila)* 2014, 7:1170–1171
 46. Garcia SF, Virag L, Jagtap P, Szabo E, Mabley JG, Liaudet L, Marton A, Hoyt DG, Murthy KG, Salzman AL, Southan GJ, Szabo C: Diabetic endothelial dysfunction: the role of poly(ADP-ribose) polymerase activation. *Nat Med* 2001, 7:108–113
 47. Li M, Yu X: The role of poly(ADP-ribosylation) in DNA damage response and cancer chemotherapy. *Oncogene* 2014, 34: 3349–3356
 48. Antolin AA, Jalencas X, Yelamos J, Mestres J: Identification of pim kinases as novel targets for PJ34 with confounding effects in PARP biology. *ACS Chem Biol* 2012, 7:1962–1967
 49. Wahlberg E, Karlberg T, Kouznetsova E, Markova N, Macchiarulo A, Thorsell AG, Pol E, Frostell A, Ekblad T, Oncu D, Kull B, Robertson GM, Pellicciari R, Schuler H, Weigelt J: Family-wide chemical profiling and structural analysis of PARP and tankyrase inhibitors. *Nat Biotechnol* 2012, 30:283–288
 50. Steffen JD, Brody JR, Armen RS, Pascal JM: Structural implications for selective targeting of PARPs. *Front Oncol* 2013, 3:301