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REVIEW ARTICLE

Anti-Müllerian hormone as a marker of ovarian reserve: What have we learned, and what should we know?

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Abstract Ovarian reserve reflects the quality and quantity of available oocytes. This reserve has become indispensable for the better understanding of reproductive potential. Measurement of the serum anti-Müllerian hormone (AMH) level allows quantitative evaluation of ovarian reserve. It has been applied to a wide range of clinical conditions, and it is well established that the measurement of serum AMH levels is more useful than qualitative evaluation based on the menstrual cycle. AMH levels are monitored during infertility treatments; in patients undergoing medically assisted reproductive technology; and in the diagnosis of ovarian failure, polycystic ovarian syndrome, and granulosa cell tumor. It is also useful in the evaluation of iatrogenic ovarian damage. Population-based studies have indicated a potential role for serum AMH in the planning of reproductive health management. While AMH is currently the best measure of ovarian reserve, its predictive value for future live births remains controversial. Furthermore, there is a serious practical issue in the interpretation of test results, as currently available assay kits use different assay ranges and coefficients of variation due to the absence of an international reference standard. The pros and cons of the serum AMH level as a definitive measure of ovarian reserve merits further review in order to guide future research.

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Introduction

Ovarian reserve is a concept that reflects the quality and quantity of ovarian follicles at a given point in time and therefore predicts potential ovarian function [1]. Anti-Müllerian hormone (AMH) is produced by the granulosa cells of primary, preantral, and small antral follicles in the ovaries [2, 3]. It was first discovered in the early 1990s that the serum AMH level could provide an indirect representation of the total number of available follicles, thereby serving as a marker of ovarian reserve [3, 4]. AMH is highly sensitive to changes that accompany advancing age [4–7] and it excludes uncertainties associated with the intra- and inter-cycle variability of menstruation [8, 9]. During the past two decades, the number of clinical applications of serum AMH measurement has grown, and its usefulness has been well established [10, 11]. The aim of this review is to provide an overview of the current clinical applications of serum AMH measurements and to examine the future prospects of serum AMH assays.

Medically assisted reproduction

Prediction of oocyte yield

Medically assisted reproductive technology is in great demand, and ovarian reserve tests are of value for predicting outcomes of medically assisted reproduction. While various innovations have contributed to increased rates of successful embryo implantations, even when the greatest

probability of successful implantation exists, the success of the procedure cannot be assured if only one or two embryos have been transferred [12]. If the number of oocytes that can be obtained for assisted reproduction can be predicted, success rates might be increased. The serum AMH level has been known from its earliest applications to correlate well with the number of oocytes generated during cycles of ovarian stimulation by human menopausal gonadotropin and recombinant follicle-stimulating hormone (FSH) [13].

Ascertainment of the linear correlation between serum AMH levels and the number of oocytes has also allowed prediction of poor or excess responses. Numerous studies from the 1990s to the present have demonstrated the usefulness of the serum AMH level for identifying high-risk groups of poor responders, who are at risk of cycle cancellation and hyper-responders, who are at risk of ovarian hyperstimulation syndrome (OHSS). A detailed meta-analysis that was published by Broekmans et al. in 2006 [1] confirmed that the serum AMH level is a good predictor of both poor response and hyper-response, and other recent systematic reviews have also suggested that serum AMH may be the best marker of ovarian reserve when prediction of poor or hyper ovarian response is desired [14–19].

Algorithm for the selection of ovarian stimulation protocols

Based on the usefulness of the linear correlation between AMH levels and oocyte yield, some researchers have suggested that the ovarian stimulation protocol can be optimized according to the AMH level in order to minimize the risk of poor response and cycle cancellation or hyper-response and OHSS. Several different algorithms, in which AMH levels play the main role, have been proposed. These studies have mainly focused on the response to the initial dose of FSH during the assisted reproduction cycle [20–22], and successful reduction of unwanted responses (cycle cancellation or OHSS) has been reported [18, 22, 23].

Individualization of treatment in assisted conception is aimed at maximizing success, and results regarding the usefulness of a standardized algorithm have been inconclusive [24]. Certainly, the issue should not be decided based only on the results of a single cycle of assisted conception, and cumulative pregnancy rates, including successful transfer of frozen–thawed embryos, should be evaluated to optimize stimulation protocols.

Prediction of pregnancy and live birth after assisted conception

Although oocyte yield is an important factor in assisted reproduction, it is hardly necessary to point out that an algorithm for the selection of an appropriate ovarian stimulation protocol is not the ultimate goal, and researchers have now begun to investigate the association between AMH levels, pregnancy, and live birth after assisted reproduction. Preliminary studies exploring the capacity of AMH to predict these factors have shown conflicting results [1, 25–32].

Two thorough meta-analyses examining this issue have recently been published [33, 34]. One of them includes data from 19 studies reporting pregnancy in patients with unspecified ovarian reserve, diminished ovarian reserve, and polycystic ovarian syndrome. The diagnostic odds ratios for AMH as a predictor of clinical pregnancy for each of these categories were 2.10 (95 % confidence interval [CI] 1.82–2.41), 3.96 (95 % CI 2.57–6.10), and 1.18 (95 % CI 0.53–2.62), respectively [34]. The other included 13 studies comprising from 6856 cycles in 6306 women. This analysis also showed a better diagnostic odds ratio for live birth after assisted conception in women with low ovarian reserve compared to women with unknown ovarian reserve (4.63, 95 % CI 2.75–7.81 vs. 2.48, 95 % CI 1.81–3.22) [33]. These recent results support the theory that AMH has the capacity for predicting pregnancy and live birth after assisted conception, perhaps especially in women with diminished ovarian reserve. Despite these preliminary results, the predictive accuracy is not sufficient for low AMH levels to be used as exclusion criteria for assisted reproduction, even as evidence suggesting that higher AMH levels result in higher cumulative pregnancy and live birth rates after assisted conception continues to accumulate [35, 36]. Higher AMH levels may predict a greater possibly of pregnancy, but even if lower AMH levels might predict treatment failure, they should not exclude the option of assisted reproduction.

The qualitative aspects of ovarian reserve may also have strong implications for treatment success after assisted conception, and AMH levels have shown a weak association with oocyte quality, independent of chronological age. Quantitative issues have been resolved by measuring serum AMH levels. To improve prediction of pregnancy and live birth, methods for interpreting AMH levels as a qualitative marker of ovarian function, either alone or in combination with other markers of ovarian reserve, should be explored.

General population and natural conception

The intra-cycle variability of serum AMH levels is low, and AMH level measurement may also prove useful in the prediction of fertility and natural conception. Population-based analyses of serum AMH levels have shown that they peak at around 25 years of age and then gradually decline, becoming undetectable at approximately 5 years before menopause [37–41]. Cross-sectional analysis has shown

that that serum AMH levels are distributed widely within each age group, which poses a question: Does the same serum AMH level predict the same level of ovarian reserve for women at different ages? Further longitudinal studies are required to determine the pattern of decline of individual AMH levels and its meaning.

If AMH levels prove to be reliable predictors of natural fertility, they may also be extremely helpful in family planning or in early detection and treatment of infertility. Two recent prospective studies have shown conflicting results. There was a good correlation between AMH levels and natural conception in women 30–44 years of age during a 6-month observation period [42], but low AMH levels in a group of women in their twenties did not necessarily result in compromised fecundability [43]. These conflicting results may be due to the different ages of the study participants and to the small sizes of the study populations. Larger studies will be needed to draw conclusions regarding the use of AMH levels for determining the likelihood of natural conception.

Prediction of menopause/primary ovarian insufficiency (POI)

The serum FSH level, as a conventional marker of ovarian reserve, increases during the perimenopausal period [44], and serum AMH levels become undetectable within 5 years before menopause [45]. This has led to speculation that serum AMH levels could improve prediction of the onset of menopause. In long-term follow-up studies of 9 and 11 years, women in certain age groups who had lower AMH levels may have had an earlier onset of menopause [46, 47], and recent multivariate prediction models including serum AMH were shown to more accurately forecast early or late menopause [48, 49].

Menopause occurs when the oocytes are depleted. Therefore, similar to the prediction of menopause onset, serum AMH has been considered as a possible marker for identifying women with diminished ovarian reserve who are likely to develop POI. Several studies have shown that serum AMH levels are much lower in women with symptomatic ovarian insufficiency [50–53]. In an era in which it is possible to maintain fertility via cryopreservation of ovaries and/or oocytes, these trials seem to be meaningful for the presupposition of accurate prediction. Promising results have also been reported for incipient POI and autoimmune ovarian failure [54, 55]. However, more accurate data will be needed to identify a potential POI population among women with low serum AMH.

Diagnosis of polycystic ovary syndrome (PCOS)

PCOS is one of the most common reproductive endocrine disorders in women [56, 57]. Diagnostic criteria include polycystic appearance of the ovaries accompanied by anovulation or oligoovulation and/or excess androgen production [58, 59]. The increased number of cystic follicles is mostly related to AMH-producing small antral follicles. Therefore, serum AMH levels increase by 2–3-fold in women with early stage PCOS compared with normal controls. The sensitivity of serum AMH for diagnosis of PCOS ranges from 64 to 99 % [60–68]. The wide range of sensitivities among studies is likely due to variations in diagnostic criteria and in the age of the patient population. A recent systematic review and meta-analysis that included ten studies attempted to establish an appropriate diagnostic threshold and found that a cut-off level of 4.7 ng/ml maximized the sensitivity and specificity (82.8 and 79.4 %, respectively) of serum AMH levels for diagnosis of PCOS [69].

The pathogenesis of PCOS is heterogeneous, which is why a variety of diagnostic criteria have been proposed [58, 59, 70]. The ability of AMH to determine the subphenotype and severity of PCOS has also been examined. Marked elevation of serum AMH predicts higher luteinizing hormone levels [71] and severity [72, 73]. On the other hand, higher serum AMH has also been found after reproductive performance improves due to weight loss [74].

Laparoscopic ovarian drilling (LOD) has been advanced as a promising treatment for PCOS, with reported postoperative pregnancy rates of up to 39.7 % and a reduced risk of multiple pregnancies [75]. The effectiveness of LOD has also been examined in association with serum AMH levels. Amer et al. found that lower preoperative serum AMH level may be predictive of ineffective LOD [76], and this finding was confirmed in a subsequent report [77]. In sum, AMH may be useful as an adjuvant diagnostic or prognostic tool for PCOS, and it may also provide insight regarding the pathophysiology.

Chemotherapy

Decline of ovarian reserve after chemotherapy

Regular or irregular menstruation and amenorrhea are qualitative indicators of ovarian function. Some types of chemotherapy cause complete depletion of follicles, which is diagnosed by amenorrhea and elevated FSH. It is now known that some survivors of childhood cancer who have regular menses also have decreased AMH levels, and in

numerous studies, serum AMH was found useful for the qualitative evaluation of follicle depletion after chemotherapy [78, 79]. AMH has also been examined as an indicator of follicular loss in women who are diagnosed with breast cancer [80–82] and lymphoma [83]. Cross-sectional studies have shown a specific association between serum AMH level and type of chemotherapy [84]. More specifically, in a longitudinal follow-up study of young women diagnosed with lymphoma, the pattern of recovery of serum AMH levels was clearly different between those who received non-alkylating agents and those who received alkylating agents [83].

The usefulness of AMH in the field of oncofertility has been well studied, and limitations have also been found. An absence of serum AMH does not signify the complete depletion of oocytes in every case. Women with persistently undetectable levels of serum AMH after chemotherapy can resume regular menstruation [85, 86], and, as mentioned, among women in the general population, serum AMH levels may become undetectable up to 5 years before menopause [45]. These findings could change once a more sensitive AMH assay becomes available.

The use of gonadotropin-releasing hormone agonists for protection of the ovaries is another controversial issue, and measurement of serum AMH levels has also been adopted in a clinical trial (the "OPTION" trial) to better investigate this issue [87].

Prediction of ovarian insufficiency after chemotherapy

A future interesting application of AMH is its predictive potential for determining post-chemotherapy status of menstruation and/or ovarian insufficiency. Anderson et al. have recently proposed that the pretreatment AMH value may be a useful predictor of long-term chemotherapy-related amenorrhea in women who are diagnosed with early breast cancer [88]. These women may opt for fertility preservation via oocyte and ovarian tissue cryopreservation, although the invasiveness of resecting the ovarian cortex and the time necessary for oocyte retrieval could be an issue. Selection criteria for patients undergoing ovarian tissue cryopreservation have been proposed, but definitive criteria for the strict selection of eligible candidates are far from being determined [89]. AMH values in combination with other indices, such as age and chemotherapeutic regimen, could further refine the criteria, and prospective studies will be needed to firmly establish the predictive potential of AMH values in various circumstances in order to guide formulation of appropriate criteria for eligibility for fertility preservation.

Decrease of ovarian reserve in relation to gynecologic disease/intervention

Endometriosis

The impact of surgical treatment for endometriomas on the oocyte yield in assisted reproductive cycles has been controversial [90]. Not all women who wish to conceive after surgery for endometriosis will require assisted reproductive technology. Therefore, post-surgical evaluation of ovarian reserve based on oocyte yield may be subject to patient selection bias. In this situation, it is not surprising that researchers began to adopt serum AMH levels. Chang and Iwase were the first to report the decline of serum AMH levels after excision of endometrioma(s), especially in bilateral cases [91, 92]. Afterwards, numerous other reports confirmed that AMH levels decreased after removal of endometriomas [93–96], and steeper reductions were observed after bilateral procedures [97, 98]. Two systematic reviews evaluating the effect of endometrioma surgery on ovarian reserve as assessed by serum AMH measurement have been published [99, 100]. Bilateral removal of endometrial cysts is one of the greatest risk factors for severe decrease in ovarian reserve. Other risk factors include high revised American Society Reproductive Medicine score, larger cysts, thermal damage caused by bipolar coagulation, and removal of the ovarian cortex [94, 97, 101–103].

Excisional surgery has been recognized as the gold standard for the management of endometriomas because women have higher rates of spontaneous pregnancy and lower rates of recurrence after treatment [104]. Decreased serum AMH levels after excision of endometrial cysts has been regarded as a marker for the assessment of surgical outcomes. It has also been proposed that the method of hemostasis after laparoscopic excision of endometriomas affects ovarian reserve, and several of these methods, including suturing, bipolar coagulation, and application of hemostatic materials, have been compared to determine which is best in terms of preservation of ovarian reserve [102, 103]. Moreover, a clear advantage in the preservation of serum AMH levels has been shown after combination treatment with vaporization and GnRH agonists vs. excision [96]. These findings could be useful to decision-making during treatment planning for patients with endometriomas. However, maintenance of ovarian reserve will ultimately be confirmed by pregnancy and live birth rates, and to date, only preliminary data are available to show an association between post-surgical AMH levels and pregnancy.

Other gynecologic conditions and ovarian reserve

Excisions of benign ovarian tumors including mature cystic teratomas are common surgical procedures. These procedures might also affect ovarian reserve. However, they are generally regarded as less invasive than comparable procedures for endometriomas, allowing better preservation of ovarian reserve. This has been confirmed by comparison of serum AMH levels [91, 92, 105, 106].

Blood supply to the ovaries may also affect ovarian function, including folliculogenesis. Women undergoing assisted reproductive procedures who have had previous salpingectomy as a treatment for hydrosalpinx may experience recurrent failure of assisted reproductive cycles. Salpingectomy and uterine artery embolization, which is a fertility-preserving intervention in cases of postpartum hemorrhage, may have lasting effects on blood flow to the ovaries, leading to a decline in ovarian reserve [107–110]. To date, decreases in serum AMH levels related to surgical procedures or gynecologic diseases other than endometriomas do not seem to have strong influence on ovarian reserve.

Diagnosis and follow-up for granulosa cell tumors

Adult-type granulosa cell tumor is a less common ovarian tumor that causes irregular vaginal bleeding due to a rise in serum estradiol levels in postmenopausal women. The symptoms are less pronounced in premenopausal women. AMH and inhibin B are both produced by granulosa cells and may therefore be useful as markers of proliferation of granulosa cell tumors. Several studies have shown that the serum AMH level has high sensitivity in the diagnosis of granulosa cell tumors. In addition, AMH can be a useful marker for detecting recurrence of these tumors [111–114].

Standardization of the AMH assay

Lastly, standardization of the AMH assay is one of the most pressing issues in AMH research. AMH immunoassays were first developed by Hudson et al. in 1990 [115]. Thereafter, two proprietary AMH assay kits, Active AMH and EIA AMH/MIS [Diagnostic Systems Laboratory (DSL) and Immunotech (IOT)] were brought to market. Each kit used different AMH antibodies, resulting in different assay ranges and different inter- and intraassay coefficients of variation [116, 117]. Beckman Coulter merged DSL and IOT and developed a new AMH assay kit (AMH GenII). Although the three kits have shown good correlation in assay values, considerable diversity exists in conversion values among the kits [118]. Therefore, caution is required when comparing absolute values from clinical studies that use different assays. An important task that should be undertaken as soon as possible is the formulation of an international reference standard for AMH assays.

Another issue concerning AMH assays is that of their sensitivity. Several studies have shown that live births are possible even when AMH levels are undetectable [119, 120]. Serum AMH level is generally considered a better marker of ovarian function than basal FSH level. However, undetectable AMH is less specific for the detection of loss of ovarian function than elevated basal FSH. Ansh Labs has recently developed a hypersensitive AMH ELISA kits that allow ultra-sensitive AMH and pico-AMH measurements. Several studies have confirmed that these kits are capable of detecting AMH at low concentrations [121–

Table 1 Utility and limitations of measurements of serum anti-Müllerian hormone (AMH) levels in various clinical conditions

	What have we learned?	What should we know?
Medically assisted reproduction	Good correlation to oocyte yield	Predictive potential for live births
	Predictive potential for poor and hyper-response	Optimization of protocols to improve treatment success
General population	Peaks around 25 years of age and gradually declines	Predictive potential for future fertility
	Very low serum AMH level does not necessarily mean sterility	
Menopause/POI	Undetectable serum AMH level is followed by menopause within a certain time period depending on age	Selection and diagnosis of subclinical POI
PCOS	Elevated serum AMH level is correlated with severity	Association with pathophysiology
		Optimization of treatment schedules according to serum AMH levels
Ovarian toxicity/surgical intervention	Decline depending on chemotherapeutic regimens and surgical interventions, especially cystectomy for endometriomas	Indication of fertility preservation
		Optimal interventions according to ovarian reserve

POI primary ovarian insufficiency, *PCOS* polycystic ovary syndrome

124], and they may therefore be helpful for improved follow-up and a more detailed understanding of declining ovarian reserve immediately prior to the loss of ovarian function.

Conclusions

The quantitative measurement of serum AMH levels has revealed that ovarian reserve may vary in women of the same chronological age. Moreover, we can safely say that AMH is the most reliable marker of ovarian reserve, which may be useful for a wide range of clinical applications including the optimization of fertility treatments, the diagnosis of disorders of reproductive endocrinology, and the assessment of ovarian toxicity due to medical and surgical treatments (Table 1). However, no definite conclusions have been reached regarding the utility of serum AMH as a predictive marker for live births or its potential to improve reproductive healthcare and cost-effectiveness.

Compliance with ethical standards

Conflict of interest Akira Iwase, Tomoko Nakamura, Satoko Osuka, Sachiko Takikawa, Maki Goto, and Fumitaka Kikkawa declare that they have no conflicts of interest.

Human/animal studies This article does not contain any studies with human or animal subjects performed by any of the authors.

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